

The AeroElectric Connection



Bob Nuckolls
12th Edition

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Robert L. Nuckolls III, AeroElectric Connection,
P.O. Box 130, Medicine Lodge, KS 67104-0130,
Email: bob.nuckolls@aeroelectric.com

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Direct Current and Wiring Fundamentals

Every discipline has its own spoken and written language. Carpenters speak of "cripples, jacks and studs" while illustrating their tasks with familiar shapes that describe something as yet to be. Hydraulics designers use words like "pilot valve, cylinder, and bleeder" described on paper with yet another set of symbols. We promise not to try to make you an engineer but there are a few rudimentary analytic tools and language that will help you navigate this new terrain. If you already have a working knowledge of Ohm's Law, how to calculate power consumption and read schematics and wiring diagrams, then proceed directly to Chapter 2. If you do not possess these skills, spend some time with us in this chapter and we'll tell you about it:

The Story of Electron Behavior

A long time ago, in a galaxy not very far away there were four gentlemen named Volta, Ohm, Ampere and Watt. They aren't around any more but they left us with some tools that help us predict the behavior of some very tiny critters known as electrons. Nobody has ever seen one but we know where they are because they can be made to do some amazing and otherwise difficult tasks.

The Force Behind the Flow

The first behavior trait is described in terms proposed by Mr. Volta. The Volt is a unit of measure that represents the PRESSURE behind a source of electrons; its generic name is "electromotive force". The Volt has been given attributes much like pressure exerted on a liquid or a gas. For example, you can have an air bottle filled to 100 PSI of air. The PSI value represents a potential for doing work. The air could be used to run a rivet gun or drill motor. If the bottle's valve is closed, there is no movement of the air in spite of the pressure and no work is being done. In the electrical world, a 12-volt battery has twice the 'pressure' behind its stored electrons as a 6-volt battery. Until you connect wires to the battery and route the energy to some location to do work then the potential energy contained in the battery stays there waiting to be used.

Voltage is measured as a difference in electromotive force between two points. Voltmeters come with probes on two test leads and you touch the probes to two points simultaneously to measure the voltage between them.

The Flow

The next trait is measured in Amps, a unit that represents a RATE like jelly beans per day, miles per hour, and the like. An ammeter is a device that is hooked in series with a conductor supplying an electrical device with power. The term 'in series' means that you literally break the wire and insert the ammeter in the gap. In this way it can detect and display the number of electrons per second that pass through on their way to do work. If we made a comparison in the compressed air bottle analogy we would need to place a gauge in the air line to measure molecules per second of air flow.

A flow of electrons (amps) together with pressure (volts) will do work. They start engines, light lamps, spin gyro motors, run radios and do all manner of nifty tasks.

Tight Places Along the Way

Unfortunately, there is no way to move the electrons from their source (such as an alternator or a battery) to the location where they are to do work without losing some of their energy along the way. If you hooked one mile of air hose to the 100 PSI air bottle, you would be disappointed at

Ohm's Law in algebraic terms:

$$(1) \text{ VOLTS (FORCE)} = \text{AMPS (FLOW)} \times \text{OHMS (RESISTANCE)}$$

$$(2) \text{ OHMS} = \frac{\text{VOLTS}}{\text{AMPS}}$$

$$(3) \text{ AMPS} = \frac{\text{VOLTS}}{\text{OHMS}}$$

Figure 1-1 Ohm's Law - Three Variations on a Theme

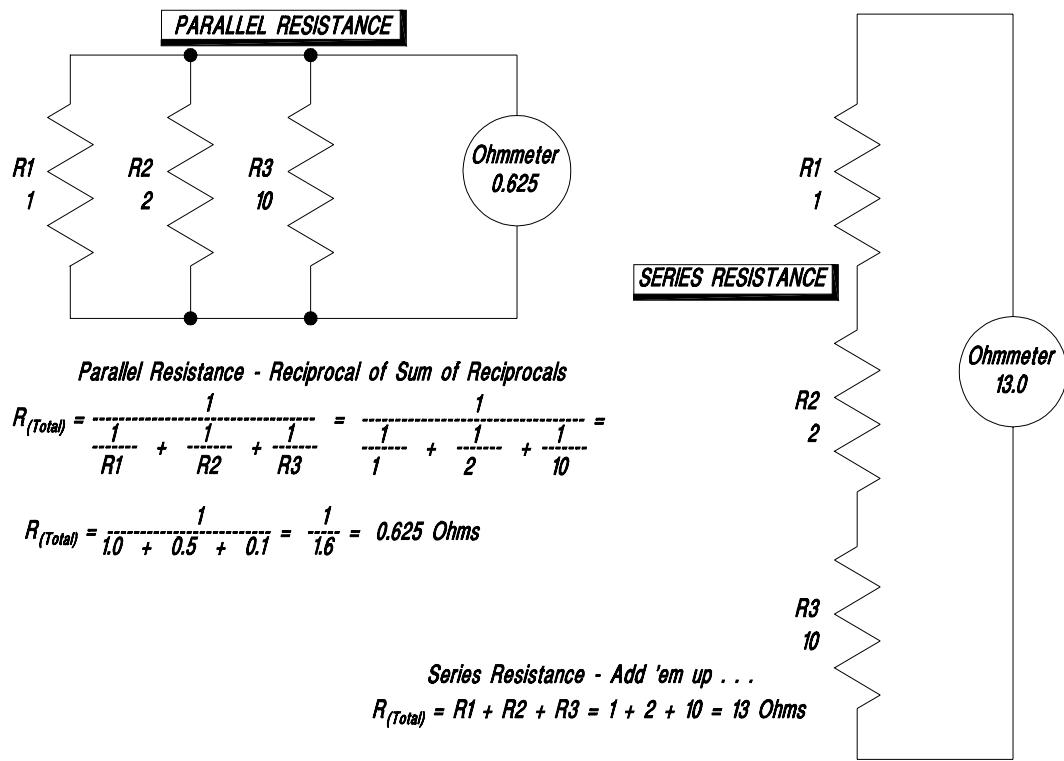


Figure 1-2. Series and Parallel Resistance Calculation

how little energy the air contained when it got to the other end. Something similar happens when electrons flow through a wire. The wire's ability to carry electrons is limited by its resistance, a sort of electrical friction.

The name for this characteristic is the Ohm. Ohms represent nothing but a potential for wasting energy. They are of little practical use in an airplane electrical system but they're always there. You can minimize them, make peace with and endure a certain number of them, but you cannot make them all go away. In order to talk about ohms and understand their effects, Mr. Ohm wrote a law. He said that if you pass one amp (electrons per second) of current through a conductor having a resistance of one ohm, you will experience a drop of one volt (pressure). If the flow is increased to two amps, then drop is two volts, etc. This gives rise to this mathematical model in Figure 1-1.

Resistance Combinations

When resistances to current flow are connected in series they are simply added to obtain of total resistance. Series means that they are connected end to end in a string. Parallel connection means that the resistors are connected up laying side by side like cordwood. Paralleling resistors is a little different. If all the resistors are equal, then the net total is equal to the value of one resistor divided by the number of resistors. For example, five 10-ohm resistors in

parallel net a total of 2 ohms. If the resistors are not equal, then you need to get your calculator out and apply the following rule:

"The parallel value of any number of resistors is equal to the reciprocal of the sum of the reciprocals of each resistor." In Figure 1-2 I've illustrated a parallel combination of 1-ohm, 2-ohm and 10-ohm resistors that produces a resistance of 0.625 ohms for the combination.

When resistors are connected in series, the same current flows in each and the sum of the voltage drops across each resistor equals the total voltage applied to the string. When resistors are paralleled, the same voltage is impressed across each resistor. The sums of the current flowing in each resistor is equal to the total for the combination. These principles will be used throughout this publication to aid in selecting wire sizes, predicting performance of various equipment items and understanding the limitations of other items.

Energy Rate - The Watt

Now we can introduce the last gentleman of the quartet I mentioned before, Mr. Watt. He described a unit of energy rate (now named after him) as being proportional to the product of pressure and flow. The mathematical model for this and two corollaries are given in Figure 1-3..

Rules for calculating power:

$$(4) \quad \text{WATTS} = \text{AMPS} \times \text{VOLTS}$$

$$(5) \quad \text{WATTS} = \frac{\text{VOLTS}^2}{\text{OHMS}}$$

$$(6) \quad \text{WATTS} = \text{AMPS}^2 \times \text{OHMS}$$

Figure 1-3. Mathematical Identities for Calculating Watts.

Suppose you found a landing light bulb marked "150 Watts" on its face. It may or may not be marked for its rated operating voltage but in 14-volt systems (12-volt batteries) the design point for many large lamps is 13.0 volts. Later on in this publication there will be a section on

wiring where you will find a wire table that says a 16 gauge wire has a resistance of .004 ohms per foot. Not much but significant. Let's suppose that your airplane is a composite structure and that the landing light is out on a wing tip. You need to run two lengths of wire, a source and a return line for the electron flow since there is no metal airframe to provide the second path. Suppose that the total run of wire in the schematic is 24 feet times .004 ohms/foot yields a total loop wiring resistance of .096 ohms.

To figure the voltage drop in the wiring, we must first deduce the amount of current required by the lamp. Applying formula (4) above we can say the following:

$$150 \text{ Watts} = \text{Amps} \times 13.0 \text{ Volts}$$

Transposing we can say:

$$\text{Amps} = 150 \text{ Watts} \div 13.0 \text{ Volts}$$

$$\text{and Amps} = 11.54$$

If the total resistance of the wire is 0.088 ohms then we can apply formula (1) from Figure 1-1 as follows:

$$\text{Volts} = 11.54 \text{ Amps} \times .096 \text{ Ohms}$$

$$\text{and Volts} = 1.1$$

This hypothetical is illustrated in Figure 1-4. The schematics don't show an alternator charging the battery but let's assume there is one so that the voltage at the battery terminals is 13.8 Volts. We have calculated a drop in the wires of 1.1 volts. Figure 1-4 shows 0.5 volts dropped along the ground path, and 0.6 volts dropped in the other (the switch adds a tad more resistance to the circuit). The lamp is being supplied with $13.8 - 1.1 = 12.7$ volts. Not much below the rated 13.0 volts.

In working this example we have uncovered techniques used by manufacturers of electrical components to make your selection and application easier. Most heavy current devices are designed and rated for some voltage less than the nominal system voltage. In this case, a 13.0 volt rated lamp might be used in a 13.8 volt system and a 26 volt rated lamp would be used in a 27.6 volt system. The parts are

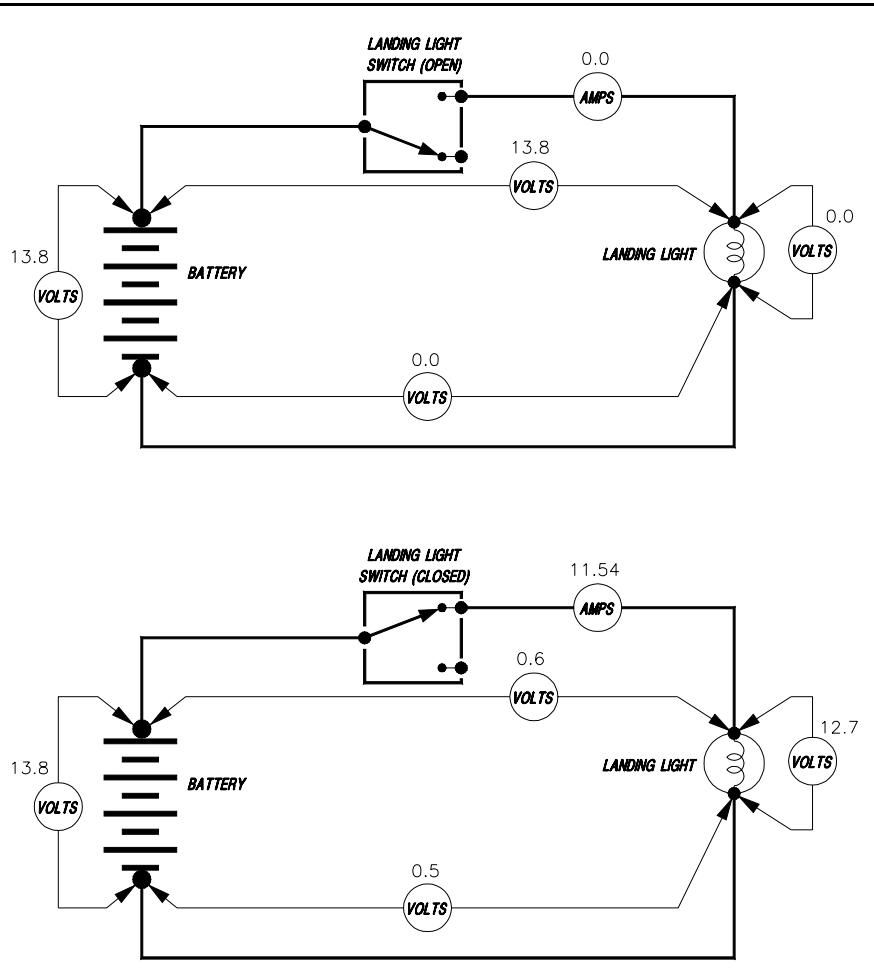


Figure 1-4 Current and Voltage in a Simple Landing Light Circuit

designed with the knowledge that it is not practical to supply power to the product with wire so large as to have insignificant resistance. We must compromise and selected wire that is reasonable in size and wastes a tolerable amount of power. How much power? Applying formula (4):

$$\text{Watts} = 11.54 \text{ Amps} \times 1.1 \text{ Volts}$$

$$\text{and Watts} = 11.78$$

Not too bad considering; 150 watts of energy DOES get to the lamp's filament! But you can see there is a compromise that says an 8% or so loss of power IS acceptable.

Open the switch and the path is broken. No flow (amps) can occur. The voltage is still there as a potential for keeping the lamp's filament hot but you cannot stuff electrons into one end of a device without having some place for them to go out the other end. Figure 1-5 shows what the voltage readings would be when the lamp is off.

Wirebook and Schematic Symbols

WIRES: We've already used some symbols to described an electrical circuit for purposes of explaining how the units of electrical measurement are related to each other. Let's start with those devices and work up.

The most rudimentary component for herding electrons is

a wire or other conductor used to covey electrons from one place to another. This symbol is a line. Like road maps for cars, conductor maps for electrons may embellish the line with variations in width, style or color. There are no hard conventions or rules for variations on a theme of diagraming a wire or any other component. If you compare the wiring diagram for a European automobile with a similar diagram for an American or Japanese product, you'll see some striking differences in presentation philosophy and some minor variations in how the same kinds of components are portrayed. By-and-large, these variations are simple variations of "linguistics" akin to the use of "pancake, flapjack or griddlecake" being used to describe the same item of food.

The style I've developed for the AeroElectric Connection is a blend of my experiences in electronics and aircraft power distribution. In 40 years I've worked with many styles of schematic and wiring diagrams. Some features (in my not so humble opinion) detracted from ready understanding of meaning. Other features were not esthetically pleasing. However, like mathematics, wiring diagrams and schematics have a degree of commonality that crosses all barriers of spoken language.

Because the 'Connection is not yet printed in color, variations in our schematic representations for wire will be limited to weight of the line combined with some label that will convey additional information about the wire's size, color and position in the system. For example, if you see a wire label like this:

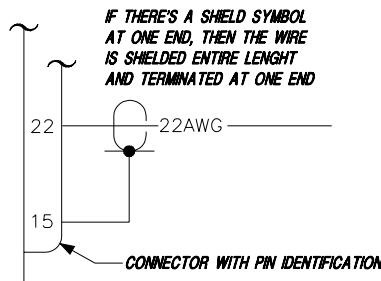
-----20AWG-----

You may deduce that this conductor is a size 20 American Wire Gage conductor. You can assign no additional meaning to this label. In many cases, this is all that's needed. Suppose you see this:

----- RED22 -----

Here we'll suggest that the wire is 22 gage in size and red in color. This is about as far as we need to go for labeling wires in our relatively rudimentary drawings.

Wiring diagrams



IT IS POSSIBLE TO EMBED A LOT OF INFORMATION IN A WIRE'S LABEL
BEST ADVICE: KEEP IT SIMPLE

RED20
AWG20
L4A16
12

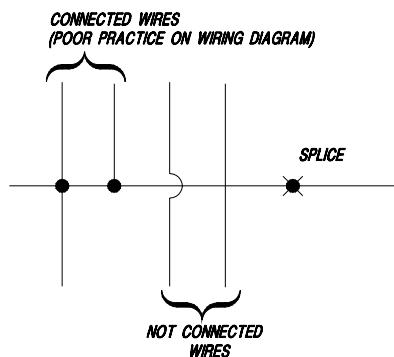


Figure 1-5. Wire and Wiring Symbols

provided for other people's products may use more elaborate system for wire labeling. For example. Suppose you see a label wire label in a wirebook that looks like this:

----- L4A16-----

In many airplanes this label is also repeated on the wire itself by means of hot-stamping or other means; usually about every 6" along the entire length of the wire. The wire marking operation is accomplished on special machines that measure, mark and coil every conductor in the airplane as if it were a separate part number.

With verbose wire marking systems, the wirebook should include a key for decoding the system's labeling conventions. For example, if I found this label on a wire an a B-52, my first pass at decoding it would suggest that "L" means some kind of lighting circuit. The "4" would mean it's the 4th lighting circuit of perhaps several more. The "A" means it's the first segment in that circuit. Segment A might run from circuit breaker to switch. Segment B would go from switch to perhaps some connector at the wing root. Segment C would continue on out to a light fixture. The digits "16" would suggest this circuit is wired with 16AWG material.

Obviously, this kind of wire coding scheme can be used to convey a lot of meaning about the wire and its function - valuable information when dealing with complex systems on complex airplanes with fat wire bundles.

I don't recommend that the owner-built-and-maintained (OBAM) airplane project be extended to include such effort. First, the relative simplicity of our airplanes will not benefit much from being able to tell which wire in a bundle of dozen or so wires is used to power a landing light vis-a-vis the nav lights. Second, it takes TIME to design, document and fabricate this kind of detail in your project's drawings. Unless you plan to build the ultimate show aircraft where one may gain points for crafting and implementing an articulate wirebook, this kind of detail is a waste of time.

However, if you're designing a new Sky Thrasher 2000 with a goal of manufacturing kits and pre-fabricated wire bundles, then your project's documentation will have to be more comprehensive with a bill of materials that includes the actual length of each wire segment. This is the only case where I could justify spending much effort on a complex wire labeling system.

If you want to label your wires for easing future maintenance efforts, a simple numbering of a wire segment will suffice. The 4AWG wire from battery contactor to starter contactor might have the number "1" depicted at each end of the segment. Similarly, the next segment from starter contactor to starter might be "2" . . . or any OTHER

number unique to that segment. The same number would be used to label that segment on your wiring diagram where you might call them "1-4" and "2-4" meaning segments 1 and 2 fabricated from 4AWG wire. I wouldn't bother to put the wire gage callout on the wire itself as most wire suited for aircraft is already labeled as to its size.

It's not even necessary or useful to use EVERY number in sequence. For example: my first drawing might be the landing light circuit wherein perhaps 4 wire segments are used to hook up the system. I might use the numbers 10-14 to label these wires. For the next system, I might use 20-26. This leaves some open spaces between system so that if you change anything later and need to add a segment, there are open numbers next to the original numbers that can be used to identify the new wires.

This gives rise to the possibility of assigning groups of wires to various systems. For example, labels 1-19 might be reserved for DC power generation and distribution. 20-29 for the starter system. 30-39 for landing light, 40-49 for nav lights, etc. This way, you can know which system a particular wire belongs to by observing the group in which its label resides. This scheme generally leaves handy gaps in the numbering so that any later additions to the system have unused numbers reserved within that grouping.

In some of wiring diagrams, I may use "fat" lines on drawing to depict the major power distribution pathways which are generally 2 to 8AWG conductors. I won't go beyond this simple convention for explaining how a system is fabricated.

When I hook wires up on paper, I try to convey as much meaning as possible and avoid ambiguous symbology. For example, wires that cross each other in a diagram may have a "hump" in one wire to show that they do not connect. It's okay to leave the hump off and assume that they do not connect unless there is a "dot" at the intersection. I never use a mid strand intersection without being very specific as to how the wires are joined. I use a specific symbol for a splice that tells you that it's my intent that the wires be simply joined in mid span between major components. Unless a mid-span splice is intended and planned, wires on our diagrams will always come together at a location conducive to implementing the connection. I.e, the stud of a contactor or the wire grip of a terminal. The act of tying two wires together mid-span with a simple dot is used on a schematic . . . a kind drawing intended to convey functionality without specifics as to the mechanics of implementing fabrication.

There are a few special cases for wiring symbology. Sometimes, the designer would like for you to twist the wires together. The most common reason to twist wires is to minimize their susceptibility to magnetically coupled noise (more on this in the chapter on noise). Sometimes it's done simply to custom fabricate a pair of wires that work

together in some system. Whatever the case, my favorite way to depict a twisted pair is shown in the adjacent figure. Another special case is shielding. When you see the little “race track” surrounding one or more wires, this tells you that they are shielded. The most common shielding techniques use either an overbraid of fine bare wires or an overwrap of thin aluminum foil. The overbraid is made from tinned copper wire. It’s easy to make an electrical connection with overbraid shields.

Foil shields cannot be soldered to. Manufacturers who produce this wire will include a bare “drain wire” in the compliment of insulated wires to be shielded. The drain wire makes connection with the inside surface of the aluminum foil shield over its entire length. Being made up tinned copper conductors, the drain wire offers a means for efficient electrical connection to the shield.

The symbol for shielding is the same irrespective of the material from which it is made. The designer should show you exactly how the shield is to be treated at BOTH ends. In some cases, both ends are connected but not always. If you see a shielded wire symbol on one end of a wire segment, it means the entire length of that segment is shielded whether or not the other end has a shield symbol. Obviously, if the designer intends that both ends of the shield are connected to something, the symbol will appear at both ends along with a depiction of where the shield is terminated at each end.

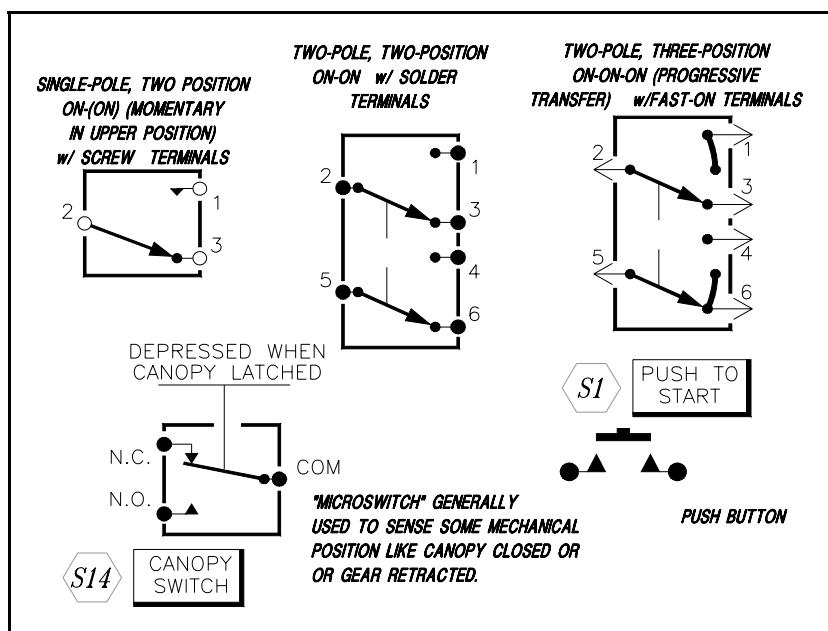


Figure 1-7. Switches and Pushbuttons

BATTERIES: The symbol for a “cell” is depicted as a long and short line where the most common convention is to assign (+) terminal of a cell to the longer of the two lines. A “battery” is a collection of two or more cells. Some folks try to be accurate in their depiction of battery symbols by including the same number of cells in the symbol as for the battery called out in the drawing. I don’t bother with that so the battery symbol you see here will be used consistently irrespective of the number of cells and the operating voltage of the battery.

SWITCHES: The symbols for switches are pretty good physical representations of switch operation. There are detailed examples of the various switches that appear in our drawings in the chapter on switches later on in this volume. A convention used by many designers and used throughout this book uses a triangular contact to denote a momentary contact while a circular contact is a sustained switch position.

Some designers will include additional information about the mode of attaching wires to their switches . . . an open circle denotes screw terminal and a solid dot is a solder joint. The $\rightarrow\rightarrow$ symbol on the wire denotes some form of pin and socket connection. I’m really sold on the reliability and convenience of the push-on spade or “Fast-On” tabs and terminals. The same symbol is shown on one of the switch depictions where Fast-Ons are featured. Detailed depictions of solder, screw, or pin-socket connections may not be consistently called out on our drawings for various products.

The intent of this discussion is to make you aware of the variety of connection technologies and how they may be depicted on a wiring diagram. You should take advantage

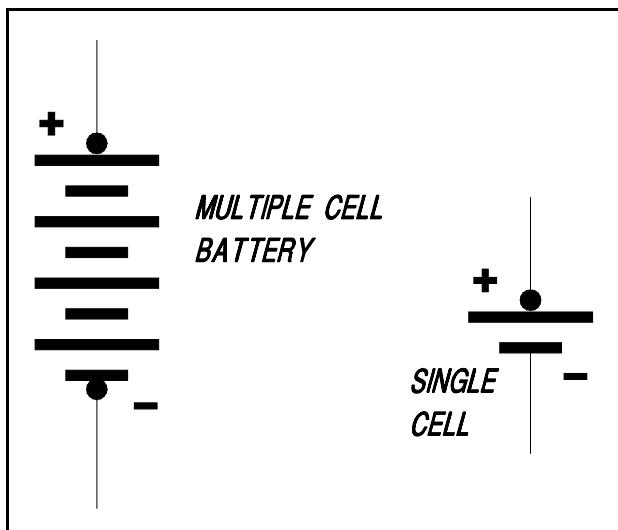


Figure 1-6. Cells and Batteries

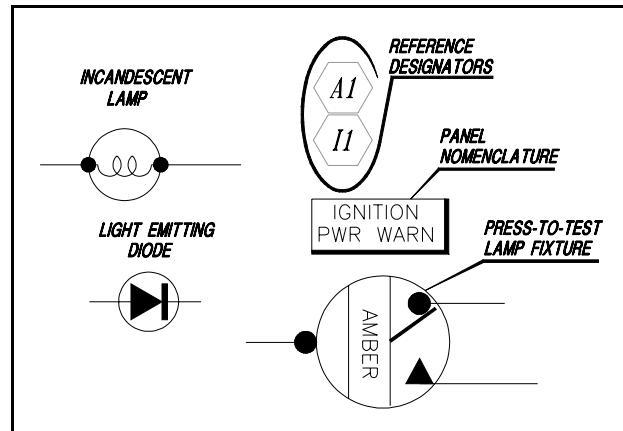


Figure 1-8. Various Lamp Symbols - plus examples of supporting data included in many of our drawings.

of this symbology to put as much meaning into the drawings you produce for your project.

Switches come in a variety of styles and functional capabilities. These devices are discussed in more detail later in this book. It's relatively easy to depict functionality in the device's wiring symbol and it's no sin to craft or revise a symbol in a way that clarifies meaning. For example, I first encountered progressive transfer, two-pole, on-on-on switches at Cessna about 1965. I was editing a service manual for an ARC autopilot. The engineering drawings provided to me drew a two-pole, progressive transfer switch looked just like an ordinary two-pole, three position, on-off-on switch.

There was a written note on the drawing that tried to explain the special functionality of this switch. I decided it would be helpful to craft a modified symbol exactly like that shown in figure 1-7. My boss about had a cow . . . NOT because he disagreed with value of added understanding offered by the "new" symbol . . . but because I had the temerity to ADD a word to a language described in great detail in "approved" military specification design language dictionaries.

LAMPS: The symbol for an incandescent lamp is another one of those graphics that nicely depicts the physical reality of an incandescent lamp. The symbol shows an envelope (glass) surrounding a curlicue (filament) inside. The other common light source depicted in our drawings is the light emitting diode (LED) that is shown as a diode inside a circle. If the lamp is to have a specific color, then it's often shown adjacent to or inside the symbol. Another symbol you may encounter in our drawings is for the classic, press-to-test fixture that doesn't even show the lamp but does show how to hook up the three leads from the fixture in order to make the press-to-test feature work.

Additionally, I've illustrated data items commonly found on wiring diagrams. When you choose a particular part or

piece of equipment for your project's electrical system, you should build a list of such parts and assign a reference designator to the part. Your list, or bill-of-materials, can be quite verbose in describing the part, its part number, manufacturer, ratings, etc. You don't want to put all that data on the face of a drawing . . . this is where the reference designator comes in. In my drawings, I enclose the designator in a hex box . . . this is not a standard convention, other folk use variations on the theme but they'll be easily recognized for what they are; a label that speaks nothing about the part's ratings or number . . . it's simply a pointer to a more verbose part description in another document.

In this case you see A1 and I1 as reference designators next to the symbol for a press-to-test lamp fixture. If you went to a bill of materials to look for A1, you might find that it's an MS-XXXX fixture. The symbol I1 might take you to a callout for a #330 lamp.

Another feature of my drawings is to add a panel label for the device. Switches and lights may have a shadow-box adjacent to the symbol to display suggested words that might be placarded on the panel to describe the device's function.

The odd-ball among lamps is the light emitting diode or LED. These solid state light emitters are rapidly replacing incandescent lamps in many aircraft illumination applications. The symbol for an LED is the diode with a circle around it.

Finally, if the light emitter is to be assigned a specific color, it's easy to add this to your diagram too. Note the press-to-test fixture is an amber colored device. I might include a small "R", "G", "A" etc inside the circle of a lamp symbol to call out red, green, amber, etc. colors for that particular device.

RESISTORS: We've already had some discussion about resistance as an impediment to the free flow of electrons which always warms things up and turns otherwise useful electrical energy into wasted heat.

From time to time, there are instances when we WANT to do a little considered "wasting" and there are thousands of varieties of resistors available to do just that. Check the blister-pak racks of any Radio Shack store and you'll find a selection of wired devices ranging from 250 milliwatts of dissipation rating to 10 watts or more. The power rating of the resistor is determined by its ability to reject the heat dissipated in operation without getting so hot that the part self-destructs. As you might well expect, a 10 watt resistor is much larger than a 25 milliwatt device.

Resistors come in a huge range of sizes. The surface mount devices in your cell phone may be only 0.030" by 0.060" and rated for 100 milliwatts of dissipation. The dynamic braking resistors in a diesel-electric locomotive wouldn't fit

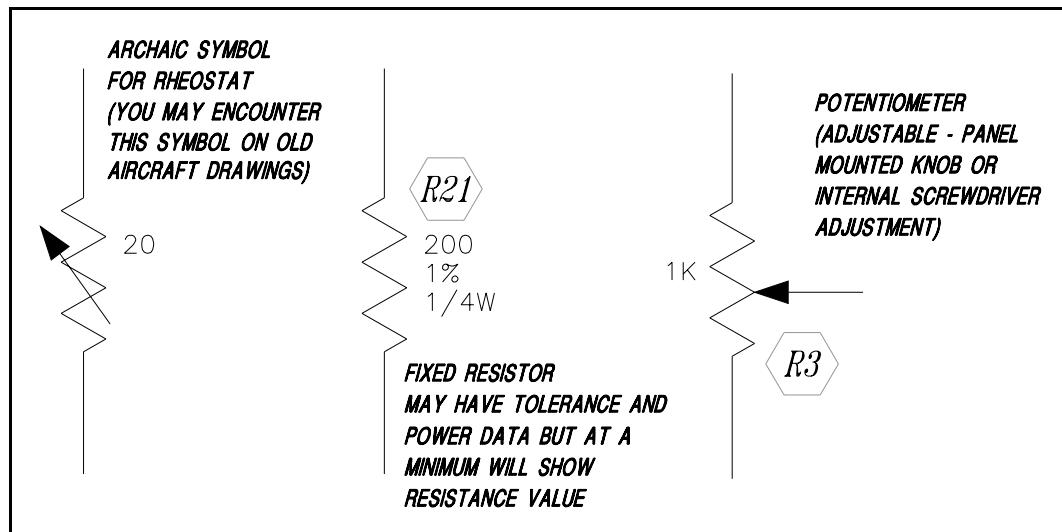


Figure 1-9. Resistor Symbols

into a 35 gallon drum and are designed to turn tens of thousands of watts of electrical energy into heat.

The electrical symbol for all of these devices is the same. You will find this symbol used very seldom on our power distribution diagrams . . . potentiometers are used to dim panel lights and the occasional resistor may show up as a current limiting device to be used in lieu of a fuse in some applications. By-in-large, resistors will show up only as components internal to some appliance like an audio distribution amplifier or other "black box".

DIODES: Diodes will appear in most of our drawings for two purposes. (1) Spike catcher diodes are connected across the coil terminals of some relays and contactors and (2) Power control or steering diodes are used between the main bus and essential bus of our drawings to make up the normal power feed path for the essential bus.

A diode is an electrical check valve. Current will flow through one direction of the diode and not if it's reversed. Alternators use diodes inside to rectify the AC voltage of

the power output windings into DC voltage. A variation of the diode symbol is also used with light emitting diodes as described earlier.

The silicon junction diode is the most mature semiconductor device in your electrical system. Power versions of the device were incorporated into alternators back in the 60's. Compared to

their vacuum tube and selenium rectifier ancestors, they ARE a lightyear ahead in terms of efficiency and compactness.

Diodes come in lots of sizes and packages. Surface mounted devices for electronics can be as small as 0.030" in diameter and 0.080" long. These diminutive devices may be rated at a few hundred milliamperes forward conduction current and 50 to 100 reverse volts. Diodes used in locomotives can be the size of a gallon bucket, rated for thousands of amperes and have reverse voltage ratings in the kilovolts range.

A diode is not a perfect check valve . . . when current flows through the device in the forward (conductive) direction, there is a relatively fixed voltage drop on the order of 0.6 to 0.8 volts. Generally speaking, this has little if any practical effect on system performance but it does mean that the critter gets warm.

For example: a steering diode between the main bus and essential bus insures that the e-bus is powered any time the main bus is up. Assume an e-bus continuous load of 6 amps.

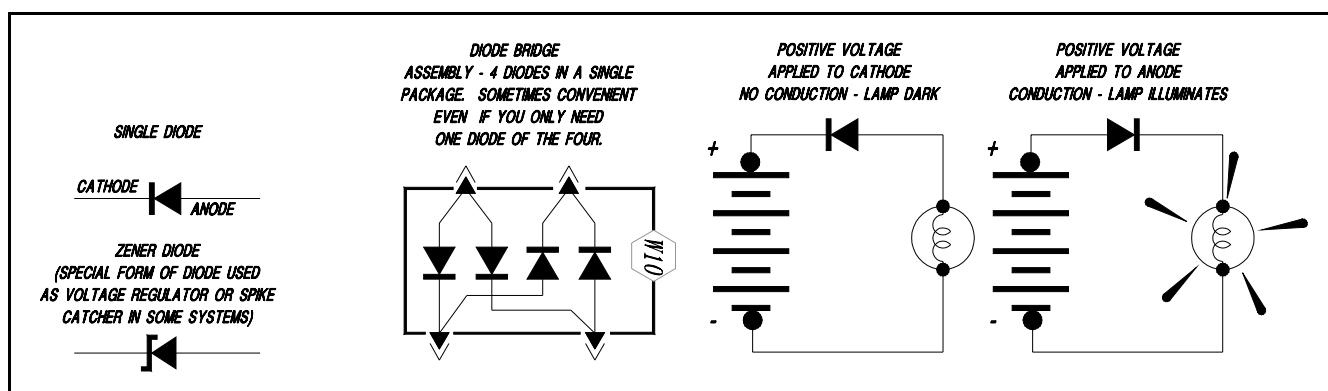
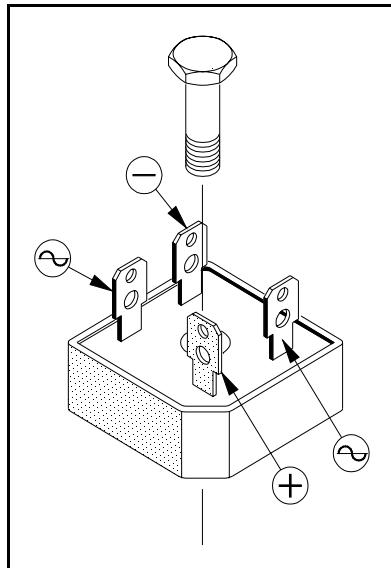


Figure 1-10. Diode Symbols

6 amps times 0.6 volts = 3.6 watts. Not a great deal of power but significant in terms of what a small, lead mounted device can handle without external heat sinking. You can purchase leaded devices good for this kind of current but they're difficult to deal with. Small plastic cylinders with wires coming out each end are intended to be soldered into an etched circuit board.

Here's a handy product for dealing with applications requiring a diode to carry more than a few amps. There's a genre of diode assemblies called "bridge rectifiers". A full bridge is assembled from a ring of 4 diodes with terminals brought out for connection into a full-wave rectifier for a DC power supply.

A version of particular interest to us looks like the adjacent view.



steering diode. Only one of the four diodes is used (two unused connection tabs can be snipped off). The mounting and interconnection features of this device make it very useful in our airplanes.

If you're looking for this device, most electronics supply stores can provide you a device that LOOKs exactly like this one. This package houses assemblies rated at 25 amps or more and nobody builds a diode with less than a 50 volt rating. So, irrespective of it's part number, any device

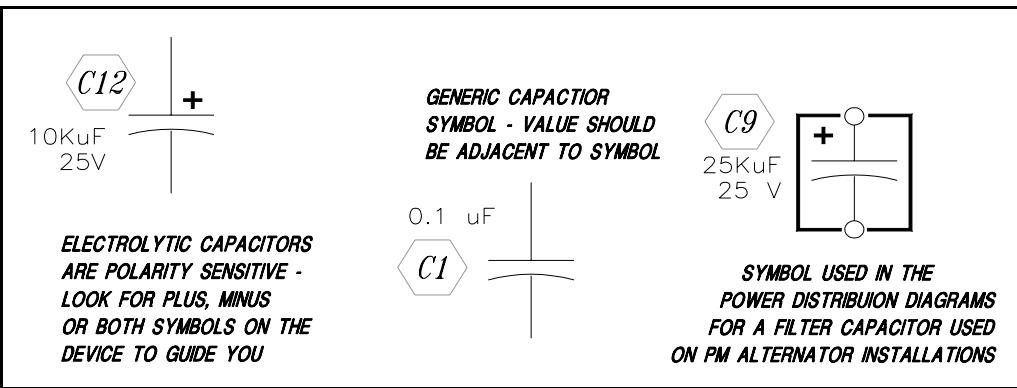


Figure 1-11. Capacitor Symbols

packaged as shown above is suited as a main-bus to e-bus steering diode or any other task in your airplane that needs a continuous current capability of more than a couple of amps.

Note this package has a chamfered corner. Note further that the terminal adjacent to the chamfered corner is turned 90° to the other three. The "odd" terminal is always the (+) connection to the diode bridge assembly (two cathodes tied together).

CAPACITOR: The capacitor is a device constructed not unlike its symbol suggests. Two conductors or plates separated by an intervening insulator or dielectric material. A couple of pieces of aluminum with a sheet of glass sandwiched between them is an excellent example of a capacitor. This device can store a charge, it can also couple varying or AC voltage variations across the insulator.

Capacitors come rated in Farads (a really big capacitor) or in smaller, more convenient sizes called microfarads (1 millionth of a Farad), nanofarads (1 billionth) and picofarads (1 trillionth). They'll also have a voltage rating that describes the largest voltage to which the capacitor can be charged without arcing over or damaging the insulator between the conductive plates. Physically, they can range in size from the tiny surface mount devices up to bathtub sized devices. Capacitors are also offered in a huge combination of construction methods to best suit the task. The capacitor you will find most often in our drawings is an aluminum electrolytic. It's a plastic covered cylinder 1.3 to 2.5 inches in diameter and 3 to 6 inches long. It will be fitted with two 10-32 threaded connections on one end. The schematic symbol I use for this device is illustrated in figure 1-x and depicts the threaded fastener connections as represented by the open circles in the drawing.

INDUCTOR: The inductor's symbol is intended to convey the notion of many turns of wire - usually wrapped around some core of magnetic material. There are some minor variations on the theme for inductors but they'll be recognized for their similarity to the devices depicted here.

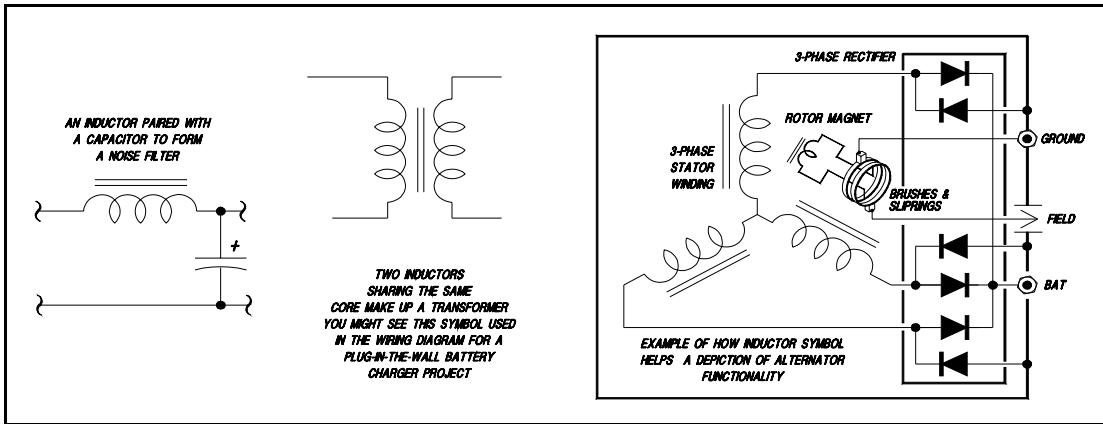


Figure 1-12. Inductor Symbols

You won't find the symbol used very much in this book. Inductors as unique components that you install to accomplish some task are rarely used or needed at the airplane system assembly level.

In the chapter on noise we'll speak to the use of inductors to fabricate noise filters that can reduce or prevent noise from propagating into or out of some part of your electrical system. The places I'll most often use the symbol is in the depiction of internal workings of devices that utilize inductors such as motors and alternators.

FUSES, CIRCUIT BREAKERS AND BUS BARS

BARS: I get a lot of questions about "bus bars" and "busses". The word is used a lot in aviation vernacular but I'm not sure its well understood. The general term "bus" refers to a common connection or distribution mechanism for a variety of power and/or signal connections. For example, our airplanes have data busses . . . a means by which multiple components talk to each other on a common connecting structure. That structure could be a wire, a coax cable, a twisted pair of wires, even a fiber optic link. Bussing things together speaks more to a concept than to a piece of hardware.

Buses discussed in this work are more narrowly confined to

discussions about power distribution. We'll speak of battery busses, main busses, essential busses, auxiliary busses and ground busses. In some cases we may have need to fabricate a lighting bus. In each of these cases, the bus is

simply a technique by which a number of loads can receive distributed power or a number of ground returns can come to a common point. The bus may be a strip of metal drilled at intervals to accommodate interconnection of a row of circuit breakers. In our favorite fuse blocks, the bus is a part of the purchased device that runs down the center of the fuseblock and provides power distribution for a suite of plastic fuses. The symbology you will find in this work is illustrated in figure 1-13.

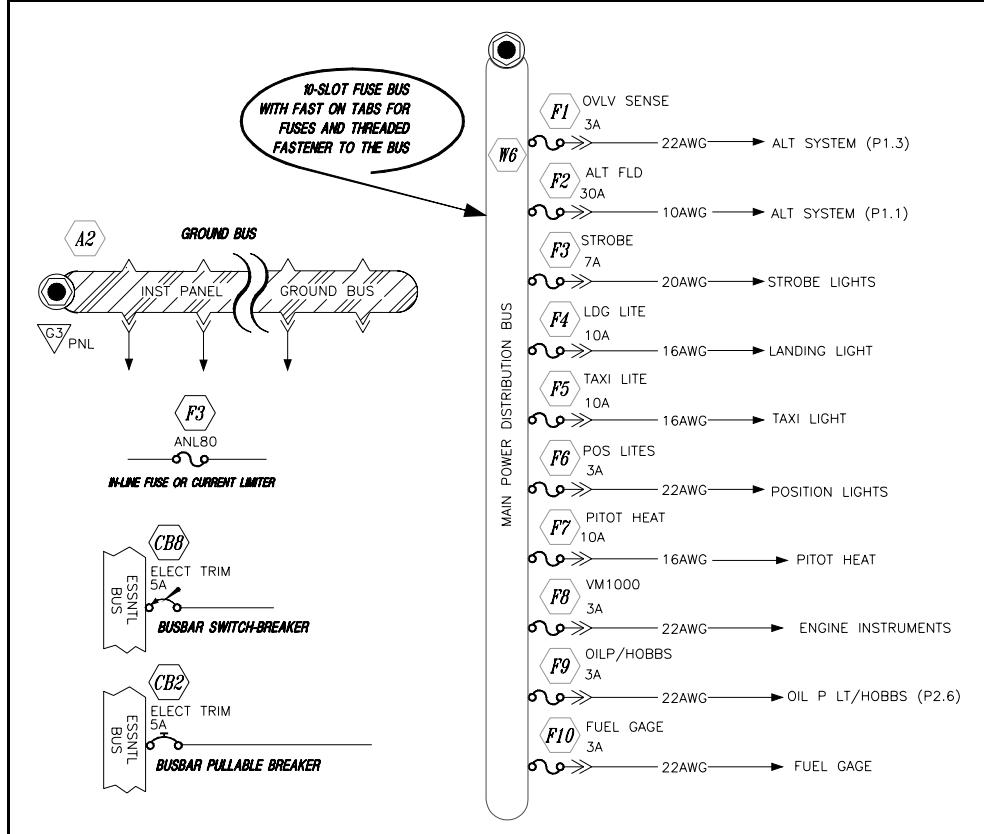


Figure 1-13. Fuses Breakers and Bus Bars

The first thing I do when planning an aircraft's power distribution system is to draw up the busses. Whether distributed to breakers or fuses, it doesn't matter. Every device needing power in the airplane has to pick it off of some protected circuit and that circuit is generally fed by a "bus".

Make a drawing for each bus and list every breaker or fuse attached to it along with the fuse's reference designator, size, function, size of wire attached to it and then some lead-off label that tells you what page the system will be found on. The first pages of your wirebook become the basis for planning a load analysis for your electrical system's various sources. These pages also become an index for the rest of the book - find the breaker that supplies the system of interest and follow the lead-out label to find the page where the system is described.

On each system page, the bus and circuit protector are repeated with just a segment of the bus illustrated. The segment needs to be labeled as to which bus the protection is fed from which leads you back to the "index" page.

This figure also shows a ground bus . . . no breakers or fuses, just a place where the suite of grounds assigned to that bus can be brought to a single location. Later in the book we'll discuss the importance of "single point ground systems".

So, there's nothing magic about a "bus" . . . in early Pipers, the bus was simply a piece of solid copper wire soldered to a row of fuseholders. Any distribution or commoning bus should be built such that no single failure along the bus will disconnect the rest of the loads. For example, I have a bus bar and circuit breaker assembly removed from a "certified" and many times annualized single engine Piper. The "bus" is fabricated from three separate pieces of aluminum strip that runs along the row of screws behind the circuit breaker panel. Loosening of any screw at the joint between the three pieces would cause electrical continuity to the remaining downstream loads to be lost as well. I've also seen builders crimp

terminals on a handful of 2-inch wire segments and then daisy-chain them down the row of breakers . . . these multi-piece fabrication techniques negate the purpose of a bus. Insofar as you can, busses should be cut from single pieces of metal. Even in a multi-row breaker panel, you can cut strips of brass or copper to build the bus structure and then solder the strips together where they would otherwise be held together by a threaded fastener.

RELAYS and CONTACTORS: Just about every airplane will have at least two contactors. One for the battery and one for the starter. Contactors (and relays) are remotely controlled switches that operate because you apply power to a coil of wire (see the inductor symbols) which in turn creates a strong magnetic field. Magnets attract magnetic materials and in this case, the magnetic material is mounted

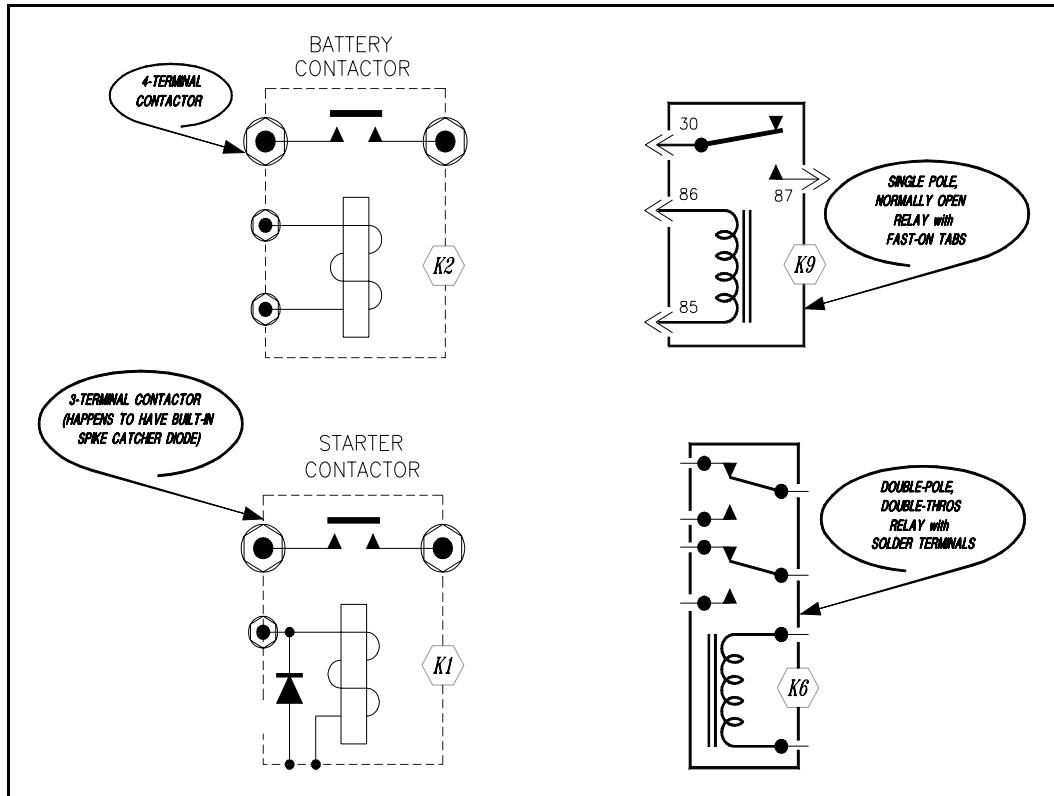


Figure 1-14. Relays and Contactors

on the movable contacts of some form of switch.

The schematic symbols for contactors and relays are strongly suggestive of their construction. Relays are generally smaller and designed to switch currents of up to 30 amps. Contactors are much beefier devices and rated to switch loads of 50 to hundreds of amps and carry loads in the hundreds of amps. You can see how the starter and battery contactor symbols suggest that a magnetized coil of wire pull down on a shorting bar to make electrical

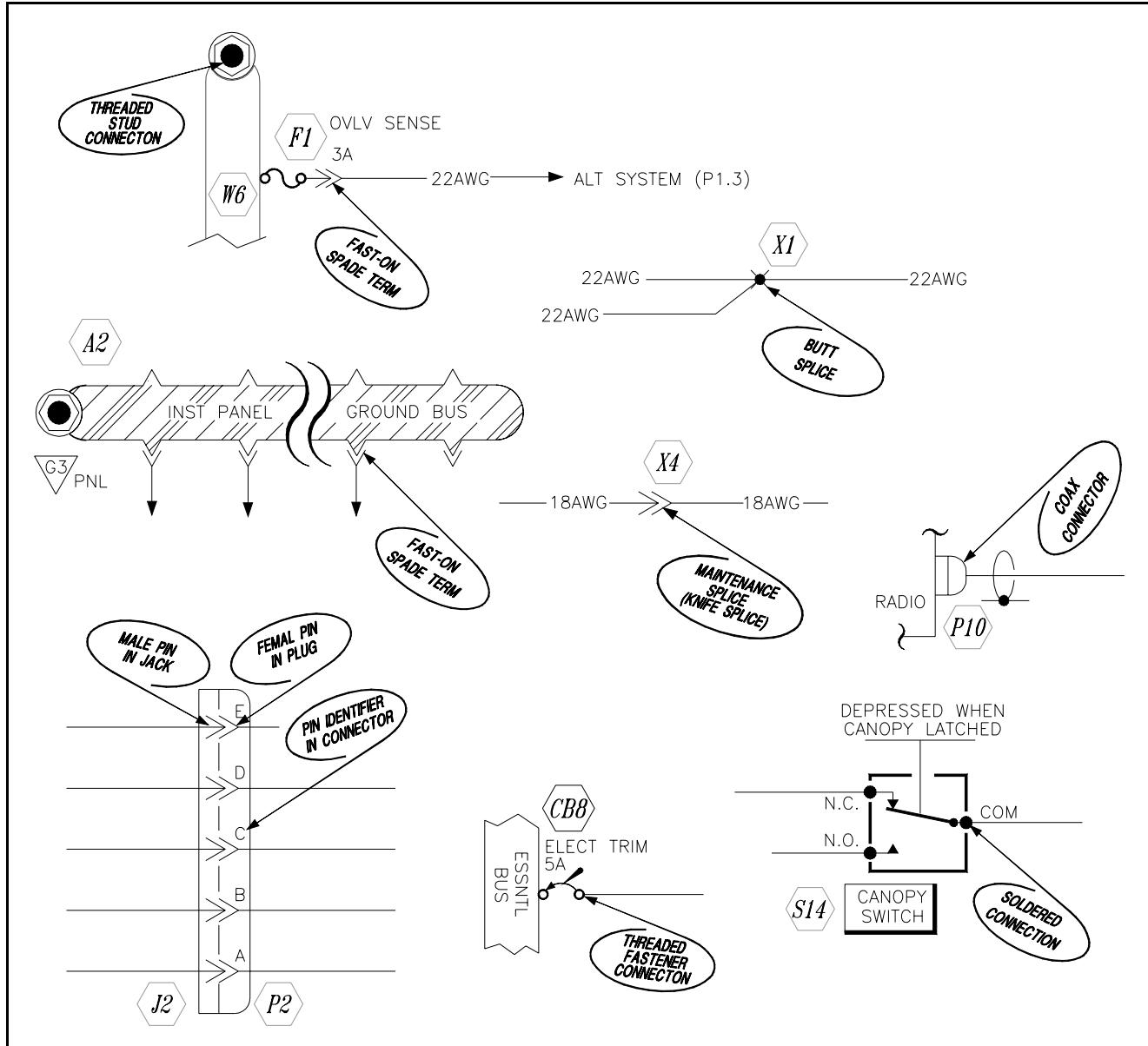


Figure 1-15. Connectors and Connections

connection between two main terminals. Note that the starter contactor symbol shows a built in diode . . . NOT ALL contactors have this feature . . . but if the contactor you've selected includes the spike catcher diode, figure 1-14 suggests how to depict it.

There is nothing unique about the symbol for a contactor to differentiate a continuous duty contactor (for battery, crossfeed and ground power applications) from the intermittent duty devices (used on starters and some landing gear pump installations). This differentiation is described in your reference designer list or bill of materials.

Relays are more like switches in that they are available in multiple poles. If needed, you can easily acquire up to 4 poles of double-throw relay in a compact, single device.

Your project may not need any relays but they can be useful in flap and trim motor control systems, over-voltage control implementation on small alternators and pilot-priority microphone selection.

CONNECTORS and CONNECTIONS: As the various wires wend their ways about your airplane, they have to start and stop somewhere and somehow. There are basically two ways to attach wires to things, crimp the buggers with some form of solderless connection or warm up the soldering iron and stick them together.

Wires will terminate either in some device that mounts the wire to a stud, a passageway through a de-mateable connector, or solder to the terminal provided on some device.

Figure 1-15 illustrates a range of connecting technologies and some symbols to help describe them. Note that the $\rightarrow\rightarrow\rightarrow$ combination of symbols are universally used to depict pin/socket combinations in connectors, Fast-On spade terminations and maintenance joints using knife splices. It's sufficient to indicate that the joint in the wire exists and resolve ambiguities with hands-on observation of the part and/or referring to the bill of materials.

MISCELLANEOUS SYMOLOGY: Ground symbols depicted in Figure 1-16 labeled in accordance with their optimum locations. Every airplane has three specific locations for instrument, electrical and avionics grounding. G1 is called out as the "engine" which automatically includes alternator, starter and any sensors that find their way to electrical ground by virtue of their mounting.

Permanent magnet motors are most common for trim actuators, flaps or fan motors. The PM motor will reverse

its direction of rotation by reversing the two leads that attach to the brushes. There are a few articles of surplus aviation hardware that run a wound field, brush type motor. The motor's field flux is supplied by a wound-field . . . lots of turns of small wire. Both the field and armature (brushes) are supplied with bus voltage to make the motor run. Reversing either the field -OR- the armature supply leads will cause the motor to reverse direction.

Various appliances will be fitted with some kind of connector, screw terminals on a terminal strip. Perhaps you'll have to splice onto pendant wires. It's easy to visualize how one would draw a circle or rectangle, label it as to name or function and then describe the methodology by which wires are taken to and from the device.

It's not uncommon for some publishers to draw accurate pictures of various devices recognizable as to name or function by observation. I've fielded a few complaints about

our drawings from builders who have purchased one or more accessories wherein the installation drawings used "pictorials" to show how wire up the product.

These work well if the device is wired with very few wires but it's time consuming and tedious to develop this type of drawing and adds no more meaning than can be deduced from the simple graphic that concentrates more on wiring details than on the physical appearance of the device be wired.

Most if not all of the devices discussed in this chapter will be covered in more detail in later chapters of this work. This introduction to the language and symbology of aircraft electrical system analysis, design and documentation should assist your travels into this new venture.

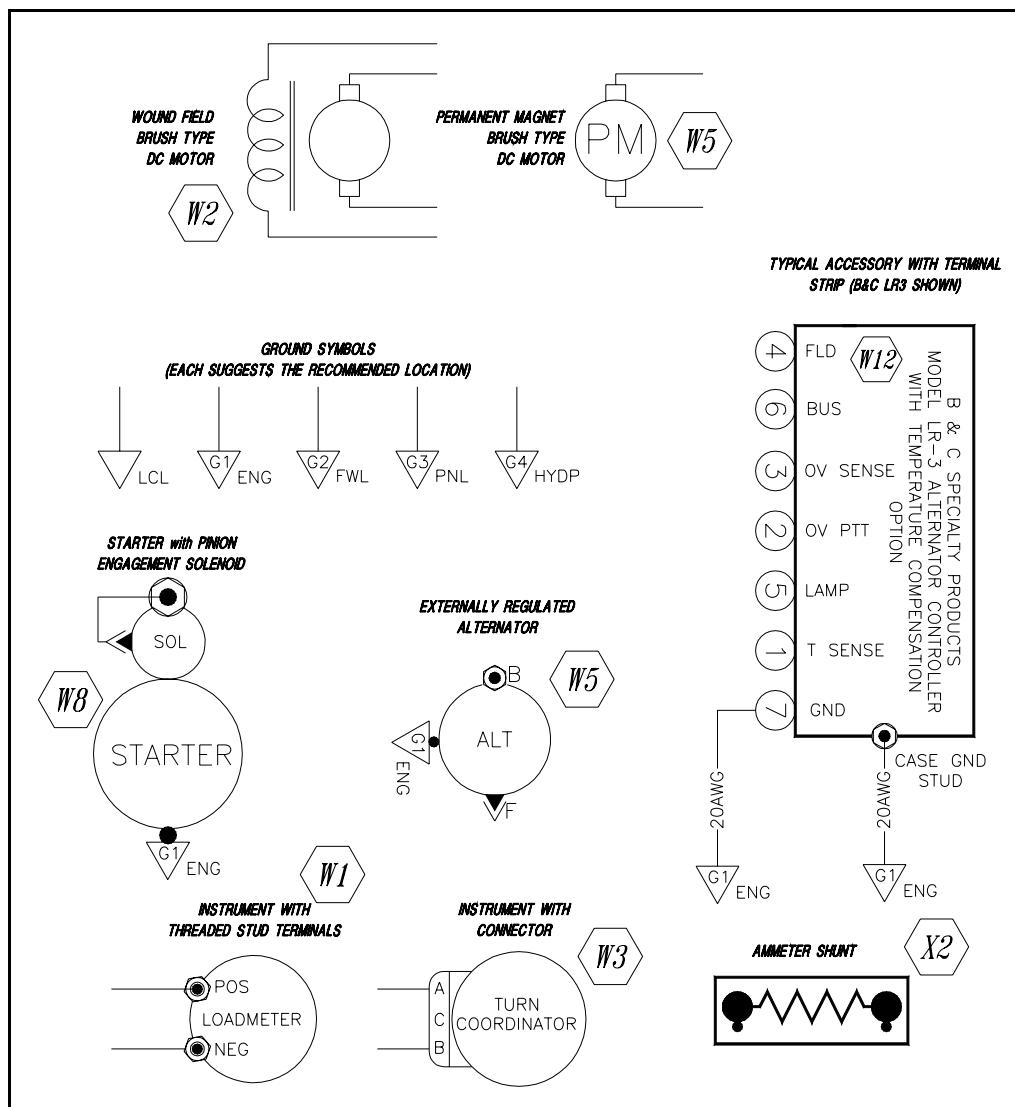


Figure 1-16. Miscellaneous Wiring Symbols

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Batteries

In this writer's opinion, a battery is the most important component of your electrical system. Without a functioning battery you cannot:

- Crank an engine.
- Effect some mitigation of electrical system noise.
- Expect continued function of critical electrical equipment in case of alternator/generator failure.
- Expect an alternator to come on line after engine start.
- Finally, a rarely needed but exceedingly handy feature of battery functionality is they will "throw themselves under the bus" to slow rate of rise for system voltage at the onset of an alternator runaway event. Batteries offer over voltage protection systems small (100 mS) but comfortable windows of opportunity to do their job.

In spite of a prominent responsibility, batteries tend to languish in the solitary confinement of battery boxes until they simply cannot perform at any useful task. Most consumers of battery technology are ambivalent on battery maintenance. They've come to expect poor or unpredictable battery performance. By the time you finish reading this chapter, I hope your personal awareness of battery responsibilities and limits will be raised a few notches.

HISTORY OF OBSERVATIONS IN ELECTRICAL PHENOMENA

Electro-chemical cells were the very first sources of electrical power that could be made to do practical tasks. Electrical phenomena were observed two centuries before the battery made its debut as a useful power source. In James Burke's book Connections we read how a French astronomer, M. Jean Picard observed a strange phenomenon inside a newly invented instrument called the barometer. Seems he was on his way home from the Paris Observatory one night in 1675 when the partial vacuum space in a

barometer he was carrying began to "glow." The glow became brighter as he shook it more. A few years later in 1706, the Englishman Hauksbee produced a machine consisting of a glass globe that could be partially evacuated and spun on an axle by means of a hand crank. When a hand was pressed lightly to the globe's surface, a strange luminosity would appear inside. These gentlemen were demonstrating the visible phenomenon of motion induced static electricity in a partial vacuum.

These events mark the earliest recorded observations of static electricity and subsequent studies of electron flow. In 1729, Stephen Gray demonstrated that the attractive forces of static electricity would propagate long distances. When he "charged" one end of a cord, a feather would become attracted to the other end about 800 feet away! It wasn't until 1800 that the Italian Alessandro Volta discovered that dissimilar metals in the presence of an acid would develop an electromotive potential between the two metals. Further, he showed that by stacking the "cells" together in series, the strength of the force increased. The new source of electron flow was dubbed the "Voltaic Pile." A few years later in 1820, a Dane by the name of Oersted set up an experiment to show that there was no connection between electron flow and magnetic fields. Much to his surprise, the opposite was true. By 1850, alternators and generators using electromagnetic principles were producing practical amounts of electrical energy to do real work like power an arc lamp or generate hydrogen gas from water to fire brighter lamps in lighthouses.

When Edison first began to distribute electrical energy for public consumption, generators turned by steam engines were used to produce DC electricity that was distributed on overhead wires to the backs of peoples houses and businesses. There was a problem with calculating the consumer's bill for electricity used. I recall reading that early "meter readers" were equipped with scales. A single Voltaic Cell was connected in series with a customer's electric service. The cell actually produced a small percentage of the customer's total consumption. As the cell was depleted, one of its plates was consumed. The meter reader simply

weighed the plate from time to time. The customer's bill was calculated from the battery plate's weight loss. Of course, the cell would require periodic refurbishment to continue its service as a gauge of energy consumption.

When the automobile industry began to emerge about 1895, many inventors assumed that electric drive would be adopted for most vehicles. From a purely technical perspective, the state of the art of components for electric cars was well advanced at this time. The DC motor, for example, had gone through a decade of improvements with the spectacular growth of the trolley industry. Indeed, most of the circuitry of the electric cars was a scaled-down version of that of the streetcars; e.g., the motor controller, to regulate speed. Lead-acid storage batteries which provided power had enjoyed fifteen years of commercial development. Unfortunately, batteries were the most expensive and recalcitrant technology on the car. Funny thing . . . even today, batteries are the biggest engineering headache in electric car design.

Early batteries, being electro-chemical, lacked the inherent durability of electro-mechanical devices. Nevertheless, fifteen years of experience demonstrated continuous improvement. Inventors in the U.S. and Europe struggled to produce small, transportable batteries for use on self-propelled streetcars. Although the battery streetcar was never successful, the technology of transport batteries received a tremendous boost. The technology advancement was transferred to the electric car and ultimately to a portable power storage medium used in automobiles for the past 87 years.

In the period 1895 to 1900, batteries for electric cars were very unreliable. The first decade of the new century brought us several developments in lead-acid battery technology. By the time C.F. Kettering's work on starter motors for Cadillac came to fruition in 1911, the foundations for aircraft DC power systems were well in place.

Batteries are assembled from individual cells having the ability to convert latent chemical energy into electrical energy. All batteries use a chemical reaction that DOES NOT occur simply because the two reactants are in close proximity. The chemical reaction inside the cell progresses when a flow of electrons occurs external to the cell's chemical system. This flow of electrons is the benefit to be realized; we can make the flow do the work. There are many forms of single use batteries. The zinc-carbon battery used in radios, flashlights and other small appliances dates back to the early 1900's. Some battery chemical systems reverse if the electron flow is reversed; the battery may be recharged. Like automobiles, airplanes also make good use of compact sources of stored, replenishable energy.

LEAD-ACID BATTERIES

The sulfuric acid electrolyte, lead-acid battery is the most common battery used in automotive applications, both airborne and earthbound. Specialty manufacturing of these batteries for aircraft service has been going on for over 40 years. The major feature of this technology is a chemical system that utilizes plates fabricated from lead and compounds of lead submerged in a liquid electrolyte consisting of water and sulfuric acid. Stacks of plates in the cells of early lead-acid batteries were held separate from each other by thin slices of wood. Modern batteries use plastics. Modern designs for lead-acid batteries use thin sheets of Fiberglass mat that looks for all the world like a few layers of tissue.

The form of electrolyte containment in lead-acid battery has been marketed in three flavors:

- "Flooded Cell" batteries are familiar to everyone: they're still the most common battery found in automobiles. These feature loose, liquid electrolyte that can be accessed by removing a filler cap on the top of each cell. If turned upside down, they leak. After a year or so in service, they often grow patches of green fuzz around their terminals.
- "Gel-Cell" batteries have been around for decades and were the first commercially viable products that reduced the hazards and mess associated with portable lead-acid power storage. Cleaner than their sloppy cousins, they still develop green fuzz and don't perform well in cold weather.
- "Starved Electrolyte" also popularly known as "Recombinant Gas" batteries are also decades old but until recently, the RG battery has languished in relative obscurity. Consumer markets for clean, odor free power in portable power systems have mushroomed. The personal computer explosion fed the demand for super clean batteries as stored energy for uninterruptible computer power supplies.

FLOODED CELL BATTERIES . . .

Today's flooded cell batteries are direct descendants of the batteries that whisked Great Grandma to the grocery store in odor free silence. They are strong contenders in automotive markets. In my not so humble opinion, it's sad when they're still the battery of choice for many airplanes. Flooded cell batteries routinely expel explosive gases laden with droplets of sulfuric acid. Because of the requirement to vent these gases while retaining liquids they must be constructed with

special cases and filler caps. It is mandatory in airplanes to enclose the liquid electrolyte lead-acid in a separate box for the safe venting of gases and containment of any spills of corrosive liquid.

IMMOBILIZED ELECTROLYTE
-OR-
"GEL-CELL" BATTERIES . . .

Immobilized electrolyte lead-acid batteries have been around for many years and enjoyed wide acceptance in portable power applications. They're still manufactured in special deep-cycle versions for electric wheelchairs. The first widely marketed gel-cells in the US were manufactured by Globe-Union. The gel-cell is not dead but it's sliding fast. I did an Internet search and could find only two major manufacturers of gel-cells. Johnson Controls has the old Globe product line while Sonnenschein in Germany still produces real gel-cell devices.

Both companies produce well known examples of a battery with demonstrated utility in aircraft. The major feature of these batteries is the fact that the water and sulfuric acid used as the active ingredient in the chemical system is not a liquid. Other materials are added to the electrolyte to convert it to a gel. The gelled electrolyte technology was a major breakthrough for reducing the mess and risks associated with flooded cell batteries. The battery is also well sealed . . . it will not normally leak acid-laden moisture. In the gelled state, the electrolyte is somewhat immobilized between the plates but the battery still cannot be operated in any position.

When charged too aggressively, gel-cells will vent risky volumes of explosive and corrosive gases. While much less messy than their flooded cell cousins, they're the poorest performers in terms of cranking power and low temperature operations of any of their close cousins. The true gel-cell battery is very rare. Most of the sealed, lead-acid batteries on the market today are modern recombinant gas designs.

STARVED ELECTROLYTE
-OR-
RECOMBINANT GAS BATTERIES . . .

The first RG batteries appeared on the scene over 20 years ago. A US patent held by Gates Energy Products on early RG battery technology was the basis for their Cyclon series, sealed lead-acid batteries. B&C was offering a 12-volt, 25 AH Gates RG battery when I first met them about 1984. It was NOT a popular battery. At that time it was expensive (\$175 retail) and not very suited to aircraft (vibration liked to disconnect the negative leads inside the cells).

These batteries never leak. Their self-discharge rate is a fraction of the best flooded-cell or gel-cell battery. They may be mounted in any position. Best of all, they have very low internal impedance and crank like Ni-Cads. They are often confused with gel-cells. Some distributors even call them gel-cells, thus displaying their ignorance of the product they sell. Nowadays, the RG battery is offered by virtually every major battery manufacturer in sizes from 1 to hundreds of ampere hours capacity.

RG battery technology is characterized by four major features:

- **Totally Sealed:** Under proper operating conditions, it will never out gas its internal moisture and is truly maintenance free.
- **Phenomenal Cranking Ability:** I've seen tests where a 10 AH RG battery successfully cranked a high compression IO-360 engine for 5 successive starts without recharging. When we conducted cold cranking tests of the RG battery, a brand new flooded cell aircraft battery was placed alongside a new RG battery in the freezer and cold soaked at about -10F overnight.

The following day, we applied a 300 amp load to each battery in turn while observing the battery's terminal voltage. *The RG battery had a higher terminal voltage at the end of 30 seconds than the flooded battery presented at the beginning of the test.* We didn't even bother to test a gel-cell. Earlier experience with these batteries told us that no useful energy could be expected from a gel-cell at this low temperature.

Some time later, I conducted a test whereby the multi-kilodollar Ni-Cad battery in a C-90 King Air was replaced with \$250 worth of B&C RG batteries. A data acquisition system was attached to the battery to monitor current and voltage throughout a PT-6 engine start sequence. After gathering data on the RG battery, I replaced the Ni-Cad and repeated the tests. When plotted together, the current/voltage curves lay right on top of each other!

- **Absolutely Clean:** RG batteries are incapable of leaking corrosive liquids. The electrolyte in an RG battery is liquid water and sulfuric acid . . . installed with a calibrated syringe. The Fiberglass mats between plates are about 80-90% saturated with the liquid. To get any of it back out, one would have to wring it out . . . you can drive a nail into an RG battery, pull it out, and continue to operate the battery until it simply dies from having dried out. No liquid will escape the hole.

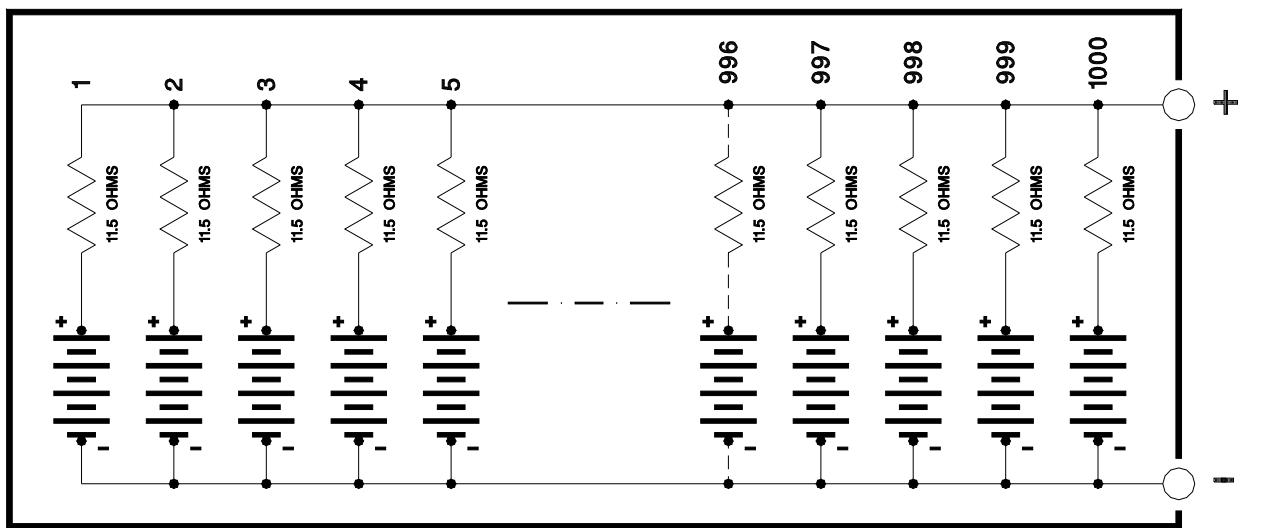


Figure 2-1. The Multiple Cell-Site Analogy for a Battery.

This means that the RG battery may be operated in any position. It also means no battery box is necessary. Just strap the puppy down in a tray that captures the footprint. A couple of 1" webbing straps with 6" of overlapped Velcro would hold a 24 AH battery in place for crash safety.

- Very low self discharge rates: The RG battery may be stored for longer periods of time without intervening attention. Sealed cells have very low concentrations of dissolved oxygen in the electrolyte . . . the major antagonist for self discharge.

CHEMICAL SENILITY AND INTERNAL RESISTANCE

There are important characteristics of all batteries that require understanding before we can adequately discuss battery performance and maintenance. Figure 2-1 illustrates an imaginary 12-volt battery composed of 1000 tiny 12-volt batteries, all connected in parallel, each having an effective internal resistance of 10 ohms. Of course a real 12 volt battery is a concoction of thousands of 2-volt cell-sites in series parallel but the simplified model in Figure 2-1 is sufficiently accurate for our needs.

From the battery's terminals looking back inside, this combination appears to have 1000 units of capacity with a net internal resistance of 10 milliohms (one thousand 10-

ohm resistors in parallel yields a 10 milliohm equivalent). As the battery ages or succumbs to abuse, the sites for these units of capacity begin to die off, one at a time. At some point, we'll be down to 500 units of capacity or HALF of what we started with. Another interesting thing happens at the same time. Five hundred 10 ohm resistors in parallel have an equivalent impedance of 20 milliohms, TWICE what it was when new. Not only is the capacity of the battery down by half, its ability to deliver energy has fallen to half as well. It is a precipitous slide once the critter starts to roll belly up. A battery that is only half gone may well contain enough energy to crank an engine, but a commensurate rise in the battery's internal resistance stands between what energy is available and the electrical gizmo that needs it! Internal resistance, while seemingly very small . . . (it's expressed in milliohms) can have a marked effect on battery performance as we shall see . . .

BATTERY PERFORMANCE: WHAT'S ALL THIS AMPERE-HOUR STUFF ANYHOW?

To choose a battery for any given electrical application, you must consider three things: a) the rate at which energy must be withdrawn from the battery, b) the total capacity of the battery and c) the ability of the battery to perform in the environment in which it is installed.

Design data is available on virtually every battery as to its total capacity and performance in environmental extremes.

Total capacity should be the first consideration, and there are some things you need to know about published ratings. All battery manufacturers give an ampere-hour (AH) rating for their products. The definition of the ampere-hour is exactly what the name implies.

However, the astute purchaser of a battery will check the manufacturer's data for the product under consideration. For example, one of my favorite products for use in light aircraft is a very common form factor of RG (also called sealed, valve-regulated, lead-acid or SVRLA) in a 16 - 18 AH package measuring about 3.0 x 7.0 x 6.7 inches. This is a

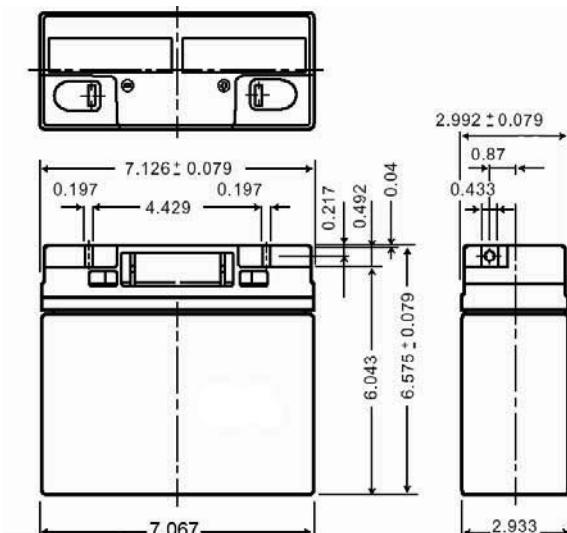


Figure 2.2 Exemplar Dimensions for a 16-18 AH SVLA Battery

popular form factor used by thousands of consumer products . . . virtually everybody who builds RG batteries will build this one.

A few exemplar brands and part numbers are:

Panasonic LC-RD1217
Odyssey PC680
Power Sonic PSH-12180FR

There are probably dozens of nearly identical batteries, ALL of which are potential candidates for use in your airplane. The only hard requirement for considering any brand of battery are the connections. You need be able to bolt 4AWG wire to the battery's terminals. There may be similar size and capacity of batteries that use the 1/4" fast-on tabs. These

are NOT suitable for engine cranking currents.

When it comes to sizing the battery, the device must first crank the engine. There are relatively small batteries on the order of 12 AH that will do that. However, the battery is also your back up source for electrical energy if the alternator fails. Your ENDURANCE under battery-only operations is the primary driver for sizing a battery.

In bizjets, battery endurance is established by regulation to

Time	Watts (W)	Amps (A)	Capacity (Ah)	Energy (Wh)
2 min	1486	143.0	4.8	49.5
5 min	792	78.8	6.6	66.0
10 min	512	49.3	8.4	87.1
15 min	389	36.7	9.2	97.4
20 min	318	29.6	9.8	104.9
30 min	236	21.6	10.8	118.2
45 min	173	15.6	11.7	130.1
1 hr	138	12.3	12.3	138.0
2 hr	79	6.9	13.8	157.2
3 hr	56	4.8	14.4	166.5
4 hr	43	3.7	14.8	172.8
5 hr	35	3.0	15.0	177.0
8 hr	23	2.0	16.0	187.2
10 hr	19	1.6	16.0	192.0
20 hr	10	0.8	16.0	204.0

Figure 2.3 Exemplar 16 AH Battery Performance

be no less than 30 minutes to end of battery life (80% of new capacity). Hmm . . . what's YOUR requirement for battery-only endurance? I'll suggest that it could be no less than flight-time-for-fuel-aboard. I.e., fuel should be the only expendable commodity that forces you to put the wheels on the ground.

Let us hypothesize that we can trim the endurance bus to 4.5A of load. Further, we'd like 3 hours minimum endurance at 80% of new battery capacity. This means that we're looking for a battery offering 3 hours times 4.5 Amps or 13.5 AH. Allowing for 20% degradation for end of life, this means that the new battery has to deliver 17.0 AH at 4.5A. So will our 16 AH battery illustrated in Figure 2-2 do the job? Let's see.

The chart in Figure 2-3 depicts typical performance for the PC680 Odyssey battery at various loads. Note that this

battery delivers RATED output when loaded to 0.8 Amps for TWENTY HOURS. The 20-hour rate is the most common for batteries of this type. Okay, what's the 3 hour capability? The chart says we can load it to 4.8A when new. Under these conditions, the battery yields 14.4 AH of capacity. This suggests the battery has a high probability of meeting our 3.0 hour requirements when new. At end of life it will only give us 2.4 hours. Is that enough for YOU? Remember, YOU set design goals for this feature. Suppose your E-bus loads are 6.0 Amps. This battery will service that load for just over 2 hours when new . . . and about 1.5 hours

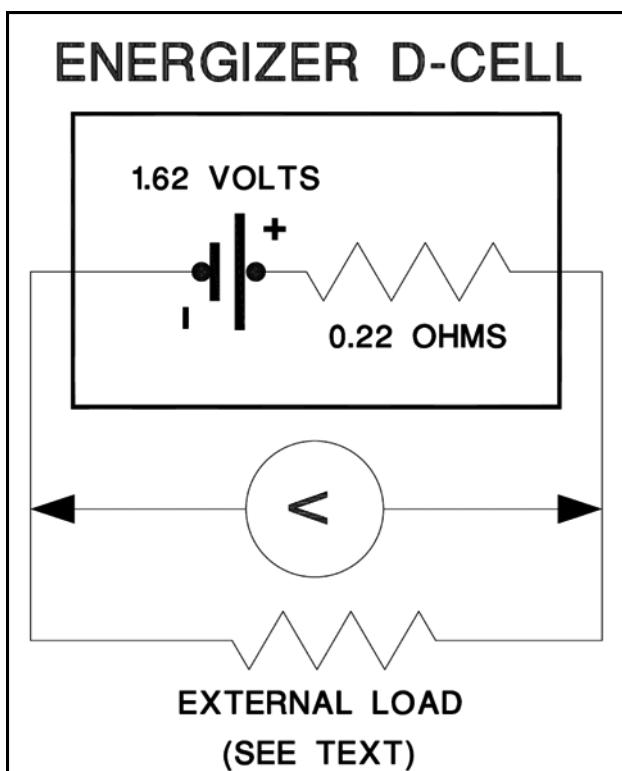


Figure 2-4. D-Cell Experiment

at end of life.

Notice the column for Capacity in AH goes down as the load goes up. This is because the battery's INTERNAL RESISTANCE wastes more energy warming the battery up instead of running your electro-whizzies.

Another example battery resistance affecting delivery of energy comes from the study of the lowly alkaline D-cell for flashlights. These devices have an INTERNAL RESISTANCE on the order of 0.22 ohms. These cells are nominally rated for 4 AH. Suppose we connected 8 cells in

series to make a 12v battery. Can we crank an engine at 250 Amps?

$$\frac{4 \text{ AH} \times 3600 \text{ sec/hour}}{250 \text{ Amps}} = 57.6 \text{ seconds}$$

In terms of energy contained within an alkaline D-cell, it would seem that there's more than enough to crank an engine for the few seconds that it takes to get it started. However, if we throw a dead short on the cell, current that flows is

$$\frac{1.5 \text{ Volts}}{0.22 \text{ Ohms}} = 6.8 \text{ Amps}$$

This means that while there's plenty of energy contained within the D-cell to do the job, the rate at which that energy can be delivered is very limited. The cell's terminal voltage drops to zero volts with a paltry 6.8 amp load!

ENGINE CRANKING A BATTERY'S FIRST TASK

In Figure 2-5 I've illustrated a cranking circuit similar to one I found in a builder's VariEz a few years ago. Where did all the resistors come from? Recall our discussion in Chapter 1 about resistance. You can minimize it but unless you can wire your airplane with super-conductors you have to live with it. I have drawn six resistors on the illustration to represent the following: a resistor inside the battery represents its internal resistance as does the resistor inside the motor. The resistors external to these devices represent the resistance of the wire that makes the interconnections.

The resistance of 4 gauge is 0.00025 ohms per foot. Let us also say that the wire between the battery and the contactor is 2 feet long. The wire between the contactor and the starter is 12 feet long and the one between the starter and the battery is 15 feet long. These are numbers that might be typical of a composite pusher with the battery in the nose. Multiplying out the numbers gives us the resistances shown in the figure. It's unfortunate that we cannot probe the interior of the battery. I include it to remind you that the voltage produced by a battery is a function of its chemical system and is constant irrespective of load. Let us say that the source voltage is 12.5 volts. What can we deduce from these numbers? First, since the terminal voltage of the battery is now down to 10.5 volts, there must be a drop of 12.5 minus 10.5, or 2.0 volts dropped across the internal resistance of the battery.

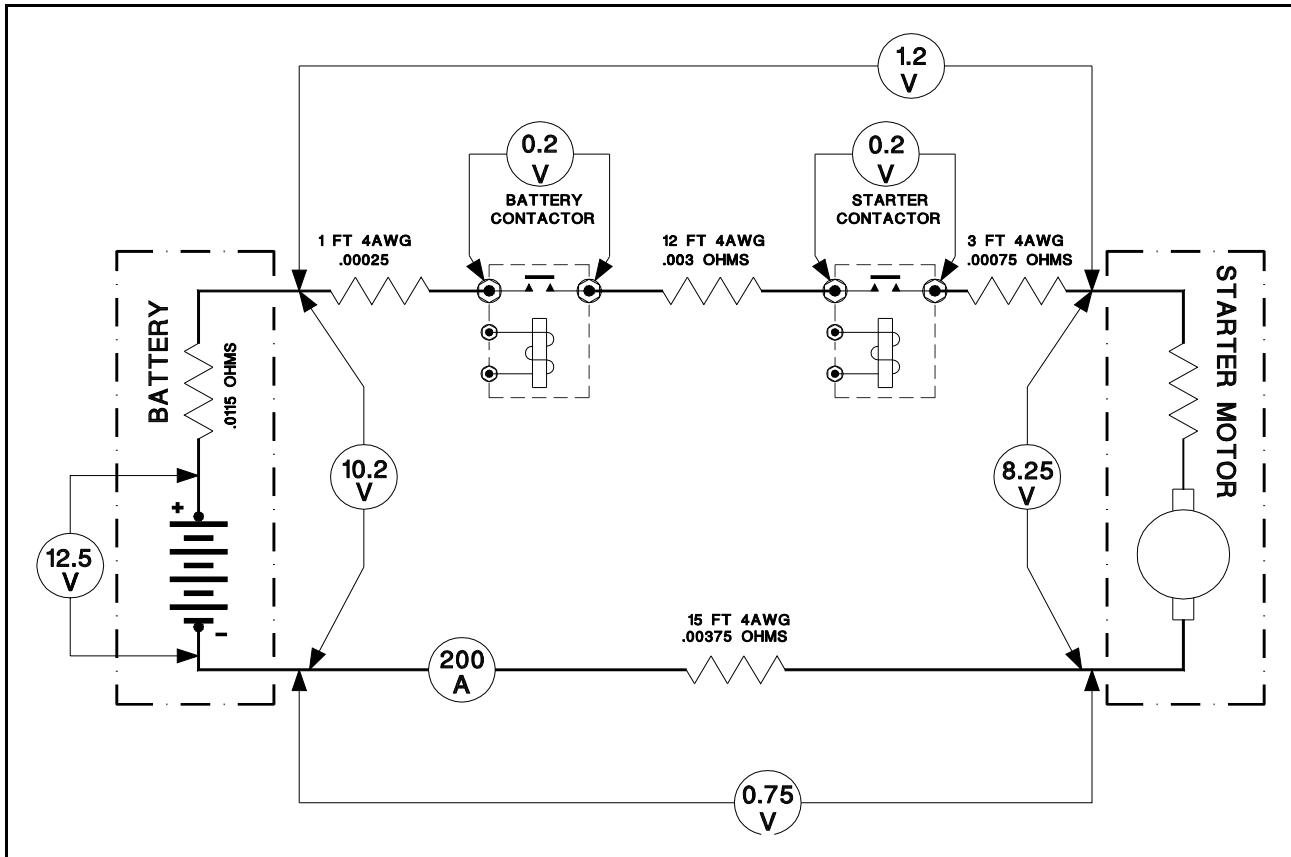


Figure 2-5. Engine Cranking Analysis

We can say:

$$\text{Volts} \quad 2.3$$

$$\text{Ohms} = \text{-----} = \text{-----} = .0115$$

$$\text{Amps} \quad 200$$

This calculation shows that the battery has an internal resistance (some call it "impedance" - for our purposes it's the same thing) of 11.5 milliohms. After you account for all the voltage drops illustrated in the cranking circuit, the starter now sees only 8.25 volts at its terminals. This is a fairly typical scenario which also points out the fact that there is no such thing as a 12-volt starter! Starters used in 14-volt systems with 12-volt batteries really need to be characterized for operation between 9 and 10 volts. I did not make any calculations or assumptions about the internal resistance shown for the motor. Motor resistance is a complex combination of features - we'll discuss it in detail in a later chapter on motors. But suffice it to say that the motor has resistance too . . . after you've cranked a recalcitrant engine for too long it is the motor's internal resistance that generates all that heat .

Now, let's repeat the exercise substituting a 4 milliohm RG battery for the 11.5 milliohm flooded device. Wow, cranking voltage at the starter comes up to 9.9 volts! What happens if we put in 2AWG wire instead of 4AWG? We get back some more losses and the starter now sees 10.3 volts. The large demands of a starter make small values of resistance very significant! Our hero's VariEz didn't crank worth a hoot . . . until he replaced the 4AWG wire with 2AWG and the little flooded motorcycle battery with an RG battery.

Remember the 7 amp flow we got from a dead short on our D-cell battery? Let's do an estimate on what happens when you put a dead short across the flooded battery. Looking at a shorted battery scenario we can say:

$$\text{Volts} \quad 12.5$$

$$\text{Amps} = \text{-----} = \text{-----} = 1,088$$

$$\text{Ohm} \quad .0115$$

We can also calculate the power dissipated inside the battery:

$$\text{Watts} = \frac{(\text{Volts})^2}{\text{Ohms}} = \frac{(12.5)^2}{.0115} = 13,580$$

That's the equivalent heat output of a dozen hair dryers; it would heat a small house very nicely. Except for the small resistance of the 'dead' short, all of the energy is being dissipated within the battery's own internal resistance. Is it any wonder why mistreated batteries sometimes blow up or spray boiling acid all over people? 'Nuf said. Be careful when you work with any battery. They can warm you up in unpleasant ways!

BATTERY SERVICE LIFE

One evening at Oshkosh many years ago we were having dinner with Darryl and Pat Phillips of Airsport Corporation. Darryl made the following observation: "We replace airplane tires when the tread is about gone, overhaul engines when the compression drops below certain limits, change oil and belts as preventive maintenance measures. But why do we flog an airplane battery until it simply dies?" Why indeed?

Generally speaking, the service life of lead-acid batteries is dependent upon how many watt-seconds of energy the battery is asked to transfer and how many times.. Further, depth of discharge on each discharge-recharge cycle will adversely affect battery life. A battery will last longer chronologically if you fly regularly, keep your technique for cranking tuned for rapid engine starting and don't run the battery down by leaving the master switch ON.

If you fly only day VFR, battery life and reserve battery capacity may not be an important issue. In this service, it may be perfectly reasonable to go flying any time you can get the engine to run. Be aware that reserve capacities for running your necessary loads in a failed alternator situation may fade faster than you think. If nothing else, do periodic battery-only, E-bus operations tests as described under Care and Feeding later on.

On the amateur-built side of the aircraft industry, many airplanes are getting dual electronic ignition systems and are operated comfortably even if the ship is fitted with only one alternator. This can be accomplished because a **properly maintained** battery can and should be considered the most reliable source of electrical power in the airplane! Some airplanes fly with electrically dependent engines . . . it can be done safely--but only if we view the lowly battery from a new perspective.

The vast majority of batteries in automobiles, snowmobiles, and airplanes receive ZERO attention until they fail to crank the engine. Batteries tend to sit in the solitary confinement of their battery boxes getting cooked, frozen, overcharged, undercharged, run flat and otherwise generally neglected. Of the three technologies we've discussed, the RG battery is most tolerant of abuse. Irrespective of your technology choice, the electrical system's ability to meet design goals will be compromised unless you cultivate good habits in battery maintenance.

The battery industry generally considers a battery to be at end of life when its capacity falls to 80% of new. What practical means do we have at our disposal for making the decision to replace a battery?

CARE AND FEEDING OF RECHARGEABLE BATTERIES

The open-circuit terminal voltage of a battery is related to the chemistry and not to the state of charge. A discharged battery will present a voltage to its terminals that's only 10% or so lower than a fully charged one. To recharge these batteries requires that the flow of electrons be reversed through the battery's chemical system. If you were to connect a 12-volt charger to a 12-volt battery, no recharging would occur since the electrical "pressure" in both devices would be the same. This is the reason why you can't charge a dead battery simply by connecting a fully charged battery to it.

A battery will accept charging only if connected to a source that is of a higher voltage than the battery. In systems which use 12-volt batteries, the required higher voltage is on the order of 13.8 to 14.5 volts. With 24-volt batteries, the charging voltage is twice that--about 27.6 to 29 volts. Battery charging voltages are responsible for the 14-volt and 28-volt numbers used to identify electrical systems. When the alternator is running, the system is operating at or about 14.2 volts. When the alternator is not running, the system voltage quickly falls to the level at which the battery can deliver energy - at 12.5 volts or less.

From time to time someone asks, "where should my voltage regulator be set?" On the Internet I've seen this discussion go on for days with numbers ranging from 13.8 to 14.8 volts. Manufacturers are not particularly helpful in this regard either for they sometimes give two recommended voltages for charging their products: a "float" or "standby" charging voltage and a higher "cycle" voltage.

The reason for two regulator set points centers on the fact that it takes time to fully recharge a battery. Recall that batteries are rated in ampere hours of capacity . . . amp is a

rate of electron motion. A unit of rate (Amps) x some unity of time (hours) is a **quantity** of electrons. This translates to a finite quantity of battery chemistry molecules having changed from a charged to a discharged state. The goal is to reverse the flow of electrons at some rate (Amps) for some time (hours) to replace the energy taken out.

When the battery is used in short "cycles," like most vehicular situations, the probability of getting the battery topped off is much better if the voltage is boosted a tad above the idealized charging level. In any case, all lead acid batteries at room temperature eventually acquire 100% of their capacity when charged at 13.8 volts if you can wait around long enough.

There's a design goal in airplanes for having a battery replenished a short time after takeoff. Since day-one, the popular set-point for generator and alternator regulators has been 14.25 or 28.50 volts DC. Yes, this is slightly abusive of the battery . . . but while setting the voltage lower might get us a slightly longer service life, it prevents realization of more critical design goals for timely recharge.

BATTERY REPLACEMENT: A PLAN FOR THROWING IN THE TOWEL

When configuring a system it is not sufficient to simply select a battery that is adequate to the task when new. The capacity of a battery begins to decline from the time it is first placed in service. The fade is slow at first but increases with age and abuse. The life of the battery in flight cycles will be a function of how much excess capacity the battery has when new and how well the battery is treated during its service life.

Monitoring battery condition becomes important when the battery is small and of limited life to begin with. If your engine starts in a few blades, then the battery never gets a chance to demonstrate its true capacity. I consider it good practice to shut down the alternator on long VFR day flights and drop to E-bus loads only. Simulate a loss-of-alternator condition. Measure the length of time that the battery supplies adequate power to the aircraft systems and record this number in your log. When the battery-only ops endurance drops to your minimum acceptable value, it's time to replace the battery irrespective of how well it cranked the engine that day. Other chapters in this publication will describe system monitoring and bus structuring techniques to make capacity evaluation procedures easy and informative.

BATTERY CAPACITY TESTING

Figure 2-6 shows a nifty product by West Mountain Radio

(westmountainradio.com) for testing batteries of all sizes, chemistries, and voltage. This device sells for about \$100 and drives out of the USB serial data port of a computer. Software provided with the product allows you to set up a discharge rate in amperes and allow the tester to deplete the battery to a cutoff voltage of your specification. For aircraft parts we use 10.5 (21.0) volts as end-of-battery-charge.



Figure 2-6. West Mountain Radio's Model CBA for Capacity Testing of Batteries

Using the model CBA Battery Capacity Tester to discharge your ship's battery at the e-bus power consumption rate, you can test exactly how long your battery will service **your** E-bus during alternator-out operations.

Come back in a few hours and you will find the battery depleted and the computer will display the discharge voltage curve for the battery under test. If you've stored previous tests of the battery on the same computer, you can bring those old plots back and overlay them on the current data for comparison. The CBA can also be used as a single-channel data acquisition system to measure and plot some voltage of interest over a period of time.

BATTERY LOAD TESTING

A second consideration of battery condition and the test most often used by battery stores, is to measure the ability of a battery to carry a heavy load. They hook a tester to the battery that contains an ammeter, a voltmeter and a heavy duty variable resistor known as a 'carbon pile'. With the tester connected, the pile is tightened down until the

voltmeter reads some test value (usually 9V for a 12v battery). Then the load is adjusted manually to keep the voltage at the test value. At the end of 15 seconds, the ammeter is read for an indication of available cranking current for the battery under test.

Figure 2-7 shows an inexpensive load tester offered by Harbor Freight. These sell for about \$50 and are a good value for the money. Your local friendly battery store will probably be glad to do the test for you periodically with its fancy tester, especially if it thinks it can sell you a new battery. Write the numbers down and track them with the age



Figure 2-7. Exemplar Battery Load Tester

of the battery. In any case, you should probably replace a battery that tests below 300 Amps for large engines, and 150 Amps for engines like a Rotax.

AC POWERED BATTERY CHARGERS

Automotive stores have lots of chargers designed to 'work with' (read minimally abuse) an automotive battery. You get what you pay for here. I've looked at chargers that claimed all manner of automatic and fail-safe features that just were not there when I looked inside.

If you've found yourself with a "dead" battery, then any charger will suffice to replenish the energy so you can go flying. The big variable is size . . . bigger chargers (higher output ratings) will recharge a battery faster than a smaller device. The capability of low cost, off the shelf battery chargers has blossomed in the past ten years or so. A host of companies offer charger/maintainer products that behave in concert with the graphs in Figure 2-8. The bulk charge cycle begins with a constant current based on size of the charger. When the battery terminal voltage reaches the "absorption

voltage" level appropriate to the battery, voltage is not forced any higher . . . and the charge current begins to taper off. As soon as the current drops to the anticipated float/maintenance level, the charger's output voltage drops to some level just above the battery's open circuit terminal voltage . . . but lower than the voltage necessary to push more charge into it.

Figure 2-8 graphs were provided by the folks who make Battery Tender brand of chargers. Other companies that offer low cost charger/maintainers are Battery Minder and Schumacher. One of my favorites is the Schumacher 1562 series devices offered at many stores including Walmart for about \$20.

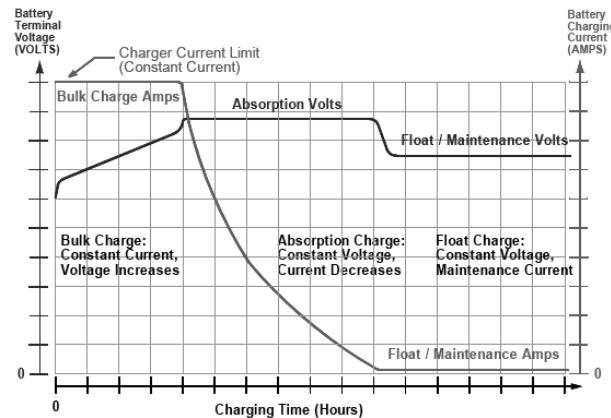


Figure 2-8. Battery Charge and Maintenance Profile

These chargers are designed to drop to a maintenance float voltage after the battery is topped off in the "absorption mode". These chargers may be connected to any battery indefinitely without concern for harming the battery.

Do the following checks on any charger you may use on your own battery. Monitor the battery voltage at the 'end of charge' as defined by the charger's front panel indicators or by the fact that the charger has simply been connected long enough to accomplish the task. If the "float" voltage is greater than 13.8 volts for a lead-acid, the charger is slowly cooking the battery.

A quick note on 'trickle' charging. Virtually all battery technologies have some very small internal drains or losses inherent to their construction. In time, even the best rechargeable batteries will discharge themselves. The idea of a trickle charge is to simply replace the energy being lost internally to the battery while it is being stored. The internal losses are very small, hence trickle charge rates should also be very small and appropriate to the size and technology of the battery. Once a battery is "topped off" at 13.8 volts, it's

entirely practical to drop and hold the float voltage to something on the order of 13.0 volts.

Recall that a battery **DELIVERS** energy at 12.5 volts and below . . . this includes energy lost in the battery's internal mechanisms. It stands to reason that if the battery is held at 13.0 volts via an external source (battery charger) then it's incapable of using its own stored energy to satisfy internal losses. Further, at 13.0 volts float voltage, the charger is incapable of overcharging the battery.

If your charger does not appear to meet these criteria then you will experience the best battery life if you use the charger only to recharge after a "run it down" capacity test or to recharge it after an accidental discharge in the airplane. Don't store the battery for long periods of time on a charger that does not meet the requirements for long term storage at a float voltage just above the battery's own open circuit terminal voltage.

PROGRAMMABLE CHARGERS

There's a class of chargers that feature lots of buttons on the front for setting recharge rates and perhaps selecting the type of battery. Some battery manufacturer's are quite adamant that you conform to some special recharge criteria for the purpose of getting the most from your battery.

But recall this, once you take the battery off some super-whippy charger and put it in your airplane (or any other vehicle) programmable recharge rates and voltage profiles are no longer an option. We set the regulators for 14.2 and watch for alternator failure . . . and that's it. Spending extra dollars to have a programmable charger has a limited and perhaps non-existent return on investment. I have some of these devices. However, if I have a simple charger-maintainer handy (Figure 2-8), I'll stick it on the battery to be serviced and not worry about it.

WHEN ARE TWO BATTERIES BETTER THAN ONE?

Most automotive conversions are very difficult if not impossible to adapt to dual alternators . . . yet automotive conversions are always electrically dependent engines. Many builders are installing all electronic ignition systems . . . some electronic controlled fuel injection.

First, let's keep in mind that modern alternators are exceedingly reliable compared to their ancestors popularly used on aircraft. Assuming that the owner/operator takes battery preventative maintenance seriously, then the probability of facing an unmanageable alternator failure is quite low. But the risk is never zero.

Further, the owner/operator has an opportunity to deliver on design goals that are seldom featured in type certificated aircraft; i.e. designing for battery-only endurance that is much longer than the 30 minute target deemed adequate for some certified designs. In my book a 30 minute battery-only endurance limit sets you up for an emergency. Some of the places I like to fly over don't have attractive landing sites within 30 minutes flying time.

Your ability to navigate and communicate with a totally dark panel should be backed up by hardware carried in your flight bag. A \$100 GPS, a \$200 nav/com and a flashlight will get you there. Keeping the engine running is another matter.

While crafting an architecture tailored to your electrically dependent airplane and the way you plan to use it, the first task is decide how much energy must be in storage to meet your personal battery-only endurance requirements. Electrically dependent engines should be wired directly to an always-hot battery bus such that the DC Power Master switch can be turned OFF and the engine runs unaffected.

It's sometimes advisable to replace one "fat" battery with two smaller ones. For example, a pair of 17 AH batteries can be run in parallel under all normal operations. This technique is illustrated in the diagrams in Appendix Z. The combined batteries give 34 AH of cranking power. The ship's electrical system should include a low voltage warning system set for 13.0 volts. If bus remains above 13.0 (or 26.0) volts, the alternator is working and carrying ship's loads. Should the voltage drop below this value, the alternator has failed. The two batteries are then split into separate tasks. Perhaps one is assigned to keeping the engine running while E-bus loads are carried by the other battery.

If you do periodic capacity tests, it's easy to determine when one of the batteries requires replacement. Alternatively, with a dual battery system, one battery is replaced every annual. This means that after the first annual, a two-year-old battery gets rotated out of the airplane. It also insures that one of the batteries is always less than one year old. This measure adds about \$50 to the cost of an annual but it affords a measure of assurance that can only be matched or exceeded by installing dual alternators.

Keep in mind that it's a very rational plan to operate from one well maintained battery of **KNOWN** capacity to keep the engine running and drop to flight-bag-backups for the purpose of completing the flight at an attractive destination without breaking a sweat.

Suppose you're flying certified iron and still fly two mags . . . how does this discussion affect you? Please consider this:

I recently downloaded a batch of service difficulty reports using "battery" and "alternator" as keywords. The resulting collection of data read like the opening lines to a Dragnet episode on the radio, "There are 150,000 airplanes in this country, each has a story to tell." Indeed. The stories ranged from benign to hair-raising but a common thread was obvious: Timely notification of alternator failure -AND- judicious utilization of battery capacity should have made most episodes into ho-hum events. In most cases, the pilot was UNAWARE of alternator failure until the panel started going black . . . which meant the battery was gone too!

In certified ships, options for reducing loads on a battery in a certified aircraft are limited even when the pilot is immediately aware of alternator failure. Numerous articles on the website along with Chapter 17 of this book speak to architectures designed for failure tolerance which translates into flight-system reliability. I won't belabor those issues in this chapter.

A FEW LAST WORDS ON BATTERY SELECTION

Choosing batteries for amateur built airplanes is pretty easy: 15 years ago, "real" aircraft batteries were expensive, lackluster performers. Automotive batteries were cheaper but heavy and messy. Motorcycle batteries offered built-in manifolds for mess-control but are suited for cranking only the smallest engines. A few gel-cell products helped control mess (they leak only occasionally!) but didn't even come close to matching performance of the poorest of flooded-cell battery. Today, the field of consumer grade, sealed, valve-regulated, lead-acid batteries are the products of choice from which the most practical systems will be crafted. Further, we're free to choose the product that best suits our need.

Most of our brothers building airplanes are able to craft failure tolerant systems with 16-17 AH batteries. Further, since many projects are going all-electric, the use of a vacuum pump pad driven alternator provides at least 8 Amps of continuous power during main alternator failure. This means that your E-bus loads can be at least 8 Amps while holding the battery's stored energy in reserve for descent and approach to landing.

If you're running two batteries, making them the same size allows a yearly swap-out of the oldest battery during annual inspection. Your design study should strive for an E-bus powered by the primary battery which is always less than a year old. When rotated into the secondary slot, its alternator-out tasks should be smaller . . . carry a single ignition system and perhaps a boost pump as needed . . . much smaller loads than the E-bus. A year later, it's outta there. **This eliminates the need to do periodic capacity checks.**

Most aircraft accessories and components have practical limits to service life. The problem with batteries is knowing when conditions for continued airworthiness are no longer met. It would be very nice if batteries just had dipsticks or "gas" gauges for making their condition known. Unfortunately, the most qualitative thing we know about a battery in most vehicles is derived from a general sense of how well it cranked the engine. When the alternator comes on line, we busy ourselves with other matters and the battery is left to fend for itself. By the time a battery is down to just a few more engine starts, its capacity as a standby power source has long since fallen below useful values. This is the saddest and most hazardous aspect of our ignorance of battery condition. I hope this chapter has given you some better tools for battery selection, operation and maintenance that will raise your confidence levels for electrical system integrity.

BATTERY INSTALLATION

If your project is designed to use a flooded battery, then a full surround battery box, drained and vented to the outside is in order. Most kit suppliers recommend or even supply this type of enclosure. Aside from the extra expense and weight of the full surround enclosure, I find the concept disturbing. If you WANT to build a bomb, you first provide an enclosure to contain the explosion as long as possible before bursting. A few years ago, a Glasair pilot experiencing electrical system difficulties was offered a surprise when the battery box built into the back of the right hand seat exploded. A series of failures precipitated out-gassing of his battery sufficient to load the bomb. A spark from a battery contactor INSIDE the box provided the ignition source. Fortunately the bomb's outer shell was not robust. The energy release was too low to cause severe damage to the airplane. The story ends well.

In my not so humble opinion, the RG battery's limited ability to generate explosive gasses combined with its lack of need for a battery box makes it one of the safest batteries ever manufactured. My first advice for installing a battery is NOT to use a battery box. Pick a battery that doesn't need one! If you do plan to use a flooded battery, at least keep the battery isolated in the enclosure. No other components of the electrical system should share the box with the battery. The box should have positive venting to avoid accumulation of explosive gasses.

Lead wires coming off of a battery's terminals can provide a challenge . . . especially when the airplane is wired with 2AWG battery and starter path wiring. Connections to the battery terminals are generally made with short pieces of wire: one from the battery (+) to battery contactor, the other from battery (-) to ground.

Even if the rest of the airplane is wired with stiff, Mil-Spec fat wires, consider making the two short battery (+) and (-) jumpers from 4AWG welding cable. We'll speak of this product again later. Suffice it to say now that welding cable is designed to lay on gravel roads and be routinely run over by dump trucks. It's also made from a bazillion strands of very fine wire . . . QUITE flexible. Much easier to work with in the narrow confines and short bend radii around the battery and its terminals. If you do use a full-surround box, be sure to use grommets to protect the (+) battery wire from damage and shorts to the battery box. Some extra layers of heat shrink over the wire where it penetrates the battery box is a good idea, too.

If you don't have a battery box, the exposed terminals need protection from inadvertent contact that might draw sparks. Rubber terminal booties are available and sometimes suited to this task. I've seen some nifty shields fabricated from PVC sheet. I once saw the efforts of an enterprising builder who cut the bottom from a Tupperware container to make a shield for his battery's terminals.

In terms of mounting strength, the battery should not become a hazard in a crash. If the battery is behind the cabin, I like to see sufficient strength in the hold downs to withstand in excess of 10 times the battery's weight, 20x is even better. This doesn't have to be titanium steel . . . a series of nylon web straps and companion plastic tensioning buckles (or even 6 square inches of overlapped Velcro per strap) can be used to provide hold-downs good for 1,000 pounds.

The limiting factor of most hold-down schemes is NOT the materials used for grabbing the battery but the structure to which the hold-downs attach. Modern aircraft structures pride themselves in lightness or thinness . . . many a 1000+ pound webbing strap has ripped loose from its mooring at a few hundred pounds. If in doubt, consult the kit manufacturer should you wish to install a battery in some manner other than the original recommendations.

Batteries mounted in front of people are not so critical. For example, batteries mounted either front or back side of a firewall do not become missiles launched against folks hoping to survive a crash. Major loading vectors for this installation are forward and down . . . a simple tray with a couple of nylon straps would be sufficient for about any size battery.

COMING OVER THE HORIZON . . .

The hey-day of Thomas Edison's DC power generation and distribution was shared by the sulfuric-acid-water-lead plate and lead-oxide battery technology. Who would have guessed that over 100 years later, lead-acid is still the low-cost-of-ownership choice for storing DC power.

The sealed batteries are technologically old-hat but there's still a great deal of interest in taking some of the weight out of lead-acid batteries. A new composite and lead foam plate under development promises to lower the internal resistance of the battery, increase capacity while taking out more than half the weight contributed by pure lead plates.

A number of wanna-be suppliers are stroking lithium ion batteries in one form or another. Some have been approved for use aboard airplanes. They're not ready for prime time in our little ships. The energy density of these cells is seductive but it's like trying to figure out a way to burn nitro-glycerine in your engine. The power density is really great but there are obvious hazards to overcome. I'm involved in a number of development programs that promise much lighter Li-Ion batteries with great power density . . . but there are significant manufacturing and system integration issues to be solved.

At the time of this writing, my best recommendation for battery selection in the Owner Built and Maintained (OBAM) aircraft venue can be made from the corner "Batteries R Us" store. Just recall that batteries have a lot in common with house plants. Most little potted beauties liberated from the Walmart garden shop sit on a shelf and get watered when they look wilted. They may never bloom and finally get tossed when too many leaves have fallen off. We've probably all met individuals who enjoy lush green leaves and prolific blooms from the same plants. These folks understand the plant's balance of requirements for optimum performance. Like house plants, batteries are not complex but they do demand some study and effort to implement a considered preventative maintenance program. The outcome assures the satisfaction of meeting design goals and no in-flight disappointments. Learn how to stroke your battery well and it will be there when you need it. What's more, it will let you know when it's time to retire!

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Engine Driven Power Sources

Converting mechanical energy to electrical energy for a vehicle's systems has been the task of two classes of machine for over 100 years: the alternator and the generator. Generators precede the alternator by a good many years. Both devices have one important feature in common. The conversion is accomplished by moving wires through strong magnetic fields or vice versa. The major difference between them is that alternators have a higher number of magnetic field transitions (north-south-north-south-etc.) for each power producing wire for each revolution of the shaft. Further, current carried to rotating parts in an alternator is via small brushes running on smooth slip rings. Unlike the generator, an alternator will run happily at 10,000 RPM. This high-frequency, low brush-wear combination allows gearing an alternator to run faster than generators on the same engine. This offers exemplary low-speed performance in smaller and lighter machines.

The practicality of an alternator before the 1960's was

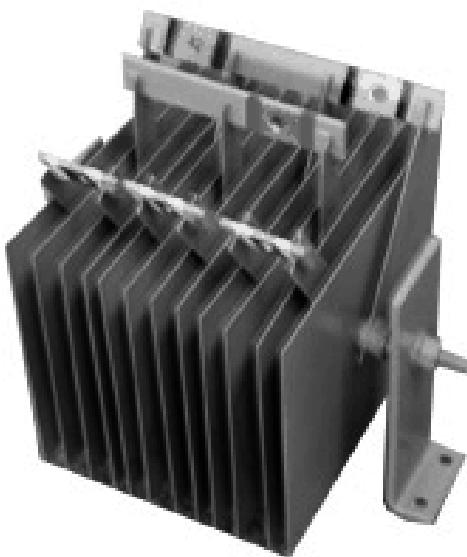


Figure 3-1. Selenium 3-Phase Power Rectifier.
Circa 1955

limited due to the lack of compact, high efficiency rectifiers. The first alternator installations I recall were in 6-volt taxi cabs in the early 50's. The radios they needed drew a lot of power and the alternator system could supply the necessary energy at curb idle. The rectifiers were external to the earliest machines; very impressive looking things with lots of heat dissipating fins.

The regulator alone was about the size of a loaf of bread! Electrical system requirements for light airplanes were quite modest at this time; the generator was the power producing machine of choice. Few light planes had any radios at all. The landing light was the largest single load in the system. A 20-amp generator sufficed quite nicely; an alternator installation for an airplane was virtually unheard of.

The development of small but powerful silicon diodes offered compact and efficient, solid state rectification of the alternator's AC output. The semiconductor age brought mobile power generation a quantum leap forward. Transistors followed a few years later to offer long lived replacements for the electro-mechanical regulators. Large volume production of alternators by the automotive industry created a wide choice sizes and suppliers of alternators adaptable to airplanes. Simultaneously, the availability of compact, low priced, sophisticated avionics packages and electrical accessories drove the lowly generator into relative extinction. Piston engine singles from Cessna feature 60-amp, 28-volt alternator systems as standard all the way down to the lowly model 152.

ALTERNATORS

The major magnetic components of the alternator are shown in Figure 3-2. The power output windings of the alternator are stationary and the field pole assembly is rotated by the power input shaft. Slip rings and brushes are needed to convey field excitation to the moving field assembly. Even the very largest aircraft alternators need only 3 amps or so of field excitation. Low current requirements along with the smooth slip rings are conducive to the very long life of an alternator brush.

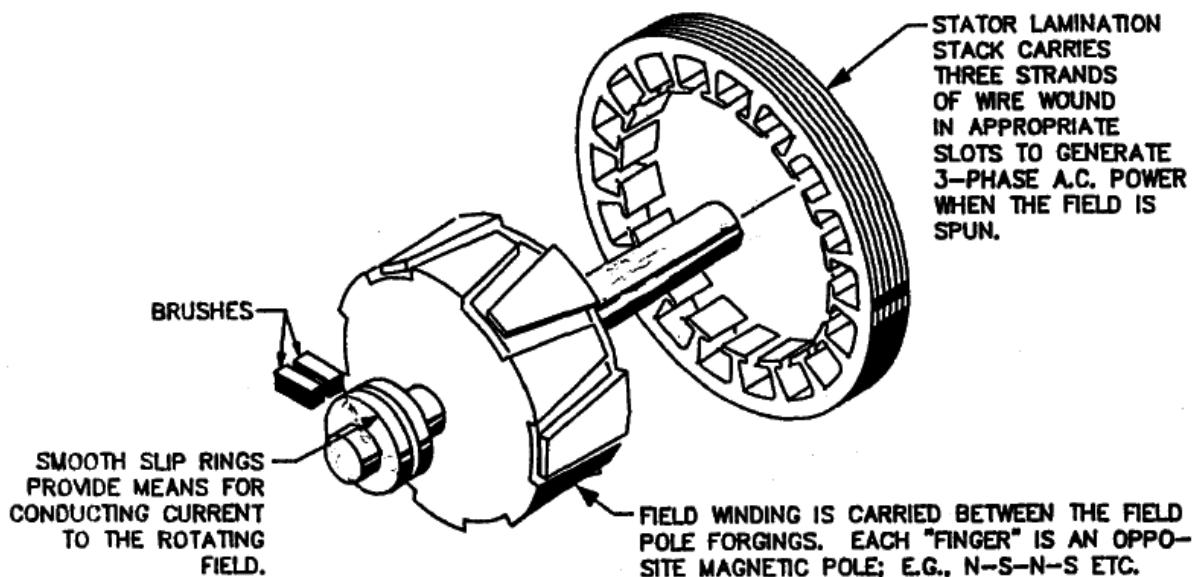


Figure 3-2. Major Components of an Alternator

The interleaved "fingers" of the alternator field assembly generate many reversals of the magnetic field around the stator windings for each revolution of the alternator shaft. This higher frequency of operation is the major factor in the superior watts per pound ratio of the alternator. There is a direct relationship of the weight per watt of power handling capability of AC devices with respect to operating frequency. For example, a 100 watt transformer for a 400 Hertz (cycles per second) aircraft power system weighs about 1/6th as much as a 100 watt transformer for a 60 Hertz house powered system. New generation automotive alternator designs have smaller drive pulleys to make them run still faster. The increase in basic operating speed (operating frequency) combined with high efficiency silicon rectifiers has produced some impressive performance in the

latest generation of products.

Some alternators bring out extra terminals to accommodate special regulators. Others ground one of the field connections internally while others may connect it to the "BAT" or "B" terminal. Some will bring out both field terminals. Still others may be found to have nine diodes in their rectifier assemblies with the extra three used to support a special regulator or control function. It is a fairly safe bet that any alternator can be modified to work in the aircraft application with the extras either removed or ignored. If the alternator has good mechanical characteristics then the electrics can usually be made to work.

The most prevalent architecture for automotive alternators calls for built in voltage regulation. At this time, the author is not aware of any certified alternator installation that utilizes built in regulation. Design goals for aircraft power generation include:

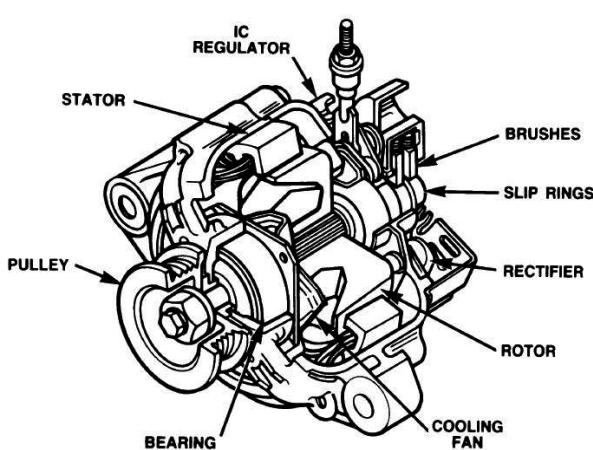


Figure 3-3. Exemplar Alternator Cutaway

- In airplanes, we'd like to have absolute control over the alternator by means of switches in the cockpit. This means that the system must be capable of any time, any conditions, ON/OFF control without hazard to any part of the electrical system. It's been this way since generators were installed on day-one . . . and there are good reasons to preserve the tradition of this design goal.
- There are no regulators made that offer 10^{-9} failures per flight-hour of reliability. This tiny failure rate is what the FAA considers "failure free". As a result, power generation systems incorporated into certified aircraft always feature some form of over-voltage protection.

The earliest adaptations of commercial-off-the-shelf (COTS) alternators to owner built and maintained (OBAM) aircraft modified alternators to remove built in regulators and

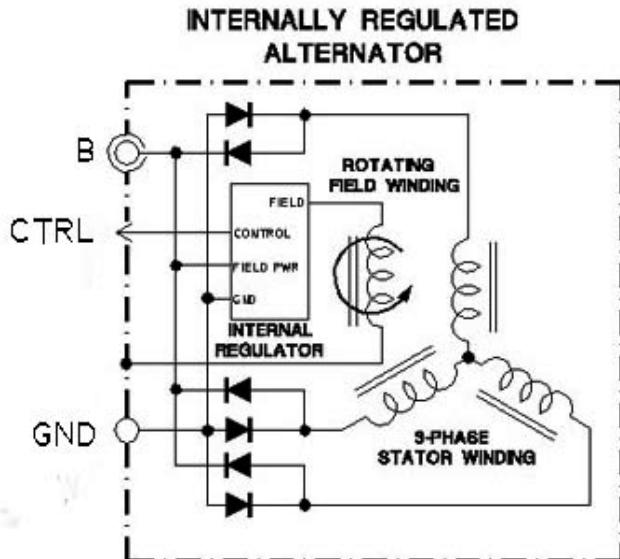


Figure 3-4. Schematic of Internally Regulated Alternator

integrate them into the airplane with external regulation and OV protection.

Figure 3-4 illustrates the electrical architecture common to internally regulated alternators. Power to excite the field comes directly from the alternator's power output terminal or "B" (Battery) terminal.

Internally regulated alternators pose a challenge to contemporary electrical system design goals. This is because there are solid state devices within the regulator's integrated control circuitry -AND- a power transistor to control field current that are vulnerable to rare but catastrophic failure that causes the alternator to operate uncontrolled at "full throttle". This "runaway" mode of operation pushes system voltage upward. Under some conditions, the voltage will quickly rise to over 100 volts. The "control" input to the alternator has no direct ability to open the field supply circuit and halt a runaway condition.

Alternators are inherently limited by magnetics in their ability to deliver current. This means that a runaway alternator will try to push the bus voltage up at some current delivery value just above the device's ratings. As I cited in Chapter 2, the ship's battery willingly, for a short time, accepts a majority of surplus energy. In the first few hundred milliseconds, a well maintained battery will keep the alternator output from pushing the bus over 18 volts or

so. This gives the over voltage protection system plenty of time to shut the alternator down and protect the system from damage. OV protection systems will easily detect and react to an over voltage condition in a few tens of milliseconds.

WHAT'S THIS "AIRCRAFT" ALTERNATOR STUFF ANYHOW?

Figure 3-5 is typical of electrical architecture when alternators first hit the automotive scene.

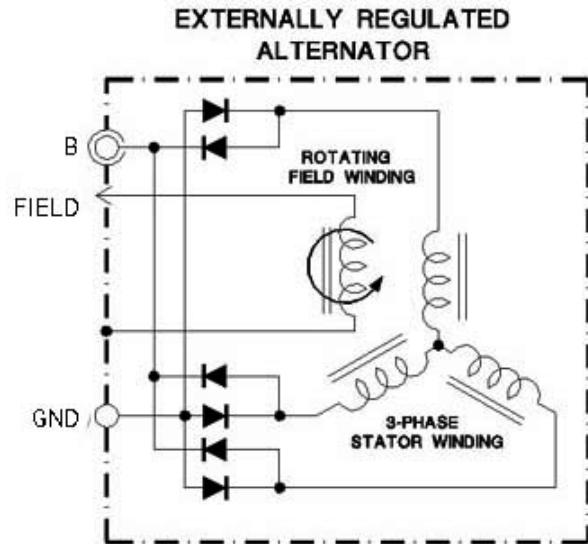


Figure 3-5. Schematic of Externally Regulated Alternator

Note that unlike the internally regulated alternator, the field supply must come from outside the alternator. In the days before OV protection, control of energy to the field was a singular responsibility of the regulator. Even before the advent of solid state regulators, there were failure modes in electro-mechanical regulators that would full-field the alternator and produce a runaway.

Unlike generators, alternators were capable of output voltages several nominal . . . delivered at the full current rating of the machine. It didn't take too many OV events before we scrambled to add independent means of interrupting field supply current when an OV condition was detected. Given that all field supply came from outside the alternator, adding OV protection in series with the supply line was a no-brainer. Your's truly developed the circuitry that was ultimately installed in thousands of single engine Cessnas before solid state regulators came with OV protection built in.

In the story of alternator evolution, solid state electronics made it practical to move voltage regulation inside the

alternator. Before this juncture, there was little difference between alternators destined for use on airplanes or cars. But as soon as the regulator moved inside, we lost the ability to exercise absolute control over the alternator's field supply. This feature was contrary to traditional design goals for (1) any time, any conditions, ON/OFF control combined with (2) independent detection of an OV event and subsequent alternator shut-down. It became popular speech to separate internally and externally regulated machines into "automotive" and "aircraft" categories.

In reality, there was little difference in the two products with respect to robustness or quality of craftsmanship. In fact, alternators qualified to fly on aircraft became bogged down in bureaucratic and regulatory tar pits that essentially halted their evolution. At the same time, design, manufacturing and aftermarket services for automotive products evolved into some of the most efficient, compact and cost-effective machines for DC power generation in light aircraft.



Figure 3-6. "Aircraft" or "Automotive"?
That IS the Question.

I'll suggest that the term "aircraft alternator" has no significance except perhaps to notice the field supply current source. Further, there ARE ways that the astute system integrator can successfully install a COTS alternator right out of the car parts store.

To be sure, there are lots of choices for configuring your alternator package. Duplication of a proven installation is the \$time\$ saving decision for moving your project forward. There are a number of suppliers who offer alternators with or without installation kits. Before you turn your nose up at

the idea of buying those funny pieces of bent-up sheet-metal, consider how much \$time\$ it might take you to find the right material and carve them out yourself!

INTERNAL OR EXTERNAL REGULATION?

There is no compelling reason to assert that any of the popular alternator, regulator and OV protection schemes are better or worse than others . . . assuming they were crafted with aircraft operability in mind. They need to meet design goals for performance, controllability, and compatibility with other systems. Electro-Magnetic Compatibility (EMC) looks at keeping noise emissions from your alternator system below those levels which pose problems for other systems along with immunity from radio transmitters in your airplane.

Understand that the 'Connection promotes system architectures and operating philosophies that have evolved from an artful application of good science, simple ideas and validated by a long history of experience.

All of Z-Figures at the back of this book go to meeting the design goals cited earlier. There's a body of thought in the OBAM aircraft community suggesting that pilots can do without an ability to shut down an alternator at will. Some folks have also suggested that independent and dominant OV protection is unnecessary with certain COTS alternators. Their failure modes are sufficiently benign . . . or their designs sufficiently reliable to make concerns for OV protection moot. Design goals for your airplane are your choice. Please go with the fabrication and operating philosophy that gives you the most comfort. I can confidently assert that a faith in the relative goodness of a particular brand of alternator is ill advised. More on this later.

It is entirely possible and perhaps even practical to convert an internally regulated alternator to externally regulated. The variables for accomplishing a conversion on so many otherwise suitable brands of alternator are too numerous to attempt useful coverage in these pages. There are a number of articles on the Internet that describe successful external regulation modifications for specific alternators.

The goal is simple. Deduce a means by which one of the existing brushes can be grounded to alternator frame and the other brought out on a lead that bypasses the built in regulator. This can usually be accomplished with a little study of the proposed alternator's internals.

There are alternatives to such modification that still meet traditional design goals illustrated in the Z-Figures.

FITTING THE ALTERNATOR TO AN AIRPLANE

Successful adaptation of any alternator to airplanes requires attention to (1) electrical and (2) mechanical interfaces. The mechanical interface is pretty straight-forward. The most robust alternator support calls for mounting ears on BOTH end-bells. The alternator in Figure 3-6 is a good example. The bolt that passes through these holes should also pass through two ears on an engine mounted bracket. Before you make purchase decisions, take a look at the popular options on other folks airplanes. All of the hardware used to attach an alternator to your airplane should be STEEL. No aluminum . . . I don't care how pretty that bright anodized attached bracket is. I've seen and participated in too many mechanical integration problems where even steel brackets were breaking . . . aluminum just isn't an option.



Figure 3-7. Exemplar Lycoming Boss-Mount Alternator Bracket - BEEFY!

One thing in your favor for bolting modern alternators to airplanes is the small diameter of the machine. A long time ago, Piper negotiated what they thought was a good deal for Chrysler "pancake" alternators. The diameter of these alternators made their low speed outputs attractive . . . but the mechanical overhang moments were horrible. For many years, owner/operators of Piper single-engine airplanes were plagued with a rash of bracket failures.

The bracket in Figure 3-7 is made from 1/4" thick steel. An excellent example of adequate support for a small diameter machine like that shown in Figure 3-6. When bolting your alternator of choice to the engine, be aware of clamp up forces that tend to spread or compress the ears of either the bracket or alternator. Note that the mounting ear on the rear end bell has a split liner in the hole. This liner-spacer is designed to slide in the hole to relieve any such clamp up forces. If your alternator of choice doesn't come with the slip-fit liner, then install spacers/shims between mounting bracket and alternator mounting ears to minimize if not

eliminate clamp up forces as the bolt is tightened.

There's a requirement that the two pulleys line up for proper belt tracking and finally, you need a means by which belt tension can be adjusted and maintained. This is usually accomplished with some bracket or brace that engages the single ear on the alternator's front end bell.

Your alternator will need to be fitted with a pulley that matches the belt that matches your engine pulley. If you have to change the alternator pulley, the nut that holds the pulley on the shaft should be installed with an impact wrench. When picking a pulley size, be aware that some of the most successful alternator offerings to OBAM aviation feature pulleys that cruise the alternator at over 10,000 RPM! The smaller pulley and high RPM offers these attractions: (1) better support of electrical system loads at taxi speeds while rapidly recharging the battery. (2) better cowling clearance and (3) better cooling of the alternator due to increased flow through internal fans. The rationale offered most often for slowing an alternator down is to accommodate some idea about bearing or brush limits. Know that many suppliers don't find this idea compelling.

ALTERNATOR INTEGRATION WITH THE ELECTRICAL SYSTEM

Once you're satisfied with the mechanics, the electrical integration is easy. The architecture drawings in Appendix Z pretty well cover the options for wiring up internal or externally regulated alternators. All the options offered feature positive ON/OFF control from the pilots seat and independent, dominant OV protection.

SO MANY CHOICES, SO LITTLE \$TIME\$

I often use the word "time" bracketed by dollar signs in my writing. I think it's important to keep track of the value of time when it comes to making choices for how your project goes together. We know that education is always expensive. There are builders who have learned how to do it right and are flying trouble-free systems that perform to design goals.

But if they're on the third or fourth configuration having invested much \$time\$ in learning how to do it, might they have been \$time\$ ahead by purchasing an off-the-shelf system with a track record? If you enjoy the learning process, then ignore the above. As long as you craft failure tolerant systems, it matters not whether you're flying the second or tenth iteration of an evolving design.

There are few topics of discussion in the OBAM aviation community that have demanded so great an expenditure of \$time\$ as the selection and operation of alternators. Much of the opinion offered arises from some bad experience by

a pilot . . . frequently offered in what I call “dark and stormy night” stories. Written with enough attention (or inattention) to the reader’s lack of knowledge, such stories usually generate many concerns and precious little if any understanding. So when it comes to alternator shopping, let us assume you’re game for playing the field.

In the fall of 2008, I had the privilege of touring the research, development and manufacturing facilities of Motorcar Parts of America. What I witnessed was amazing and enlightening. I’m working on a detailed narration of that experience to be published on the website. However, this chapter would be incomplete without touching on the highlights of the story..

When it comes to purchasing any commercial off the shelf (COTS) alternator, questions usually focus on pedigree, “Is it good enough to perform well on my airplane.” Some of the most powerful discoveries from my trip went to questions like these:

- “If I want to offer a really cheap product for the purpose of attracting the \$low\$ customer, what can I do to take costs out of my product?”
- “What fraction of total customers have purchase price of the product as the primary concern?”
- “How much difference is there between cost of building the bargain basement product and the best-we-know how to do?”

The MPA manufacturing facility in Tijuana (Motorcar Parts of Mexico) employs 1100 folks producing 22,000 units per day (starters and alternators). For a 9-hour day, this translates to an average investment of direct + indirect labor of 27 minutes per unit. This includes receiving, sorting, warehousing by line-item, tear down, cleaning, reassembly with new wear-out-items, automated testing, warehousing by line-item, packaging in customer’s branded boxes, palleting and shipping. Hmmm . . . obviously not enough time to do a good job you say?

It takes twice as long to put one together and test it as opposed to taking it apart and cleaning. So bins of grimy cores are dropped at a tear-down-and-clean station that is sandwiched between two assembly stations. All motions for the twisting, prying and pressing of parts for disassembly and reassembly are accomplished with power tools. Time lapse from grimy-bin removal to shiny-bin replacement is about 45 minutes.

The factory is bright, clean, odorless and staffed with folks wearing street clothes with perhaps a plastic throw-away apron. One lady I saw was in tan slacks, white shirt and

didn’t have a spot on her clothes anywhere. The factory was an exemplar demonstration of *lean manufacturing* which suggests you *don’t do anything to a part heat does not add value*. Further, you offer your workers *every labor/effort reducing tool available*.

The MPM shipping department loads alternators into a host of house-branded cartons, including brands of some big name original manufacturers. The whole process from incoming identification of cores to the loading of pallets on trucks is digitally aided and tracked. The average out-the-door cost of any one product wouldn’t take a family of four out for a round of Big Macs.

The next day we visited their IR&D facility in Torrance, California. This facility includes a lab that automatically exercises dozens of test articles at once and operates 24/7. The test articles are evaluated for performance and life issues. They gather and archive over 800 test-hours of data per day. There’s a constant effort to improve on performance as demonstrated by reducing the rate of return for fielded product.

In the lab we witnessed a full-load, max RPM, hot alternator load dump. As the technician removed a large fat-wire clip at the B-lead, a flash of electrical fire was so bright that attempts to video the event with my camera failed miserably. You saw the technician in the video before and after the event but only one or two solid white frames during the event. This and all MPA/MPM products are expected to shrug off this abuse 5 times in a row!

I asked the engineering director’s opinion as to the best brand of alternator. He looked quizzical and admitted that he didn’t have an opinion. The various alternators that come to his facility are simply raw material. His job was to track the quality of specific part numbers based on distributor, dealer and customer satisfaction. If any particular alternator was producing an unusual or unacceptable rate of real failure, it was his job to rectify that condition. He cited situations where perhaps a regulator on a particular OEM alternator was found lacking. These discoveries generated re-design efforts that produced a better-than-new alternator.

The significance of his explanation was quite clear. His company stocks 2800 line-items of starters and alternators. A mere 400 line-items were responsible for 80% of their business. But if they were going to be in the business, they could not limit their attention to the hot numbers. They needed to *do it all or do nothing*. The logo on the incoming alternator had no particular significance with respect to their business model. They took no notice and had no interest in whether the part was coming in for it’s first or tenth rebuild cycle. After the part leaves his factory, it’s an MPA/MPM part wherein the most expensive but non-wearing raw

materials were salvaged from carcass of another, essentially irrelevant brand name device.

Products from this facility have been sold in three “quality levels” with each level demanding more dollars from the customer at the counter. Rates of return for the three quality levels were noteworthy. I don’t recall the exact numbers but the ratios were startling. “Lowest quality” produced the highest return rate . . . yeah, you might expect that.. The “mid quality” was about 2/3 that of the low quality rate. “Highest quality” parts came back at about 1/3 the rate of the low quality parts.

A bit of research into these disparities showed that rates of return had more to do with skill, understanding and integrity of the installer than it did with real value of the *same exact part!* Irrespective of the “quality level” offered over the counter, additional dollars only buys the customer a longer service policy for the same piece of hardware. This begs the question, why not offer the highest quality level only? Not only do you take in more cash you reduce the rate of return. No doubt folks have used that business model for a host of products . . . and watched the majority of prospective customers gravitate to their competitor’s stores.

What might we deduce from this information about the suitability of a particular alternator for your airplane? Let us understand that quality has more to do with the last guy that worked on it than with the original manufacturer. If you’re going to be successful in the after market alternator business, you’d better figure out the most effective way to deliver the best-you-know-how-to-do.

End-to-end labor and “service contracts” are the largest driver of sale price at the counter. Quality of parts used in a re-man have little to do with the final selling price. It follows that there is no advantage in cost-cutting the bill of materials. Successful automotive re-manufacturing requires a supplier to meet expectations of a chain of stores that buys \$millions\$ per year in parts.

These chains cater to consumers at *all skill levels*. It would be exceedingly foolish to sell these clients short. An unhappy customer costs you an occasional hit on one item. An unhappy distribution chain costs you your rear end! The idea that any big name re-manufacturing operation isn’t delivering product equal to or better than OEM just doesn’t make sense.

Consider that the OEM gets a constrained view of product performance. Virtually all OEM development activity is based on in-house testing before the design is finalized and field history for a relatively benign service environment (new cars). The re-man guys are gathering performance and service history in the rough-and-tumble world of aftermarket

sales where the end user is everyone from the master mechanic to the shade-tree-do-it-yerselfer having only a pair of pliers and a hammer for tools. It seems likely that the re-manufacturing folks have a richer opportunity to apply statistical process controls to the improvement of their products. That is precisely what I believe I witnessed at MPA/MPM.

Let us suppose you crave a model of factory-new alternator. The aftermarket re-man operations are so efficient and cost-effective that even dealers will be loath to stock truly “brand new” alternators. You can get one off a car on the show room floor but probably not off the parts-room shelves. The re-manufacturing guys are buying the most expensive but non-wearing parts at scrap prices and folding them into zero-time product at a small fraction of the price for all new parts. The factory-new guys simply cannot compete with the competent, lean, re-manufacturing business model.

Okay, suppose you’re adventuresome and have elected not to buy a plug-n-play alternator. All brands of alternator offer dozens of styles with sufficient power output capability. Getting suitable attach hardware that lines up the pulleys and sets belt tension is the problem to be solved first. If you find a “kit” of mounting parts, the shape of those parts puts an immediate boundary on your choices for suitable alternators. Your field of choices drops from perhaps a few hundred line-items down to a few dozen examples of a particular alternator frame.

After that, you need to choose a product that meets design goals consistent with those cited earlier -OR- design goals suggested by others. If you choose the legacy design goals described in these pages, then the Z-Figures at the back of this book will guide your integration of either an internal or externally regulated alternator.

For reasons stated, alternative design goals are not included in these pages. However, if alternative ideas are attractive and should you discover performance pot-holes later, I’ll suggest you join us on the AeroElectric-List (an email based forum hosted at Matronics.com). The membership and I will endeavor to assist you in sorting out the alternatives.

Finally, understand that most discussions about Nippon-Denso being the “better” alternator compared to say a Bosch are unsubstantiated flooby-dust. If your alternator of choice was cycled through MPA/MPM or one of its able competitors, it’s likely to be of good value irrespective of the logos molded into the castings.

ALTERNATOR FAULT ISOLATION

Alternator charging systems are stone simple to diagnose and repair . . . assuming that you have a minimal

understanding of how these things go about meeting design goals.

The partial failure that does not kill the alternator dead may be subtle. I bought a car once that had an internal broken connection thrown in at no extra charge. Not having any experience with how the panel ammeter behaved with a good alternator I didn't have any reason to investigate and the degraded alternator performance became my 'norm'. It was months later, in the winter, when I noticed that the battery ammeter would go into slight discharge with the headlights and blower motor on with heavier discharge when I hit the brake pedal. Obviously the alternator was incapable of carrying the peak running loads of the car even though battery voltage was being properly maintained under conditions of light loading.

I replaced the alternator and the battery ammeter really came alive after engine start compared to the performance of the old alternator. I tore the old alternator down and found a cracked lead on a rectifier assembly which reduced the 45 amp alternator to little more than a 20 amp device. Some noises in my amateur radio equipment went away too! The rectified DC from a fully functional alternator is quite smooth compared to the one with a broken lead. Moral of the story: "Be sensitive to **changes** in the way your system behaves and **investigate**."

Investigation is the key word here. You should know what part needs replacing before you ever touch the airplane with a wrench. Too many of our brothers in both TC and OBAM aviation troubleshoot by takings stuff off the airplane for bench testing or worse, playing "swaptronics". Swaptronics is a game you play by putting in new stuff on the airplane until the system comes back alive.

The safest way to check for possible degraded alternator performance is to remove the thing and run it on a test bench. It is a lot of trouble but test benches don't remove pieces - well . . . **big** pieces of your body. If you do test the alternator in place on your airplane, get assistance at the controls and make test set up changes with the engine stopped. Here are some things you can do.

OUTPUT CURRENT TEST

You can test your alternator's output capability with the assistance a battery load tester described in the chapter on batteries. Connect the load tester right to your ship's battery under conditions where you can run the engine. With the load tester set to zero, start the engine and advance RPM to something above the minimum RPM for sustained flight. This might be 2000 RPM on the average Lycoming installation.

Minimize loads on the system to the lowest possible value. This might be assisted by pulling fuses or breakers for those devices that cannot be shut off. If you have an alternator load-meter installed, you don't need to shed loads.

Watch the bus voltage while you advance the load-tester's current draw until . . .

(1) the ship's alternator indicates 100% of design load meaning that the alternator is healthy and capable of rated output or . . .

(2) the bus voltage falls by say 0.5 volts whereupon you read the load current displayed on the load tester. Read the load value of current from the load-tester and add to it, any ship's loads you could not shed before the test. The total of these values should be equal to or greater than the output rating of your alternator.

If the alternator is crippled by loss of one or more diodes, you won't even get close to rated output. So we're looking for gross inability to support rated load and not looking to reject an alternator that appears to be say 10 or even 20% short of rated capability.

This test works for both internally and externally regulated alternators. It is remotely possible that inability to shoulder full load is a regulator problem. We'll touch on that in more detail in the next chapter

DIVIDE AND CONQUER

If your alternator is internally regulated and the bus voltage doesn't come up when the alternator is turned ON, then simple voltage checks will show . . .

(1) There is voltage at the alternator CONTROL pin that commands the alternator to come alive and . . .

(2) The voltage drop between the input and output of the b-lead contactor is less than 0.1 volts indicating that the contactor is closed.

If those two conditions are met, then it's time to put the wrench to the alternator for removal and repair.

If your alternator is externally regulated, you need to know if the fault is with the (1) alternator or (2) regulator, OV protection and associated wiring. Figure 3-8 illustrates a low cost test tool for the externally regulated alternator.

It's fabricated from a generic "ford" regulator, a few pieces of wire and terminal appropriate to the connections on your alternator. You disconnect the alternator field wire but leave the b-lead connected. Install this temporary regulator by

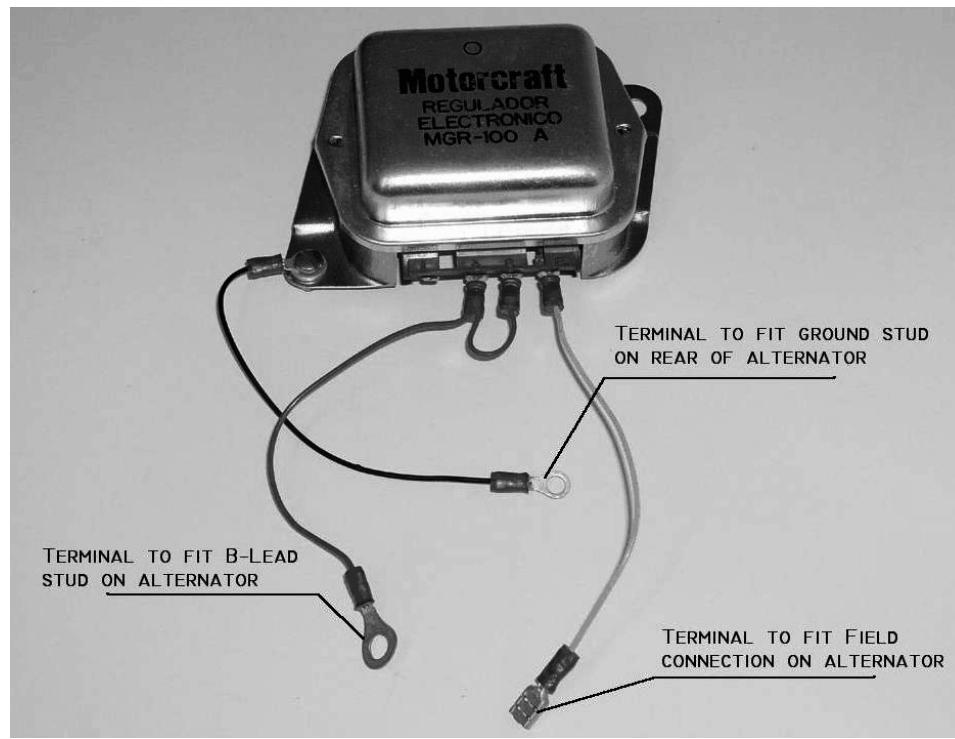


Figure 3-8. Externally Regulated Alternator Test Fixture.

attaching wires to the b-lead, field terminal and alternator case ground as cited in the photo.

Start the engine and advance throttle to 2,000 RPM or so. The bus voltage should come up to something just over 14 volts. If so, then the problem to be isolated lies with regulator, OV protection or associated wiring. If the alternator does not come alive, then it's time to get out the wrenches. Well speak to more details on regulators and OV protection in later chapters.

GOT A VACUUM PUMP PAD OPEN?

There's one more wound-field alternator of noteworthy capability because it is designed to install on the AND20000 style spline drive common to vacuum pump pads. For builders considering an all electric airplane, it would be a shame not to exploit the opportunity for driving two alternators from the same engine.

There are a handful of contemporary automotive alternators designs adapted to run on the vacuum pump pad. Most noteworthy is the B&C Specialties SD-20 illustrated in Figure 3-9.

Your's truly designed the first regulators for this product including a special version that permitted a 14 volt product to function in both 14 and 28 volt systems without having to

rewind the field coil. This alternator starts out life as an Nipon-Denso 40A machine that receives a new front end-bell and shaft modifications to accept the spline drive.

This product has proven a stellar replacement for the stand-by generators common to Bonanzas and C-210s since about 1980. I did the regulator design for those generators and I was exceedingly pleased to be a player in replacing those products with the next generation of technology.

Figure Z-12 in the appendix illustrates the most practical utilization of this product . . . although a number of builders have crafted a Figure Z-14 architecture using the SD-20 paired with a larger main alternator.

This particular product represents the Cadillac of spline driven alternators small enough to fit into the space behind an engine formerly occupied by a vacuum pump. A really cool aspect of this product's design is the fact that it's



Figure 3-9. Exemplar Pad-Driven, Wound-Field Alternator (B&C SD-20)

derated in output power due to the low speed of a vacuum pump pad. This design features bearings rated for the side

loads and operating speeds of belt drive. In this application, those loads, speeds and subsequent electrical loading is much less than original design goals. This product should demonstrate exemplary service life,

PERMANENT MAGNET ALTERNATORS

There is another form of low power alternator very suited to both primary power and stand-by service on OBAM aircraft. These parts have decades old ancestry in motorcycles and small garden tractors. Larger versions are found on Rotax



Figure 3-10. Spline Driven PM Alternator (B&C SD-8)

and Jabiru engines. This alternator is the ultimate in simplicity. Figure 3-11 speaks to the major components of a PM alternator. A stationary winding is surrounded by a cup shaped assembly fitted with magnets bonded to the inside surface. The stator winding has several 'poles' on it but there is generally only one strand of wire wound in opposite direction of successive poles. This configuration results in single phase AC power being produced by the magnets as they are rotated.

The practical power output limit for this configuration currently stands at about 250 watts max. There are some larger, 3-phase versions in the 400 watt class providing electrical power for larger garden tractors. To date, the smaller single-phase machines have seen the greatest application in OBAM aircraft.

This system is useful in

aerobatic or VFR-Day only airplanes with limited avionics. Typical outputs are in the range of 8 to 20 amps at 14-volts for single-phase products and perhaps as much as 35 amps for 3-phase devices. Since the field of this of alternator is fixed, the output voltage is proportional to engine speed. A distinct advantage of this design is that there are no slip rings. Power is taken from a stationary winding and rectified in a combination rectifier/regulator assembly. There are no high wear parts in a PM alternator. No brushes and very lightly loaded bearings. This class of alternator promises a very attractive service life.

The regulators used with these alternators are special devices that have very little in common with regulators needed for the wound field machines we've already talked about. Unlike regulators for wound-field alternators, the PM alternator's output must be rectified from AC to DC power simultaneously with controlling it to offset variation in engine speeds and electrical system loads.

The spline driven SD-8 and it's belt driven cousins put electrical systems onto many Variez and Longez aircraft about 30 years ago. Even today, the SD-8 is this writer's first choice for implementation of the "all electric airplane on a budget" depicted in Figure Z-13/8 in the back of this book.

Figure 3-12 illustrates an aircraft adaptation of a belt driven PM alternator commonly offered on small tractors. Belt drive offers an opportunity to spin the alternator faster thus producing more output power from the same size machine.

PM ALTERNATOR FAULT ISOLATION

First, because the PM alternator is so simple, the probability

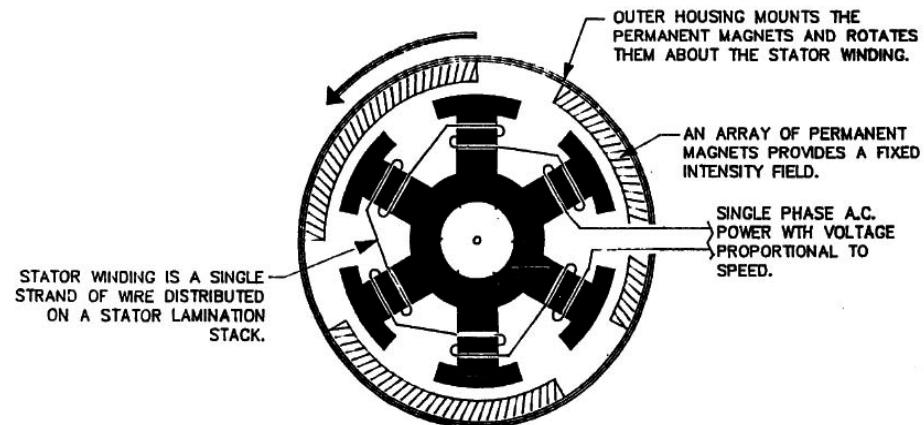


Figure 3-11. Major Components of the PM Alternator



Figure 3-12. Belt Driven Adaptation of PM Alternator to Aircraft.

of failure in the alternator itself is very low. For virtually any PM powered electrical symptom, look at the wiring first, followed by the rectifier/regulator. The alternator's output voltage may be monitored for test and diagnosis with a voltmeter but remember, it is an AC voltage. In flight, the voltage from these machines may be as high as 30 volts. We'll speak to the internal workings and unique functionality rectifier/regulators for PM alternators in the next chapter.

GENERATORS

Generators are still flying today on classic TC airplanes, on OBAM aircraft that use an engine taken from an older airplane, and several popular military trainers. If your electrical system power needs are modest and you make flights of reasonable duration so that the battery gets completely recharged in flight, there is no pressing need to replace a generator with an alternator. But they do tend to be much more troublesome than alternators.

Compare the construction of the alternator in Figure 3-2 to that of the generator in Figure 3-14. Here we find that the field assembly is the stationary part and the armature carries the power producing conductors. The current that flows in the power producing conductors of both the alternator and the generator is an alternating current. The commutator on

the generator's armature provides a sort of mechanical rectifier by tapping only the conductor that is moving through the strongest portion of the magnetic field. It also provides a means for taking power from a moving assembly. The brushes of the generator have to carry the total output current of the generator as opposed to the brushes in the alternator, which carry only a few amps of field excitation current.

The electro-mechanical switching regulator common to generator installations will be discussed in detail in the next chapter where you will see extra 'relays' used to limit output current and prevent reverse current flow in the de-energized or non-rotating machine.



Figure 3-13 Belt Driven Generator.

Unlike alternators with self-limiting magnetics and built in rectifiers, the generator is not self limiting in its ability to produce output current nor will it automatically isolate itself from the battery if the engine stops or belt breaks.

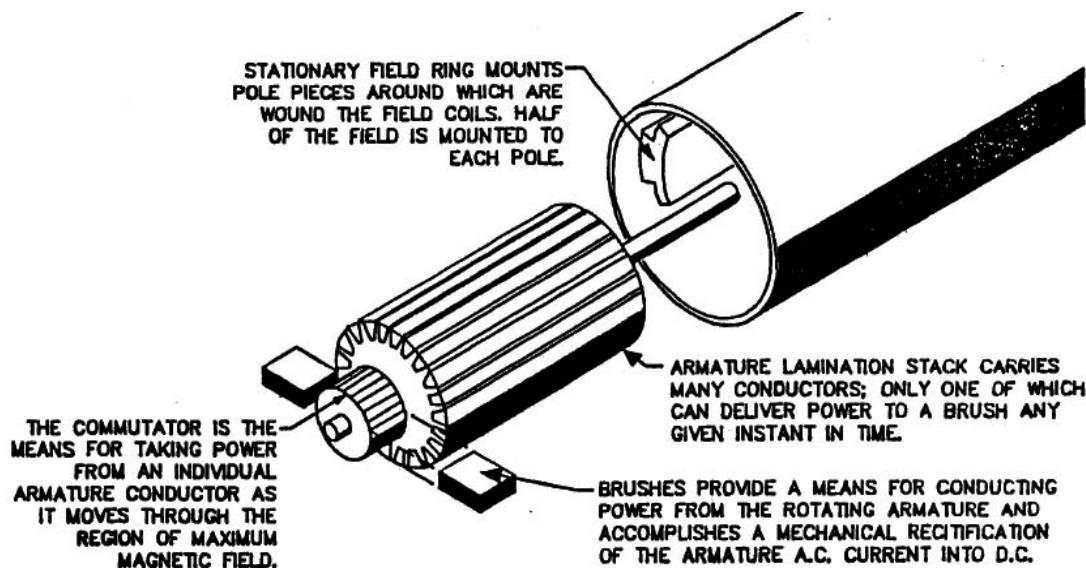


Figure 3-14. Major Components of a Generator.

Further, if the current limiter were inoperative or bypassed, a 20-amp generator would willingly deliver 35 amps . . . for awhile. Commutators and brushes would overheat as would the armature wires. It would be a race and perhaps a photo finish to see which one caved in first.

When the engine is turning too slow for the generator to produce a voltage greater than battery terminal voltage (remember, it takes 14-volts to charge a 12-volt battery) the generator must be disconnected from the system to prevent the flow of power back into the generator. For this task the generator's regulator assembly features "reverse current cutout" relay.

GENERATOR FAULT ISOLATION

If the generator output is zero, either the regulator, generator or wiring could be at fault. Use a voltmeter to see that there is voltage at the "B" terminal of the regulator with the battery switch on and the engine not running; check the wiring to the bus bar and the generator breaker if this voltage is missing.

Remove the cover from the voltage regulator and loosen the generator's belt tension. Manually close the reverse current cutout relay on the regulator. If the generator is mostly okay, it should spin up like a motor when you cause battery current to flow back into the generator. Gear driven generators will have to be dismounted for this test. If the generator will motor, it is most likely okay and you can try replacing the regulator.

Unlike alternators, generators are not directly excited

from the bus through their regulators. They depend upon residual field flux to "wake up" after the engine starts. If the airplane has been stored for a long period of time (or you're installing a new part), the generator may have lost its residual field flux and be unable to bootstrap itself on line. This condition is corrected by 'flashing' the generator's field. The act of doing the "motor test"

applies full battery voltage to the generator's field windings. The residual magnetism left in the generator that successfully passed a motoring test may now come back alive as a generator after you replace the belt. In stubborn cases, flashing can be facilitated by having the engine running at 2000 RPM or so when you close the reverse current cutout contacts.

Generator brush wear is also a common cause for failure. A tear-down inspection will reveal this problem. You can prolong the life of the commutator by many hours if you do a tear-down inspection of the generator at every annual and replace the brushes **before they fail**. In the act of failing much arcing and heat is produced, which is physically detrimental to the commutator. When replacing failed brushes or, if worn brushes are being replaced and there is a groove worn into the commutator's brush track, the commutator should be turned on an armature lathe with a diamond cutter. Commutator segments should then be undercut. Do not use sandpaper to clean up a dirty or corroded commutator. The sand will put microscopic grooves that are non parallel to commutator motion and accelerate brush wear. Use an abrasive rubber such as a typewriter eraser to remove heavy corrosion. A freshly turned commutator is the familiar bright copper color but brush track will soon turn a golden brown color when the generator is placed in service. This is the healthy glow of a happy commutator; don't polish it off.

Consider replacing bearings before they fail too. Take the old bearings to a bearing house and they will help you identify them and make suitable replacements at a fraction

of the cost of bearings through aircraft parts distribution. Generator bearings will be sealed and pre-lubricated. If you're offered a choice of lubrication, go for high temperature.

A voltage set point or stability anomaly is the fault of the regulator. If the generator has burned armature windings or commutator, be sure to check the operation of the regulator after the generator is repaired or replaced. In fact, I think I'd always replace a regulator after a catastrophic failure of the generator. The failure of the current limit or reverse current relay could have been the original failure that resulted in a secondary failure of the generator. The undiagnosed bad regulator will just as happily wipe out your new generator too!

If you have no other options, generators can continue to provide useful service in the operation of your airplane but they are expensive to maintain, demand more preventative care and are generally limited in their ability to power more electro-whizzies in your airplane. If you have an opportunity to convert to an alternator of any genre', you're money and

\$time\$ ahead for making the conversion. It's very difficult to find individuals with the tools and skills to do a good job on a generator rebuild. Suppliers of regulators is dwindling too.

LOOKING BACK IN TIME

It's interesting to compare the engine driven power generation technology available to us today with the products and markets first opened by the likes of Edison, Tesla, Westinghouse and Kettering. If you could go back in time and show them products we've been discussing on these pages, they would no doubt be amazed at the size, efficiency, and capabilities of these automotive DC power workhorses.

But the science, the simple ideas behind the operation of all these devices would be readily apparent and immediately understood. While modern materials and processes continually improve on our ability to meet evolving design goals, the science has and will continue to be as constant and relevant today as it was over 100 years ago.

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Voltage Regulators

In this chapter we will dissect the design and application of the voltage regulators, the good and bad ones, in detail. We will discuss the history and evolution of auto and aeromotive regulators. We will talk about the current market offerings of regulators and how to best cope with their limitations. We will also discuss the future in electrical power management systems.

The output voltage of an alternator or generator tends to run up and down with engine RPM, electrical system load and to some extent inversely to the machine's temperature. Both the alternator and the generator have a 'field' winding that has one or more terminals brought outside the machine's case. By adjusting the voltage applied to the field, the machine can be controlled independently of the other effects thereby providing a means for stabilizing its output voltage. Voltage regulators, as a rule, are very simple devices and quite reliable. However, their true function and the importance of their task is not very well understood. The result of this ignorance manifests itself most strongly in poor battery life and performance.

The voltage regulator has but one purpose - to keep the battery happy. A rechargeable battery requires that the voltage applied to its terminals for proper recharging be controlled to within a few tenths of a volt. Aircraft systems designers install the lightest and smallest battery possible to do one task - start an engine. After flogging a small battery by using it to crank the engine, we compound the battery's problems by forcing it to accept a recharge at some abusive rate. The final result is to allow the bus voltage to remain at some level required to achieve 100% recharge after recharge is achieved. The excessive 'float' voltage slowly cooks the battery's innards dry.

Other problems attributable to mis-applied regulators are electrical system noise and poor voltage regulation. Damage to system components is also probable when no provisions for regulator failure protection are provided. Proper selection and application of the voltage regulator can provide real solutions to and safeguards from these problems. Voltage regulators fall into two basic categories: linear and switching. We will describe both of these types and trade off their relative advantages and disadvantages.

SWITCHING REGULATORS

The 'switcher' is the most common regulator type in both the automotive and the light aircraft worlds. Even the turbo-props use switchers on their big starter generators. Switchers are most noted for their efficiency. They operate very cool; their active electronic components can be downsized and packaged more economically than in their linear cousins.

A switcher gets its name from the fact that its major controlling component is operated much like a switch: it is either turned on or off completely with no intermediate levels of current flow allowed. An analogy to this might be to compare an instrument panel dimmer rheostat with the nav lights switch. The switch has only two positions: on and off. The rheostat has many positions ranging from fully on to completely off. A rheostat does get warm or even hot when it is set for an intermediate position, but not when it is full on (zero ohms) or when it is full off (zero amps). A switch dissipates very little power in accomplishing its task; its 'on' resistance is measured in milliohms.

With only two positions for a switch, some other attribute must be present to accomplish what appears to be the linear control of an otherwise unstable power generating device. Obviously if the switch were simply closed, the field would receive full bus voltage, the machine's output would rise, the field would get more voltage, the output would rise further and so on. The effect is a voltage runaway and much smoke may follow. On the other hand, if the switch were simply opened, there would be no output from the machine at all. The secret here is that the switch is closed for only part of the time and open for the rest. Further, the rate at which it is switched is so high (100 to 2000 times a second) that the effects of the switching are not perceptible to us or to the equipment powered by the alternator. Control of the machine is achieved by varying the "duty cycle" or on/off ratio of the switch.

To illustrate this concept, let us suppose that we have a 5-volt lamp attached through a switch to a 15-volt battery. If you simply close the switch, the lamp would burn very brightly for a short period of time before succumbing to the over-voltage. However, if you could arrange a device to open and close the switch 100 times

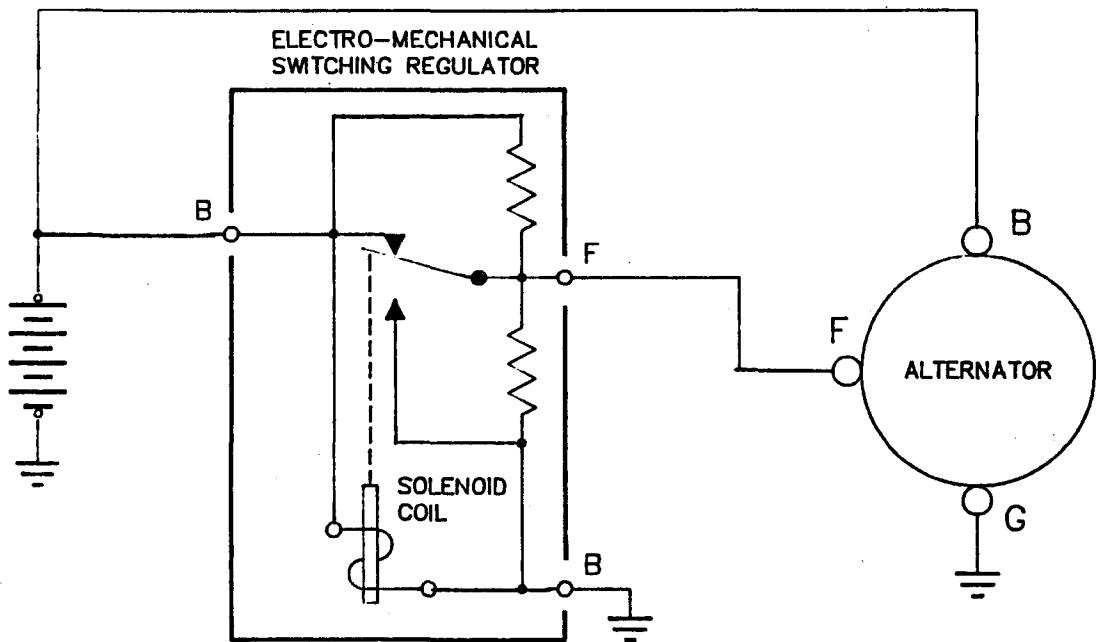


Figure 4-1. Electro-Mechanical Switching Regulator

per second and further, if the on/off ratio could be continuously adjusted so that the switch was closed for a short portion of that 100th of a second and open for the longer portion, then the AVERAGE POWER applied to the lamp could be set to illuminate the lamp at its normal intensity.

This could be accomplished in spite of the fact that a full 15 volts is applied to the lamp all the time the switch is closed. The power lost in the switch would be quite small; there is no voltage dropped across it while closed. When open, there is no current through it. If the switch were operated at 10 times per second we might well expect to perceive flickering in the lamp. However, at 100 times per second no flicker is visible due to the thermal inertia of the lamp's filament and the visual retentivity of the eye. Indeed, the common household lamp is operated from a current that goes to zero, reverses in polarity and goes to zero again 120 times per second with no visible flicker. The trick in the switching regulator is to design circuitry that accomplishes a variable duty cycle control of the switching transistor, which in turn controls the field winding of the machine.

Before the transistor, alternator and generator regulators utilized a device that looked somewhat like a relay. This was a special relay that was normally closed so that full field voltage was available to the machine. The concept is illustrated in Figure 4-1. The generator's output voltage was applied to the coil of the relay. As the voltage rose, the upper contacts of the relay would just open, at say 13.8 volts, and reduce excitation to the field. The output voltage would then fall and the relay would reclose. The resistors shown caused a reduced amount of field voltage to be applied when the upper set of contacts parted. Under very light load conditions or with high engine RPMs even the reduced excitation to the field was too high thus allowing voltage to rise further. At a somewhat higher set point, say 14.0 volts, the relay armature would be pulled harder until the lower set of contacts would close. This would result in a dead short being placed across the field, killing the output completely.

The net result of this operation was a short buzzing action wherein the contacts would be constantly opening and reclosing at some rather high rate. The on/off ratio would change depending on the machine's RPM and load. The normally closed contacts would be in

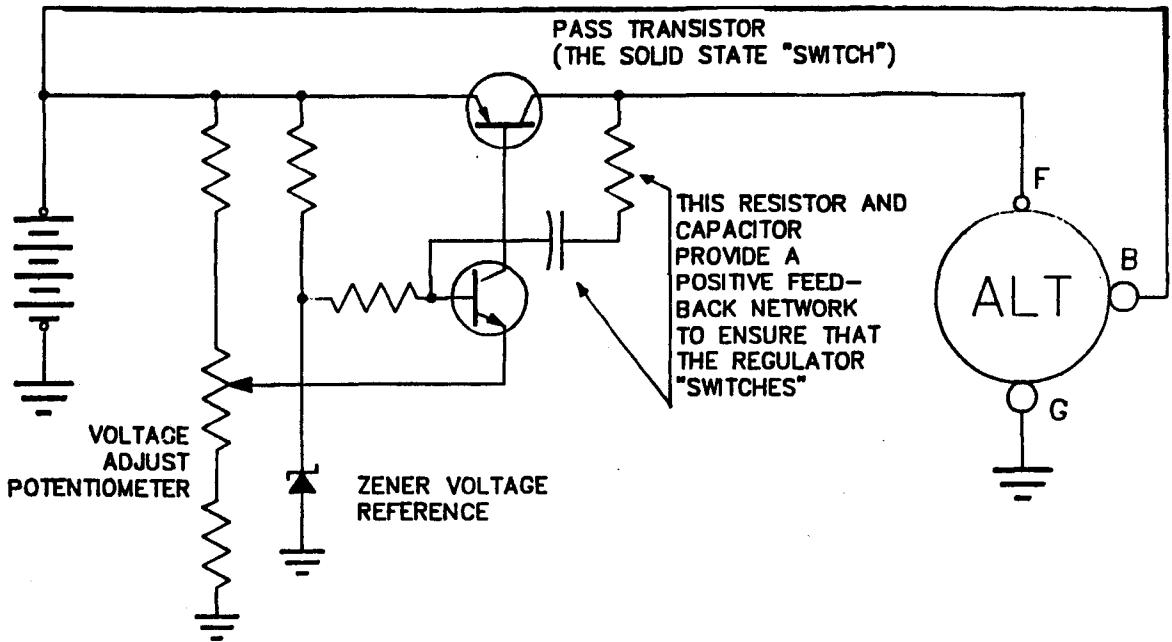


Figure 4-2. Solid State Switching Regulator.

volved in the low RPM, high load scenario; the normally open contacts would take over in the high RPM, low load situation.

A battery's ideal charging voltage is temperature dependent, so a temperature sensing bi-metal spring was usually included in the tension setting system of the relay. As it got colder, the tension increased and raised the voltage control setting. At higher temperatures, the tension was decreased with a corresponding decrease in voltage setting. This deceptively simple mechanism had a lot of clever designing behind it; aside from mechanical wear limitations and tricky calibration it performed rather well.

The availability of transistors made it possible to build a no-moving-parts switching regulator that was not subject to mechanical wear and dirty contacts. However, transistors are not without their weaknesses. Voltage spikes from other devices in the system can cause them to fail. They must be protected from their own internally generated high temperatures. Further, they require additional devices to make up the total circuit which tells them when to turn on and off. Temperature sensing must be accomplished with another kind of

device than a bi-metal spring. Figure 4-2 illustrates the schematic for a simple, solid state switching regulator.

Calibration of the solid state regulator is easier: a small adjusting potentiometer is included for this purpose. Temperature compensation is accomplished with a 'thermistor' (a kind of temperature dependent resistor). A solid state voltage reference device known as a zener (zee-nur) is used as a standard of comparison. As the bus voltage rises, transistor Q1 tends to shut off, which in turn shuts off Q2. Field voltage to the alternator is reduced which brings the bus voltage down. A network of components provide a positive feedback network that speeds up the transitions from on to off, reinforcing the switching action. The output of a pass transistor in a switcher is a train of variable duty cycle pulses.

It is possible to buy a complete switching regulator as an integrated circuit complete with temperature sensing. Most modern automobiles use very compact solid state switching regulators that are built right into the rear endbell of the alternator. They have achieved a high degree of reliability at very modest costs. We visited an automated assembly plant for automotive

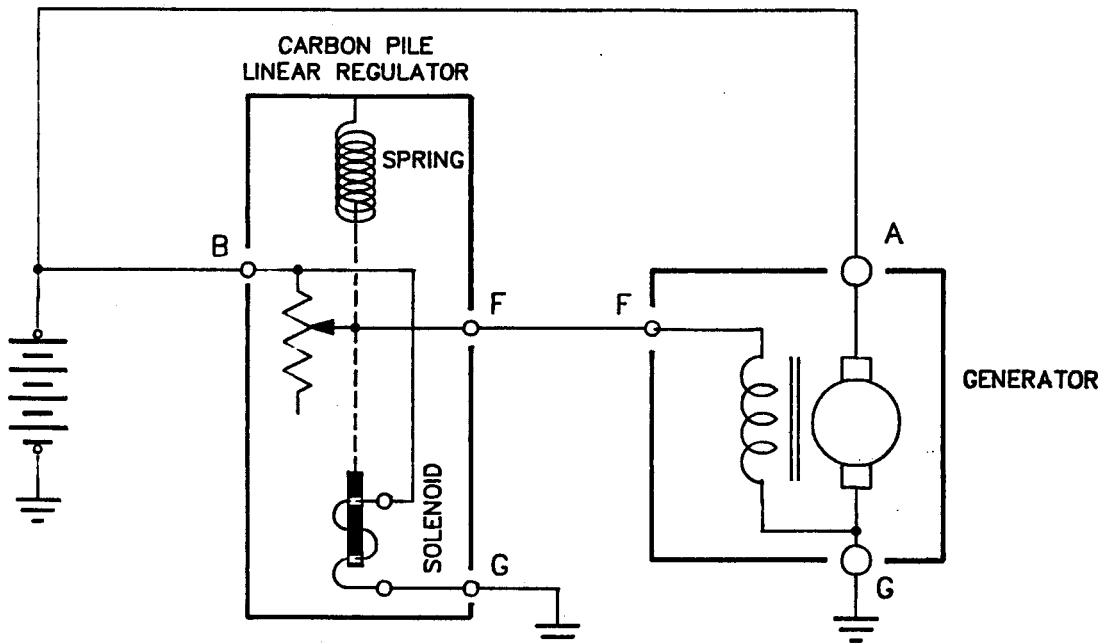


Figure 4-3. Electro-Mechanical Linear Regulator

voltage regulators in Fon du Lac during Oshkosh '86. Their out-the-door price for a very sophisticated switching regulator was less than a dollar (in lots of 100,000!).

LINEAR REGULATORS

The linear regulator controls the field winding of the alternator with a close equivalent of a smoothly adjusted DC voltage. The operation of a linear regulator could be approximated by connecting a rheostat (variable resistor) in series with the field winding of an alternator. In order to maintain the desired output, a voltmeter could be used to help adjust the rheostat.

The linear regulator has its counterpart in antiquity too. One of the best regulators available in the late 30's and through the 40's was a device known as a carbon pile regulator; its principle is shown in Figure 4-3.

The 'pile' was a stack of thick carbon washers or disks with conductors attached to each end of the stack. The resistance to the flow of current throughout this stack was a function of the mechanical pressure applied to

the stack of disks. There was little or no motion involved in varying the pressure on the stack. A spring was used to keep a constant pressure on the stack (hence a low resistance in series with the field) when the bus voltage was low. A solenoid was rigged to relieve the pressure (thereby raising the resistance in series with the field) as the voltage in the solenoid was increased. By careful design of the spring, solenoid and carbon pile, a very effective voltage regulator could be built.

Very sophisticated carbon pile regulators were developed, capable of pairing two generators such that they would share the load on a twin engined aircraft. One feature of the carbon pile device is still present in the modern solid state linear regulator: the controlling device gets a lot hotter than the one used in a switcher. If you ever come across an old regulator in a surplus store, it can be easily recognized by its cylindrical, cooling finned housing - about 2.5" in diameter and 5" long. You might be interested in buying it if you can get it cheap; it is a true antique.

The controlling device in a linear regulator is also a transistor like that used in the switcher, the difference

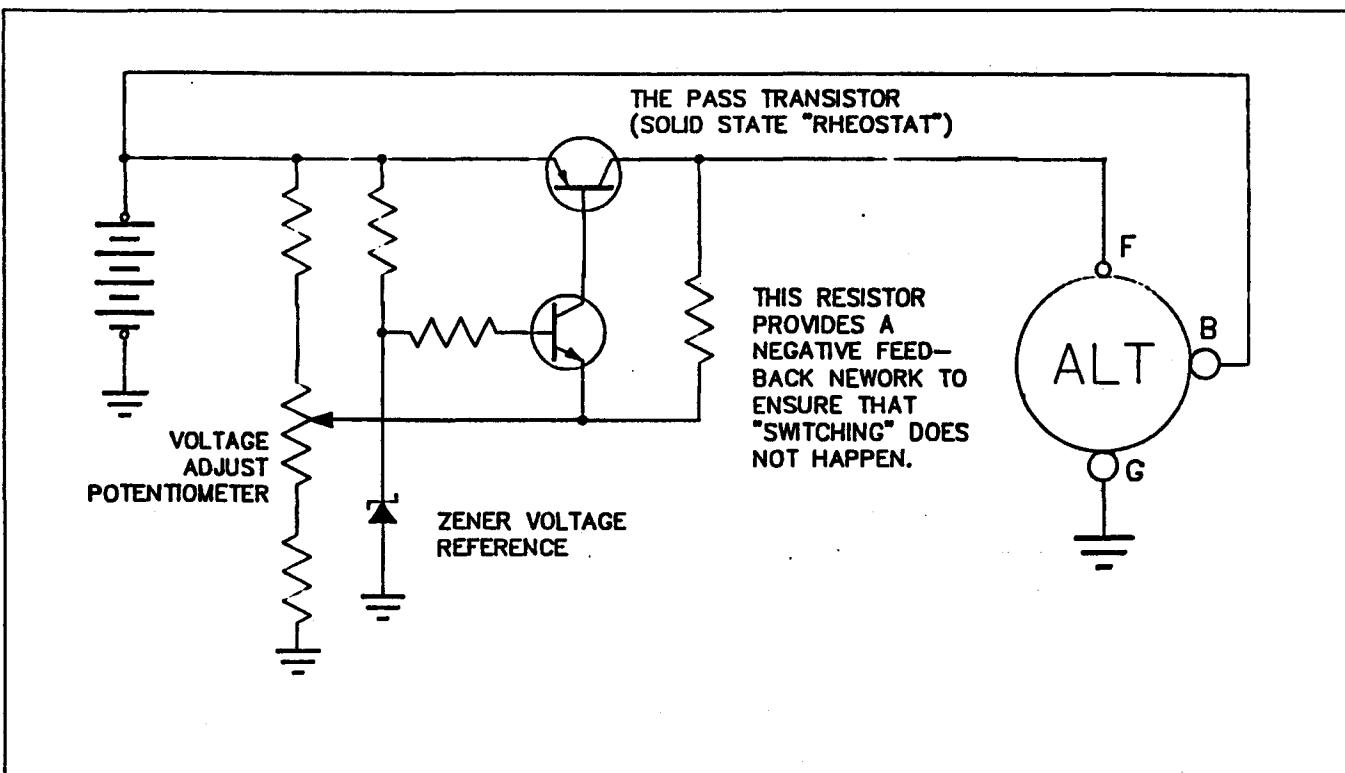


Figure 4-4. Solid State Linear Regulator

being in the manner they are driven by their associated voltage reference and comparitor circuits. The major difference between the two circuits is in the 'feedback' network. In the switcher a positive feedback network is used to increase transition speed between on-off and off-on. In the linear, a negative feedback network reduces the gain and speed of the circuit to ensure that switching does not occur. The drive to the linear pass transistor is a variable DC current designed to sneak up on and smoothly intercept the desired output voltage from the alternator. The circuit shown in Figure 4-4 is a simplified linear regulator. Not much different from the switcher shown in Figure 4-2, but very different in the way it performs.

SPECIAL REGULATORS

Some engine driven power sources flying on home-built today utilize permanent magnets instead of externally excited fields. The output voltage of these machines is proportional to engine speed and requires a special type of switching regulator to mate them to the electrical system. One example of this type of system is the small 'dynamics' sold by B & C Specialty Products. Incidentally, someone who had picked up a

flier on the Aero-Electric Connection at Oshkosh '87 sent me a request in the mail asking about these devices. Since I did not design the particular regulator that Bill uses, I will have to do some research and provide an update to these pages with the next issue.

TO SWITCH OR NOT TO SWITCH . . .

The major reason for selecting a linear regulator over a switching regulator has to do with electrical noise. Have you ever tried to listen to an AM radio while using an old electric razor? Most of the old razors used a simple pulsed motor that was commutated by a pair of contacts that opened and closed their very inductive windings many times per second; lots of arcing too! They stood high on the list of electrical noise generators; second only to an arc welder! The 'relay' type voltage regulators also suffered from the arcing contact syndrome. Careful selection of materials and associated components was able to reduce the noise from these devices to tolerable levels.

Solid state switchers certainly do not suffer from arcing contacts - there are no contacts. However, they do generate square wave voltage waveforms. An irrefuta-

ble law of physics states that a square wave signal contains harmonic energy that extends many octaves above the basic switching frequency. This energy can cause degraded performance in low frequency radios such as ADF and Loran-C, and in audio systems.

This harmonic energy is a function of the speed with which the pass transistor can be made to switch. The faster the switching speed, the cooler the transistor operates, but it generates more noise. If you slow down the transitions of the drive signal to the pass transistor in favor of the radios, the hotter it becomes. Slow it down enough and (1) the output doesn't switch at all, (2) the radio noise goes to zero, (3) heat dissipation becomes an issue and (4) you now have a linear regulator!

Switching regulators are found on virtually all production airplanes. Their predominately metal construction provides the best possible environment for isolating the radios from the regulator noise. The widespread use of composites in homebuilts presents a different picture. Shielding of radiated electrical noise and filtering of conducted noise is much more difficult. Further, antenna systems on plastic airplanes tend to suffer in efficiency (more on that in the chapter on antennas) making it more important to design the electrical environment for the best possible noise reduction. The linear regulator's only bad trait, liberating some heat, can be dealt with by reasonable heat sinking of the pass transistor.

THE ULTIMATE REGULATOR

Unfortunately, it does not yet exist but we are working out several approaches to the design. The major features of the regulator will include: (1) a remote temperature sensor that tells the regulator what the present battery temperature is, (2) a battery charging current sensor that adjusts the alternator voltage to produce a constant current charge until the battery is fully charged, followed by (3) a voltage reduction to the proper battery sustaining level after full charge is achieved.

The regulator will undoubtedly be packaged together with an appropriate over-voltage sensor and automatic shut-down circuit as well as an under-voltage warning light driver. We might also include a LED bar graph driver to indicate present bus voltage, alternator current and battery current.

HOW REGULATORS FAIL

The voltage regulator can fail in several ways. The most common failure is to simply drift out of calibration so that the battery is no longer properly cared for. If you are fortunate, the regulator is adjustable and can be recalibrated. However, if an adjustable regulator needs calibration for the first time in many hours of otherwise proper operation, watch for a continuing trend. The component or components that were once stable may be heading south and it is not unusual for the pace to pick up. Less expensive, high volume production switchers are seldom adjustable and must be replaced when they drift out of calibration.

A second failure mode is for the device to simply roll over dead and kill the output of the alternator completely. This is the more benign total failure mode.

The third mode is a thriller. Something breaks or shorts causing the full bus voltage to be applied to the field of the alternator. The output of the alternator rises as fast and as far as the things tied to the bus will allow. Batteries put up a valiant effort to absorb the excess electrons but they eventually succumb. Everything else takes it where it hurts - in the pocketbook. Insult is added to injury when you find yourself airborne at night (or worse), the lights go out and the radios make strange noises before going dead. If the situation really gets going, maybe the boiling battery will fill the cockpit with a terrible tasting fog. Forgive my melodramatic description of this unhappy event. It's the nicest way I can think of to talk about it.

Do the spouse and kids a favor (your life insurance company will appreciate it too!), install an over-voltage relay between the bus and your voltage regulator. 'Nuf said on this for now; see chapter 6, Power System Monitoring, in the next issue.

SELECTING A REGULATOR FOR YOUR AIRPLANE

First, if you do not plan to have radios, then by all means install a switcher. If you plan only vhf radios, a linear regulator might be of limited usefulness in reducing noise in the audio system. If you have plans for an ADF or Loran-C receiver in a metal airplane, I would strongly suggest using a linear regulator. If your airplane is composite well, we supplied the regulators for Voyager. We would not have considered anything but a linear regulator for that application.

WHERE TO FIND A REGULATOR

If you can live with a switcher and are willing to tolerate battery abuse that is no worse than that which occurs in your automobile, then the auto supply stores are good sources. Airparts distributors may be able to supply regulators packaged with over-voltage protection and under-voltage warning equipment. You may find some alternators with built in regulators attractive. Many of these are suited to aircraft installations with some exceptions. See the chapter on Engine Driven Power Sources in this issue and Power System Monitors in the next issue.

Some replacement regulators for early automotive alternators look like the big black box full of 'relays' that they replace. (Check on a regulator for about a '72 Chevrolet.) They may in fact be solid state equivalents and should be considered. They are light for their size and very inexpensive. Further, most automobile regulators are temperature compensated to lead-acid battery charging curves. In any case, do not pay the extra bucks to buy a switcher used on a certified production aircraft. Except for the types used on heavy twins, they are generally no better than automotive in both parts and workmanship.

I know of no sources for linear regulators outside the aircraft parts community. Inquiries to dealers of surplus aircraft parts may locate reasonably priced linears. One brand name that is fairly common is the Lamar. Be sure the offering is indeed a linear; many companies build both linears and switchers in similar packages. B & C Specialty Products is the only company I am aware of that builds a linear for single engine airplanes and combines it with all the necessary protective and warning circuitry in one package. It is the regulator we designed specifically for the Voyager.

INSTALLATION

Temperature compensated regulators are best for keeping the battery happy. If the presence of temperature compensation is unknown, cool the regulator with a piece of ice (dry ice or a small CO₂ extinguisher works well too) while running the engine and watching the bus voltage with a precision voltmeter. If the voltage goes up as the regulator case cools, it is probably compensated. If the voltage goes down, consider having the temperature compensation checked in a more accurate environmental test. A regulator with a positive temperature coefficient could be very hard on your battery.

Most production regulators I have encountered in the general aviation environment were designed to be stable with temperature. I suppose the airframe manufacturers reasoned that since they were not going to mount the regulators on the battery box it would be better to have no compensation at all.

If your regulator proves to be compensated, then you should make every effort to mount the regulator close to the battery so that they share a similar temperature environment. If the regulator is not compensated and designed to be stable with temperature, then location with respect to the battery is not important. Hot environments are to be avoided, especially if the regulator is a linear.

Poor wiring practice can cause the regulator to sense a voltage at its input terminals that is quite different from the voltage at the battery terminals. This is because wires are not available yet with zero ohms resistance. A few milliohms here, a few milliohms there and a couple of amps can make a few hundred millivolts difference. It might not seem like much but then you aren't a battery.

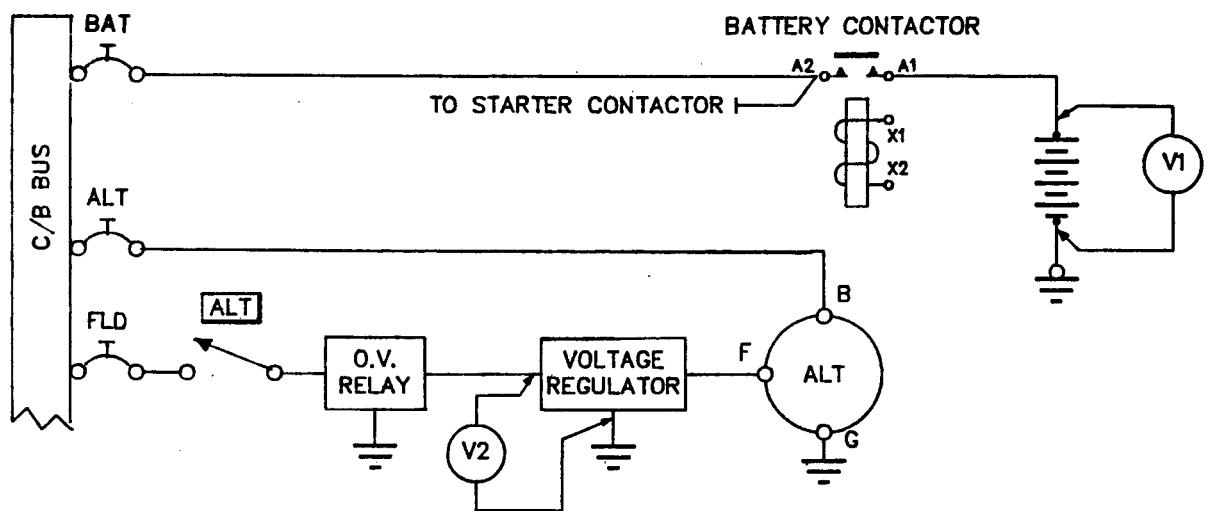
The problem is most common in a composite airplane. Figure 4-5 illustrates a wiring technique that minimizes these errors by running a separate ground and voltage sense wire for the regulator directly to the battery. In a metal airplane, a local ground to airframe will suffice but it is still a good idea to take the sense wire directly to the battery.

* CAUTION *

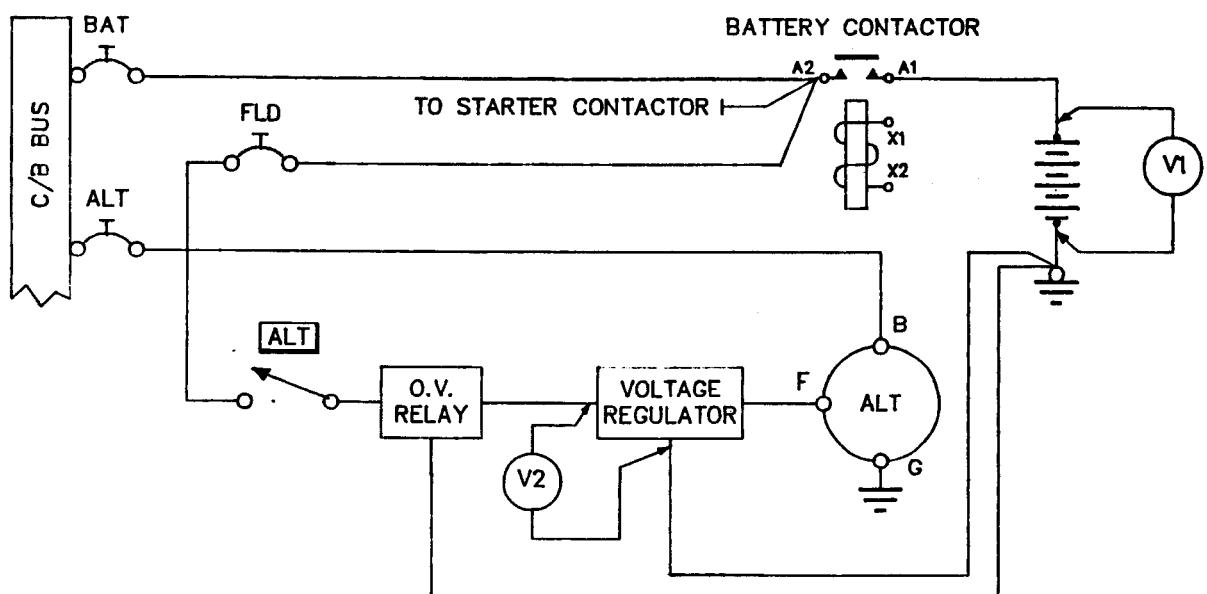
When deprived of a ground, some regulators will run away and cause severe over-voltage conditions to occur. Check the regulator you choose for this condition and be sure that your over-voltage relay is working and enjoys its own ground. Simulate the failure on the ground, radios off, so that what might happen in flight is no surprise.

IS THE REGULATOR DOING ITS JOB?

Just because a regulator is marked as having been set at 13.8 volts doesn't mean that it is still regulating at 13.8 volts. If a mediocre grade of components was used in the assembly of the regulator, its setpoint may



FOR METAL AIRPLANES THE OV RELAY AND REGULATOR ARE GROUNDED TO SEPARATE POINTS ON THE AIRFRAME. IF REGULATOR PERFORMANCE IS POOR (SEE TEXT) THEN CONSIDER RUNNING SEPARATE FIELD CIRCUIT BREAKER WIRE AS SHOWN BELOW.



IN COMPOSITE AIRPLANES, AN INDEPENDENT FIELD BREAKER SUPPLY WIRE AND SEPARATE GROUNDS FOR THE OV RELAY AND VOLTAGE REGULATOR PROVIDE THE REGULATOR WITH A TRUE PICTURE OF BATTERY VOLTAGE.

Figure 4-5. Regulator Performance Testing.

drift with time. Installation can also affect how well a regulator functions. You may have heard of the dreaded 'ground loop'. These lurking demons are responsible for many a failed or malfunctioning component or system. We'll talk about grounding in detail in Chapter 5 but we will cover grounding of the regulator here as a specific case.

Recall that a regulator is interested in the voltage presented to the battery. Further, we have seen that while the effects of resistance of wires can be minimized, it can never be zero and should be a consideration in critical cases. Figure 4-5 shows where voltages need to be measured and compared to determine if 1) the regulator is adjusted properly and 2) if the regulator is truly sampling the voltage seen by the battery. The voltmeter used to make these measurements must be capable of measuring your system voltages to the nearest 0.01 volts. We will measure the voltage at the regulator's input terminals and at the battery terminals while in flight. You may have to make temporary installations of some long lead wires to extend the voltmeter's reach during these tests. Incidentally, when we show a voltmeter probe as sampling some point close to a piece of equipment, the implication is that you must extend both leads of the voltmeter as needed to sample as close to the device depicted as possible. It is not sufficient to 'ground' one lead of the voltmeter and then probe with the (+) lead only.

First, determine what the temperature of the battery will be during this test. Plus or minus 10 degrees F is close enough; we just need to find the ballpark between a Minnesota winter and a Phoenix summer. While in flight and after the battery has had time to recharge, make voltage readings shown with your normal VFR-day electrical loads on, then again with VFR-night loads. Then if you have any heavy drain items like pitot heat or electric cabin heat, make a second set of readings with all of these devices on too.

Temporary loads such as landing lights, flap motors, and landing gear motors should not be on for these

measurements. We are concerned only with flight conditions which are relatively static and occur for hours at a time. You may wish to turn these devices on and observe their effects; any large shifts, say +/- 0.5 volts or more, may indicate some inadequate feature of the system wiring. However, such excursions of voltage are not relevant to this investigation.

Back on the ground, go into the chart in Chapter 2 for battery temperature verses charging voltage per cell. Multiply by the number of cells in your battery: 6 for a 12-volt and 12 for a 24-volt.

Compare the regulator voltage readings (V2) with this figure. If there is more than a 0.15 volt departure from the ideal voltage for a 14-volt system or 0.3 volts from the ideal for a 28-volt system, I would recommend readjusting your regulator. If you find that your regulator is adjustable but not compensated for temperature, consider readjusting the regulator for the season, perhaps four times a year to the voltage appropriate to the average temperature. Cessna used to recommend this procedure in their maintenance manuals.

Now compare the readings taken at the battery (V1) and at the voltage regulator's input terminals (V2). If these two voltages differ by more than 0.1 volts, I would recommend rewiring the regulator per Figure 4-5.

Instruments for electrical systems monitoring in flight are mandatory. Being able to interpret them accurately is just as important. A zero center, battery ammeter (discharge-zero-charge) is the most desirable and should be the first electrical system instrument you install. Interpretation of this instrument is described in the chapter on batteries. An accurate voltmeter would be my choice for the second instrument, but it must be ACCURATE! To be useful, you must be able to read a voltmeter to the nearest 0.1 volts. More on this subject in a later chapter on instruments. The construction articles will include details on building an expanded scale voltmeter that reads from 10-16 volts instead of 0-16 volts.

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Grounding

"Grounded" is an archaic electrical circuit term with a literal meaning; the circuit is connected to a metallic rod driven into the earth. The British expression "earthed" has the same meaning. The term became commonplace in the electrical power distribution and the radio/electronic fields at about the same time in history. I haven't researched the word Ben Franklin used to describe the connection of his lightning rods to the earth; perhaps the term is older than I think!

In the early days of radio, receiving and transmitting antenna systems required a good earth ground for best performance. A pipe driven into the ground was always connected to the chassis of the radio receiver or transmitter. At the same time, the people who designed receivers and transmitters used the chassis for a common connection of all the power supplies and signals within the radio set. The meaning was diluted when the electronics people began to use an earth ground symbol to denote connection to the chassis of an electronic assembly.

I have a couple of books on electronics published in the late 30's and early 40's, given to me by an uncle when I was about 10 years old. These books mark my introduction to electronics. I noted that radio antenna installations in automobiles referred to the automobile chassis as "ground" and schematics for some radio receivers used the earth ground symbol to refer to a common or chassis connection whether or not a true earth ground was needed for best performance.

Over the years the term "grounded" has acquired a variety of meanings in as many technologies. In some cases, it can have different meanings in the same technology. Some ambiguities were resolved with additional terms for ground such as "common, counterpoise, ground-plane, return and neutral." All have been used to impart a more precise meaning in specific instances. I will try to be both concise and properly descriptive when using the word "grounded."

Figure 5-1 illustrates a variety of symbols used to indicate electrical connections to ground. I know of no other electrical entity which shares so many different symbols.

Grounds fall into three broad categories in aircraft. The first and most familiar is a carry-over from other vehicle systems and it refers to the metallic portion of the chassis and skin of the vehicle. The term is common to both the power distribution (first category) and antenna (second category) systems when working with a metal vehicle. The third category is a special type of ground which is unique to the internal workings of a particular black box or piece of equipment.³³

The need for an independent section in this publication on "grounds" is brought about largely by the evolution of composite aircraft but we'll see that grounding in a metal airplane isn't necessarily "a piece of cake" either. If the frame and skin of the vehicle are not conductors, then special requirements need to be placed on the various categories of grounds. Furthermore, they may or may not be related to each other. For example, in order to provide for a power distribution ground system, a combination of conductors must be installed to provide common connection for all of the equipment which normally works with an airframe ground in a metal airplane. Antenna grounds may (and in most cases should) be separate from a power distribution ground system. Wiring diagrams which appear in later chapters will make clear distinctions as to the nature and fabrication of any required ground.

In Figure 5-1, one of the ground symbols depicted is an open triangle with the conductor to be grounded attached in the center of one side. There are characters inside the triangle that I will use to identify exactly which ground is to be used for a particular conductor.

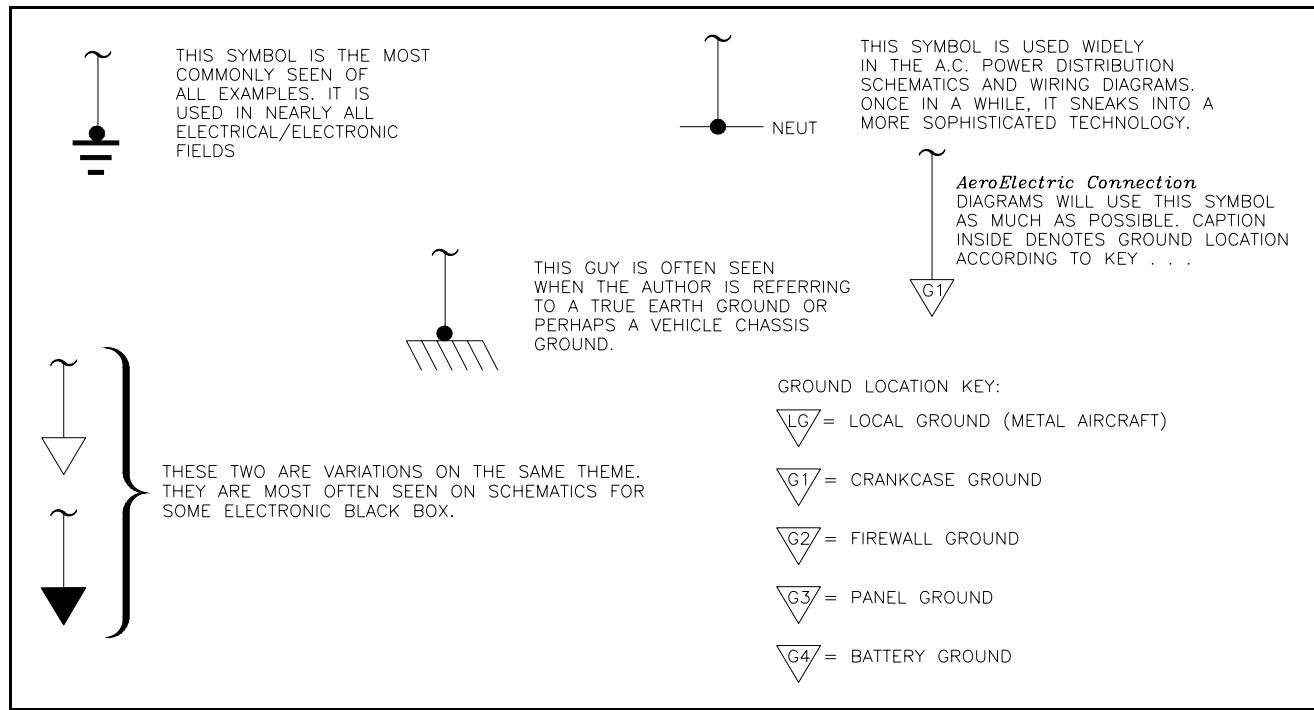


Figure 5-1. The Many Faces of a Ground System

When it's important to make the distinction, labels within the ground symbol triangle will be tied to specific grounding locations within the airplane. For example, an engine crankcase is one specific location, a ground bus behind the instrument panel will certainly be another, and the battery may have a ground bus located adjacent to it. Every power distribution diagram, set of wiring diagrams or large illustration will have a list of symbols key and describe where they are located. In our drawings used throughout the book, we're trying to standardize on ground symbols by location as follows: G1 is crankcase, G2 is firewall, G3 is instrument panel, and LG is used to denote local ground to the airframe in metal airplane. If the triangle is empty, it means (1) the diagram is a simplified discussion of wiring where a ground is needed but not defined until a specific installation is determined or (2) a ground is needed for operation but its location in the system is non-critical. In writing, the term "ground" will usually refer to a power distribution ground except when we are discussing an antenna or installation of a particular piece of equipment with special grounding requirements.

Power distribution always requires a path out and back for electrical energy but in some diagrams it is not always clear as to the need for the ground. For example, a schematic or wiring diagram may show a single wire from switch to lamp fixture. If the diagram describes a metal airplane, the "ground" path is implied: power return is made by physically mounting the fixture to surrounding metal structure. If the draftsman takes the trouble to really finish

the diagram, a ground symbol will be included right on the edge of the appliance's symbol to confirm suspicions as to how ground is to be supplied. In the case of special accessories, all of the connections required for the device to function may be carried on individual wires and the ground symbol may only connect to the enclosure of the device for radio noise shielding. Further, the amount of current which flows in the "ground" connection may not be known to you, which might further complicate the choice of how to treat the connection in a composite airplane. We cannot anticipate all of the cases here in this section and provide detailed coverage. You need to be aware of the possibilities.

WHEN IS A GOOD GROUND NOT?

Problems with poor conduction in high current paths (especially grounds) are most difficult to diagnose. Investigations into poor voltage regulation or starter performance always begin with conductors other than grounds. However, it's important to remember that for every electron that leaves the battery another electron has to return via the other terminal; the same currents that flow in the power distribution wiring also flow in ground return wiring or conductors.

Let's do an analysis on a hypothetical composite airplane where the battery is mounted about 6 feet from the engine. Let's assume the battery is a pretty good flooded (wet), lead-acid battery with an internal resistance of about 10

milliohms. Without welding it's difficult to make a joint between any two conductors that's better than 1.0 milliohms per joint. Consider 2AWG wire with a resistance of 0.156 milliohms per foot. Total length of "fat" wires in the cranking path will be about 15 feet. Therefore $15 \times 0.156 = 2.34$ milliohms resistance in the wire alone. How about the battery and starter contactors? Hmmmm . . . two contacts each in series held closed by an energized electromagnet. Can't be better than 1 milliohm per contact so there's another 4 milliohms total. Add 'em up . . .

Cranking Path Resistance - how BAD is it?

Battery resistance	10.0 milliohms
2 Contactors	4.0 milliohms
15' of 2AWG wire	2.3 milliohms
Bolted Joints (4 wire segments with 2 joints at 0.5 milliohms each)	8.0 milliohms
 Total resistance	 24.3 milliohms

24 thousandths of an ohm? ? ? ? It is difficult to imagine how so tiny a resistance can make a difference but consider that for all but the smallest engines, a starter may easily draw over 200 amps! Ohm's Law says that for every ampere of current pushed through 1 ohm of resistance, there will be 1 volt of drop across the resistor or volts = amps x ohms. 24.3 milliohms times 200 amps equal 4860 millivolts or 4.86 volts of drop. If we started with a 12.5 volt battery, we'll now see about 12.5 minus 4.86 or 7.5 volts at the starter terminals. We've lost about 1/3 of our cranking energy in the trip from battery to motor! On a cold morning, the engine is stiffer and battery resistance goes up. Just when the engine would like to have more cranking energy, the battery's ability to deliver it goes down.

Purists among you may take issue with some of the numbers I've used. To be sure, a little care in selection and assembly of parts can reduce the resistance numbers somewhat. The point is that resistance of wire, contactors and battery are built in: we have no control over them and they are never zero. Also note that bolted joints make up a significant percentage of total drop. Even minimizing wire length has a rather small effect compared to reduction in number of bolted joints. Some of the worst performing cranking circuits are found on metal airplanes where the battery is bonded locally to airframe. Engine is bonded to mount by jumpers around the vibration isolators and the mount is "grounded" to airframe through its mounting bolts.

If I had my fondest wish for ultimate performance in an aircraft electrical system, the battery, starter and alternator would all be within 1 foot of each other! Interestingly enough, Van's RV series airplanes come closer to that goal than most kitplanes. RV batteries are on firewall centerline with starter and alternator just an engine length away. Further, many single-engine Cessnas have the battery on the firewall just inches from starter and alternator on the rear of the engine.

In a grounding figure back in Appendix Z I've illustrated the most important wires in the airplane. The first wire I install is from battery minus to firewall ground stud. A braided bonding jumper goes from this bolt to the crankcase. For canard-pushers with forward batteries, an instrument panel ground bus is wired to battery minus in the nose. Ground points for stuff in the rear are provided with a second ground bus mounted on the firewall and wired to the crankcase just like a tractor airplane. This grounding architecture optimizes engine cranking performance and minimizes ground loop problems which may degrade voltage regulation, cause noises in an audio system or radio and affect the accuracy or stability of engine instruments. This mechanically simple system is the antithesis of a system installed in a Long-Eze by one of my readers: because his airplane was plastic and glass, he wanted, "plenty of places to attach wires to a good ground." A wire came forward from his crankcase and bolted to one end of a brass strip over the spar. The strip was drilled and tapped for 8-32 screws which he thought handy for making local grounds. Each end of the strip was drilled for a 5/16" bolt to which a ground wire was attached. This ground strip was repeated at the panel and AGAIN near the battery. From battery post to engine crankcase he had fabricated a bus conductor with 8 soldered and 8 bolted joints! To top it off, he used 4AWG wire as the ground conductor and steel hardware for bolting it all together. The cranking performance was abysmal!

While we're discussing ground system fabrication . . . if the battery and engine are on opposite ends of a composite airplane it's important to run battery (+) and (-) cables right next to each other as they traverse the cockpit and instrument panel areas. Tie-wrap them together every 6 inches or so. I've seen several kit manuals suggest that a couple of studs on a firewall are sufficient for termination of all system grounds. The problem with this is that all ground wires behind the panel have to come through the firewall to be stacked on the few ground studs. This is poor practice. A single stud is responsible for many grounds . . . a broken bolt or loose nut causes problems in multiple systems. The ground bus I've illustrated is a special product I designed and asked B&C Specialty Products [1] to manufacture. Forty eight, .25" wide, Fast-On-on tabs are sweat soldered to a piece of sheet brass about 1.5" wide and 6" long. A 5/16" stud is soldered to one end. There are enough ground points

to give each system all the structurally independent grounds it needs without having to share. I highly recommend its use.

There's an interesting fallout of this architecture. A few years ago we ran an airport for a short time. One of our mechanics was reinstalling an engine that had been removed for overhaul. After hooking up everything he could find that was loose, he crawled into the left seat, primed the engine and hit the starter. The propeller didn't move and a cloud of smoke poured out from behind the panel! Seems that everything got replaced EXCEPT a ground strap from crankcase to firewall. The starter tried to find a ground through shields on the p-leads along with throttle and mixture controls jackets which caused them to get very hot, very quickly! Grounding the battery directly to crankcase eliminates this possibility.

Minimizing high-current path resistances has another benefit: many airplane designs don't need a lot of battery capacity but some builders find that a larger battery (lower internal resistance) improves cranking performance. A number of single-engine Pipers have 35 ampere-hour batteries in the tail: they didn't need the extra capacity, but the lower internal resistance improved cold weather cranking operations. One of my consulting clients holds STCs for replacing the 35 ampere-hour batteries with a 25 ampere-hour, recombinant gas battery. The new battery has a 5 milliohm internal resistance and weighs 22.5 pounds. Cranking performance is greatly improved in spite of the new battery's smaller and lighter package.

METAL AIRFRAME GROUNDING

Ground connections on a metal airplane are relatively simple but some cautions should be observed. First, clean all of the paint, primer and corrosion from around the hole which is used to ground a connection. A round wire brush with a pilot in the center is called a "bonding brush." It is designed to be used in a drill motor for this type of cleaning. Grounds for heavy current flows such as for the negative lead of the battery or the grounding strap between an engine and airframe should connect to the heaviest structure available; avoid making these connections to thin sheet metal even if "heavier structure" is several feet away and you would rather not have the extra weight of the wire! Antennas may require grounding not just around mounting screws but to the total area of metal under the antenna base. Read installation instructions carefully and if you are still not sure, then check with the manufacturer directly.

COMPOSITE AIRFRAME POWER GROUND SYSTEM

In the composite airplane a builder must provide for a "common" conductor or power distribution ground which is missing because the airframe structure and skin are made of epoxy and non-conducting fibers. In a conventional tractor design the task is somewhat simpler than with the canard pusher; the major power sources, controls and loads are more concentrated in the front of the airframe. Many canard pusher designs mount the major source (alternator) along with the major power load (starter) at one end of the airframe with the battery as far away as possible on the other end with the controls and loads being scattered along in between!

FIREWALL / INSTRUMENT PANEL GROUND

Earlier I wrote about the 24 and 48-point, Fast-On tab ground bus offered by B&C and from our website catalog. These products offer a means for creation of a low noise, single point ground for all the equipment located on an instrument panel. For tractor airplanes, two such ground busses may be used back to back on the firewall to provide high quality grounding for equipment on both sides of the cowl. The technique simply calls for bolting two ground busses back to back using a single brass bolt to provide solid electrical connection between the ground busses AND a sturdy attach point for the crankcase to firewall bond strap or wire on the engine side. Battery minus lead needs to go to the same bolt on either side of the firewall depending on where the battery is located.

A word of caution when bolting the two busses back to back through a composite firewall. Don't depend on any intermediate composite material to maintain ground stud tension. In Figure 5-2 I've shown a brass bushing or stack of brass washers (Item 4) with a 5/16" i.d., a 3/4" o.d. and a length equal to the nominal thickness of the firewall. First, a 5/16" hole is drilled all the way through the firewall. Next, from the cockpit side, a 3/4" hole is spotfaced down to the surface of the firewall sheetmetal. Make temporary installation of the small ground bus (8) on the firewall using bolt (2), bushing or spacing washers (4) and one nut (6). Use ground bus (8) as a drill guide to make three #18 holes all the way through. Remove ground bus and reinstall all hardware with large ground bus (3) inside, bushing (4) in firewall, small ground bus (8) under cowl. Hold all this stuff in place with three screws (1) and nuts (5). Small hardware is for anti-rotation only; don't put a lot of torque on these fasteners-- just snug 'em up.

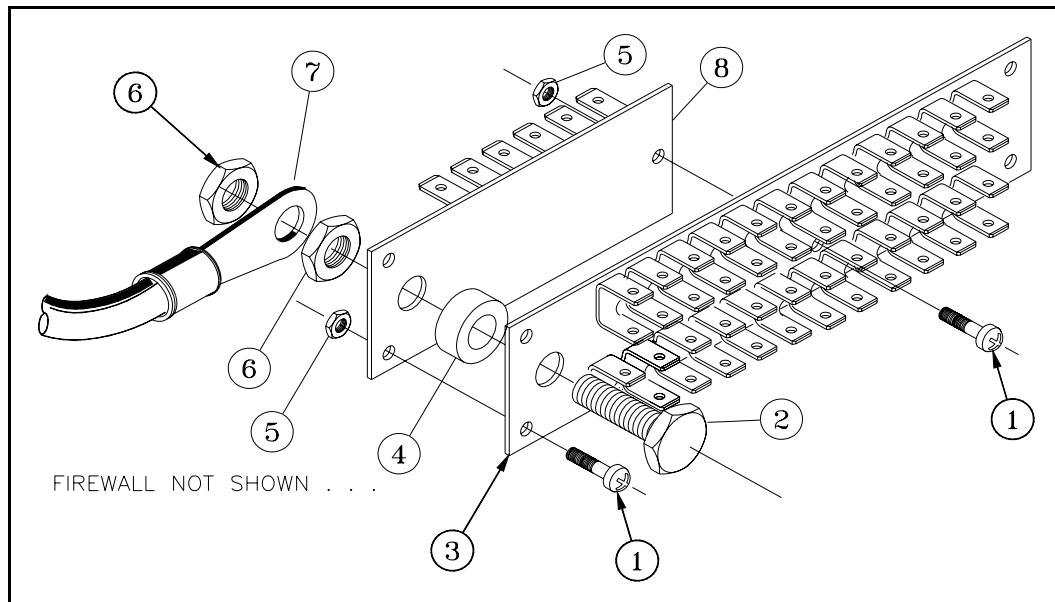


Figure 5-2. Forest of Fast-On Tabs Firewall Groundblock.

Install bolt (2) with first nut (6). Torque this feller down good. The remaining nut (6) is used to install a firewall to crankcase bond strap or wire (7).

Except for rare special grounding cases, everything in the airplane will ground to one side or the other of this system. This single-point system of grounding will provide the most trouble free, electrically quiet installation possible.

HOW GOOD IS IT?

Measuring the quality of any low resistance conductor paths would appear to be difficult. After all, not even Radio Shack sells ohmmeters that read out in fractions of milliohms . . . at least not that they would know about! A few years ago I was investigating an accident where electrical conductivity was in question: measurements in the milliohm range were called for. I visited a local Radio Shack and bought two digital multimeters. One needed to be capable of reading current on the order of 5 to 10 amperes. The other was for reading millivolts; hopefully to the nearest 0.1 millivolt. I also purchased a D-size alkaline cell, some 18 gauge lamp cord, test probes and banana plugs. The man behind the counter loaned me a soldering iron and I built the rig shown in Figure 5-3, Poor-Man's 4-Wire Milliohmmeter.

Touching the two probes together places a dead short in the D-cell . . . well, almost a dead short. Obviously, the cell has an internal impedance which limits the current that a shorted cell will deliver. The wire between cell and probes has some resistance too. As it turns out, when the two probes are touched together, multimeter M1 indicates about 6 amps.

Now, observe that the other multimeter is set up to measure the voltage between the two probes through a path that is independent of the D-cell current path. The operative feature here is that no voltage drop will occur along the voltage sense leads and multimeter M2 will read the voltage between the two probes irrespective of the voltage dropped along the D-cell current path.

Note:

You might be tempted to build this tool using a spring clip type battery holder for the D-cell . . . because of the large current that flows while taking a measurement, spring loaded holders are inadequate to the task. Solder wires right to the cell.

The leadwires in this case had to be long enough to reach from battery in tailcone to crankcase. Obviously, the measurement requires two people as well. When I pushed one probe down very firmly on the battery minus terminal bolt while probing the crankcase with the other, a current on the order of 6 amps flowed in the ground path between battery minus and crankcase. Let's assume the M1 reads 5.8 amps voltmeter reads 30.6 millivolts. Ohms law sez ohms = volts/amps so $.0306/6 = .0051$ or 5.1 milliohms. Hmmmm . . . 200 amps through this path will drop 1.2 volts . . . not great but probably typical.

Yeah . . . I know. There are some pretty nifty clamp-on type ammeters for DC current. Why not just measure starter current and the voltage drop while cranking? Several reasons. First, starter current is anything but steady. Compression strokes cause it to oscillate in a manner that prevent good readings from a digital instrument. For the same reason, voltage-drop readings jump around in sympathy with current fluctuations. Second, and most importantly, I don't like working around swinging propellers even if the plugs ARE disconnected. I was there to investigate an accident, not participate in one! A third reason was that this airplane was all wrapped up in a wad of aluminum, the prop was bent and the battery was dead. An

independently excited measurement system was indicated.

The same measurement can be applied to components of the positive power path as well. Remember, we're measuring the resistance of wire plus bolted and crimped joints. When measuring the resistance of the lead between battery contactor and the starter contactor, probe the bolt ends on each contactor. Obviously, this same test fixture can be used to check path resistance on any other circuit on the airplane and produce results with great integrity. FBOs will often have the instruments necessary to set up this fixture but not one in a hundred knows how to do it, how it is used or what the readings mean. The 4-wire ohmmeter is a standard inspection and diagnostic aid in my toolbox. Elsewhere in this work, I'll discuss techniques for using the 4-wire ohmmeter tool to track down the elusive, "jittery ammeter" syndrome.

GROUND LOOPS

A recurring problem experienced by our readers is the complaint that engine gages on a composite, canard pusher shift reading in response to changing electrical loads or when turning the alternator on and off. Another common "noise" complaint is strong alternator whine in the headsets . . . sometimes when radios and intercom are OFF! Both of these phenomenon are commonly driven by what are called ground loops.

Ground loops are pretty simple and occur only when two components of the same system (victim) are grounded in different places in the airplane. In Chapter 8, I discussed the fact that wire--no matter how big it is--can never have zero resistance. In preceding paragraphs of this chapter, I discussed the 4-wire ohmmeter as a practical means for quantifying very low resistance values and their effects on starter system performance. Starters are not the only potential victims of voltage drops around what one usually

considers to be a very low resistance, ground conductor path.

Consider that engine instrumentation measures small changes in voltage on a variety of sensors exposed to phenomenon of interest such as temperature, pressure, etc. Let us suppose that an engine-mounted, oil pressure transducer has a resistance variation of 100 to 500 ohms over the range of 0 to 100 psi on the panel-mounted indicator. Let us further suppose that the indicator system biases the sensor with 10 milliamperes of current. The voltage change across the sensor will be $(500-100) \times (0.01) = 4$ volts for 0 to 100 psi or 25 pounds per square inch per volt.

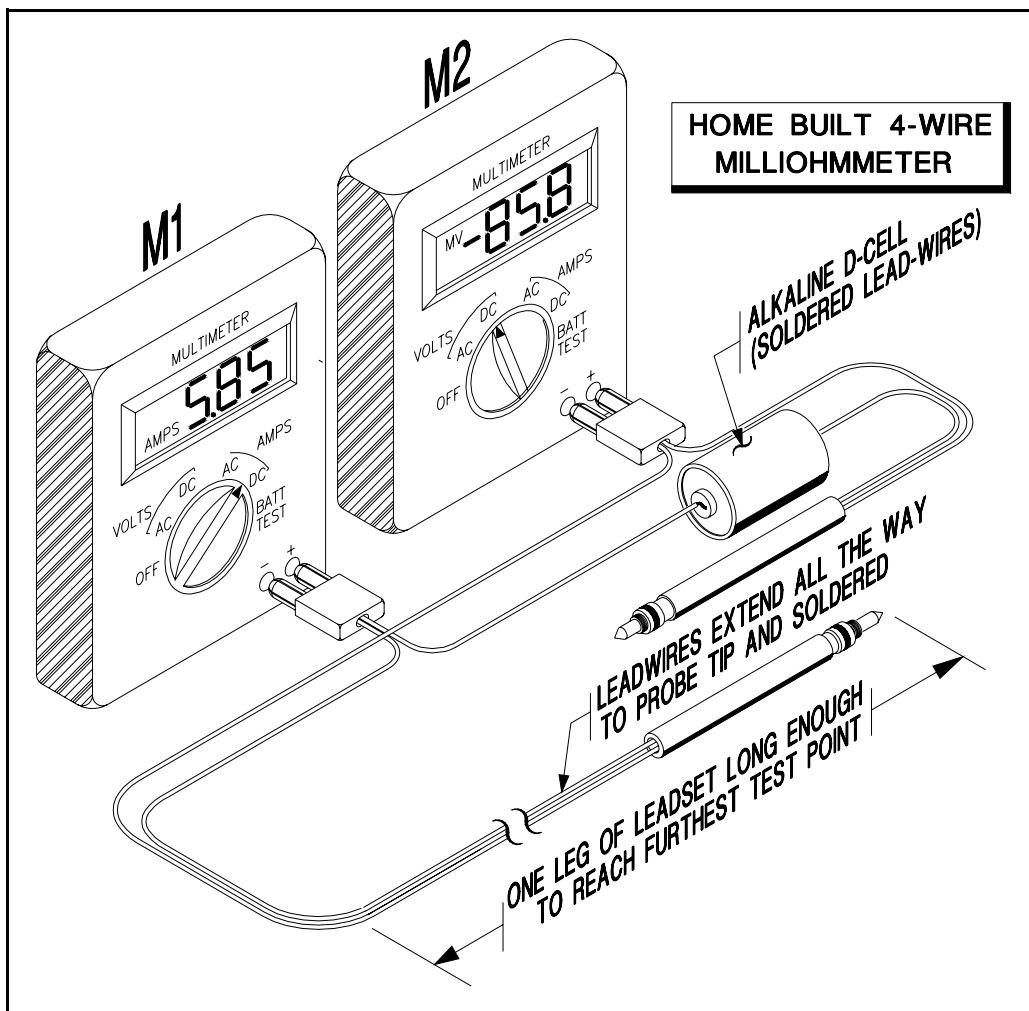


Figure 5-3. Poor Man's 4-Wire Milliohmmeter.

Consider a Vari-Ez with alternator but no starter, an oil pressure sensor grounded to crankcase and an indicator grounded to nose mounted battery, and 15 feet of 10AWG used to connect the crankcase to battery minus. Yes, 10AWG is too small for engine cranking but not too small for a 30 amp alternator. 10AWG wire has a resistance of 1.0 milliohm per foot.

If the alternator is putting out 20 amps of current to power systems and recharge the battery, the voltage drop in a #10 ground wire between crankcase and battery will be on the order of 0.2 volts. This voltage appears to the oil pressure indicator as an ADDITIONAL oil pressure of 5 psi. Turning the alternator on and off will produce a 5 psi wiggle in the oil pressure gage when in fact, oil pressure is stable.

In the case of headset grounds consider this: alternators are three-phase ac devices with full-wave, bridge-rectifiers having an unfiltered ripple equal to 5% of system voltage. On a 14 volt system, ripple voltage will be on the order of (14×0.05) equals 0.7 volts peak-to-peak. This same ripple applies to output current so if the alternator were loaded to 20 amps, (20×0.05) equals 1.0 amps, peak-to-peak. Let's assume an RV4 as the hypothetical airplane with front and rear-seat headset and microphone jacks in both seat locations. The audio signal voltages associated with both microphone and headphones are on the order of tens of millivolts. If the 1 amp of ripple we just described is flowing through airframe resistances of as little as 5 milliohms, an alternator ripple noise of up to 5 millivolts can appear between two separate places on the airframe.

Depending on where the headset brackets are riveted to structure, the 5 millivolts of ground loop noise may appear in series with a headset or microphone audio and produce audible interference in the headsets or your transmitted signal.

In metal airplanes, headset and microphone jacks should be mounted on insulating panels or insulated from metal panels by the use of fiber shoulder washers. We supply extruded fiber washers from our website catalog for the specific purpose of insulating headset and microphone jacks from local airframe ground. Microphones and headsets should take their low-side audio connections on shields or separate wires all the way back to where the interphone, audio distribution amplifier and/or radios are grounded . . . usually right behind the panel. This is one reason why I recommend the B&C forest-of-Fast-On-tabs for grounding all instrument panel mounted equipment. Single point grounds are, by definition, loop-free.

ANTENNA GROUNDING

This topic is covered in detail in Chapter 13. Suffice it to say for now that antenna grounds have nothing to do with grounds for any other systems. The manner in which an antenna seeks a "ground reference" is dependent on the antenna design, frequency of operation and whether or not the airplane is metal skin or Fiberglass.

Over Voltage Protection Systems

Before we can launch off on this subject, we need to arrive at a common language to describe system bus voltage aberrations and their causes. One of the historical causes is invoked all too often when the speaker is unwilling or unable to research the real reason for the difficulty

THE 'GLITCH' DE-MYTHED

Many times in my experiences with electronics, I have heard some presumably informed technician say to some less informed individual (usually the hapless victim), "I guess a glitch got it". He would then proceed to replace the damaged article with a new one. The victim could do nothing more than wonder who or what the 'glitch' was and try to calm his writhing checkbook! The 'glitch' may be personified as a creature of variable size and form which lurks about all manner of electrical device. I have heard it referred to by other names, "gremlin" is quite often used.

Irrespective of how one names the thing it drips with an ooze of excess electrons and breaks into fits of hysterical electrical emissions whenever it finds an a loose wire or exposed bus bar. A glitch will hit targets of opportunity which are more prolific when a mechanic has removed a cover or disconnected a wire for diagnosis of a problem. Therefore, glitches can be expected to hang around an FBO's shop at an airport. They love service stations too; there's nothing more insidious than a glitch that's high on gasoline fumes! Glitches hang around engineering labs too. I've witnessed many events wherein all of the smoke has just escaped from some integrated circuits and the tech says, "#@%&*#\$ glitch!". Onlookers nod in solemn acknowledgment. Someone may even open a window; glitches love smoke and hate fresh air.

You've all probably seen the margarine ad on television where the lady declares, "It's not nice to fool Mother Nature!". Well, she's right. It's only fair since Mother Nature will never fool with you. The laws of physics are pretty well understood in the technology we are about to discuss. There is no need to explain anything in supernatural terminology when it comes to working with aircraft electrical and avionics systems.

All things have an explanation based on the physics of the matter.

MEET THE REAL CULPRITS

Departures from normal voltage come in four classes which I will call *spikes*, *surges*, *noise* and *faults*. A *spike* is a short duration, low energy departure from normal bus voltage. By short I mean measured in tens of microseconds and the energy is so low than you would never perceive a change of intensity of a small light bulb if a *spike* were applied to it while it was illuminated. A *surge* is on the order of 1000 times longer in duration and measured in tens of milliseconds. The effect of *surge* upon the intensity of an illuminated lamp is visually discernible. *Surges* may even be of sufficient amplitude or duration to cause a failure of various components in the system. *Spikes* and *surges* are usually singular events associated with the operation of piece of equipment in the system. *Noise* is a repetitive occurrence of *spikes*, very small *surges* or a combination of the two. *Noise* may or may not be discernible by observing an illuminated lamp. It most often manifests itself in the effect it has on the operation of another device. Strange sounds in the audio system, erratic operation of an ILS indicator, and Loran-C falling out of lock are but a few ways *noise* may exert an influence. A *fault* is the least obscure of the four. It is the broken connection, the shorted transistor, the failed device which makes itself noticed in very profound ways.

Let me assure you of one fact: there is no electrical system that is totally free of the first three items in this list, unless perhaps your power supply consists only of a battery and its only load is a small radio or perhaps a light bulb. Even the space shuttle has a certain amount of *spikes*, *surges* and *noise* in its electrical system. It comes down to a matter of degree: the ability of designers to limit the disturbances at their sources balanced against the ability to design devices tolerant of some level of disturbance. I am going to deal with the first three of this family later in the chapter on dealing with system anomalies and *noise*. The reason for including so much information here is to make a clear distinction between what an overvoltage relay is ex-

pected to protect you from and to describe those things which might disturb an overvoltage relay's ability to function.

THE OVERVOLTAGE CONDITION

Can you recall ever having seen an automobile coming down the road toward you at night with headlights which seemed a little too bright? Remember the sort of blue-white color they had instead of the warm color put off by other cars? That particular vehicle was probably suffering from a failed voltage regulator. The system voltage was past 15 volts and rising. The battery working valiantly to absorb the excess energy and losing. Not long after you saw it the owner of that vehicle was getting it serviced. Failure of the voltage regulator in the automobile is a much more benign experience than a similar failure in an airplane. First, the accessories likely to be damaged by overvoltage are relatively cheap compared to a panel full of solid-state avionics. Second, the loss of components in an automobile seldom presents a life threatening situation.

OVERVOLTAGE RELAYS

The overvoltage relay has roots in the late 50's when a sophisticated avionics package required many amps of generator capability. Radios were vacuum tube devices and high power transmitters had dynamotors for generating high voltages. [A dynamotor is a 14 or 28-volt d.c. motor which shares a common field with a generator rated at 200 volts or more. Not terribly efficient but very simple, rugged and reliable.] During this time aviation electrical system designers were experiencing their first difficulties with large generators of electrical power combined with relatively small batteries. A failure of the voltage regulator could rapidly boost the system voltage to damaging magnitudes.

One of the early production fixes for this problem consisted of a carefully designed combination of relays, not unlike those found in the voltage regulators of the time (see Section 4). An example of this kind of O.V. relay is shown in Figure 6-1. The sensing relay was very carefully designed to pull in at some voltage just above normal system operating voltage. Once it was actuated an extra set of contacts called, "holding contacts", would hold the relay in an energized position until power was removed completely.

These early attempts to address the O.V. protection task were crude and troublesome by modern standards. It was not uncommon for an O.V. relay to be bypassed

in the field by frustrated mechanics and owners who experienced ten times more difficulty with the O.V. relay than they did with failed voltage regulators! But they did work most of the time when needed and saved many an aircraft radio from an untimely death.

A simplified schematic of a more modern O.V. relay is shown in Figure 6-2. An integrated circuit known as a comparator is used to sample a scaled down component of the bus voltage at the arm of a calibrating potentiometer. This sample is compared with a voltage reference device, in this case a temperature stable zener diode. Note the arm of the calibrating potentiometer connected to the (+) input of the comparator. The significance is: as long as the arm of the pot has a voltage on it that is below the voltage of the reference diode, the output of the comparator will be low. In an overvoltage situation, the voltage at the arm of the pot will rise above the reference zener's voltage and the output of the comparator will suddenly rise. The SCR (silicon controlled rectifier) will be triggered and the relay will energize, removing bus voltage from the input to the regulator. The SCR shown in this example is really intended for use in a.c. power circuits. It has a close cousin, the TRIAC, which is used in dimmers for ceiling fixtures. When used in a d.c. circuit, the SCR will latch into an ON state the first time it is triggered and remain solidly ON until power is removed from it completely. The latch-up phenomenon insures that once the offending voltage regulator and alternator are shut down, they are not allowed to come back on line when the voltage returns to safe levels as a result of having shut down the failed system.

Earlier I wrote about designing to be tolerant of certain abnormal conditions which may be present on the bus. In the case of the overvoltage relay, one would not wish to be plagued with nuisance tripping of the O.V. protection system due to intermittent and harmless *spikes, surges and noise*. This is accomplished in part by adding the capacitor C2 from the arm of the calibration pot to ground. The effect of this addition is to slow down the response of the O.V. relay so that the *spikes and low amplitude surges* from the alternator system don't cause nuisance trips.

To put the word "harmless" into perspective, there are a number of specifications published by the *Radio Technical Commission for Aeronautics* otherwise known as the RTCA. One of their specifications is called DO-160 and it deals with the certification of avionics components for aircraft. The document specifies that if a 14-volt device is air-worthy it must be able

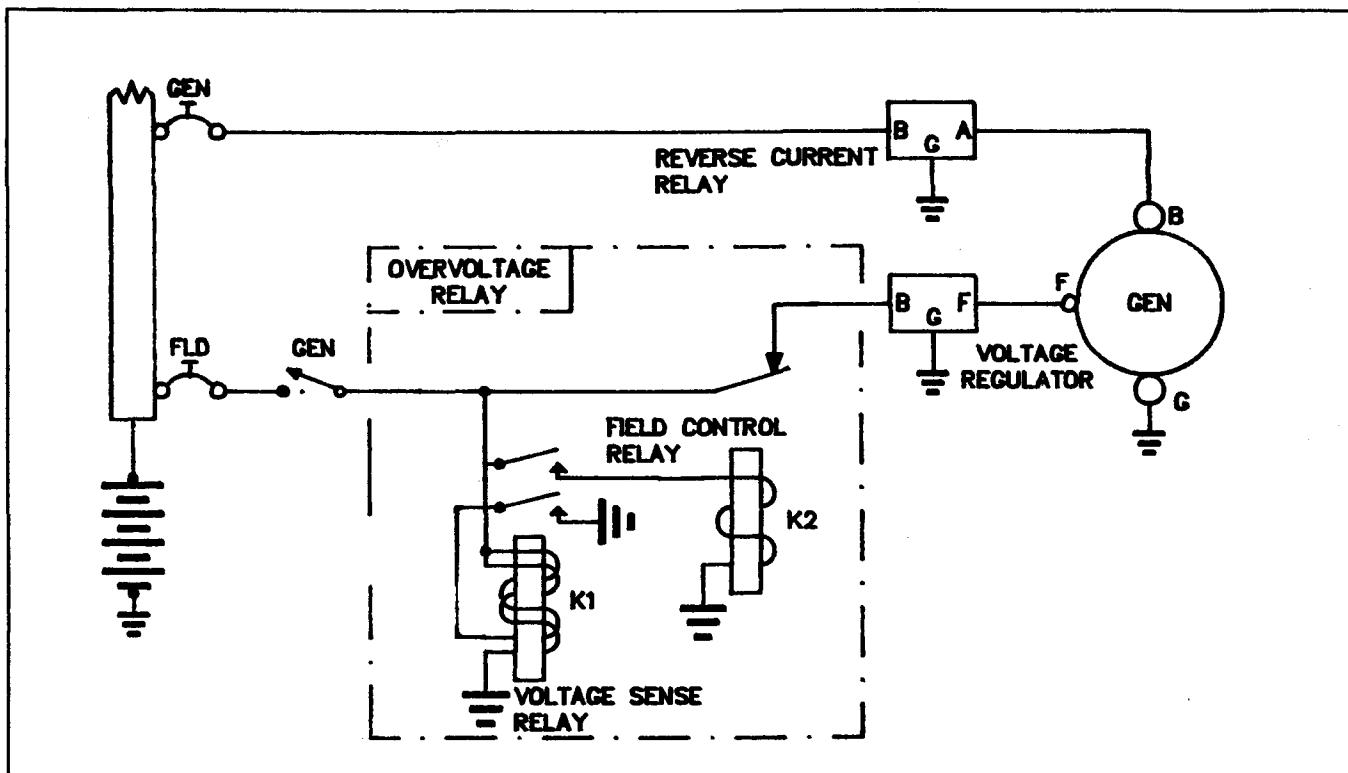


Figure 6-1. Electromechanical O.V. Relay

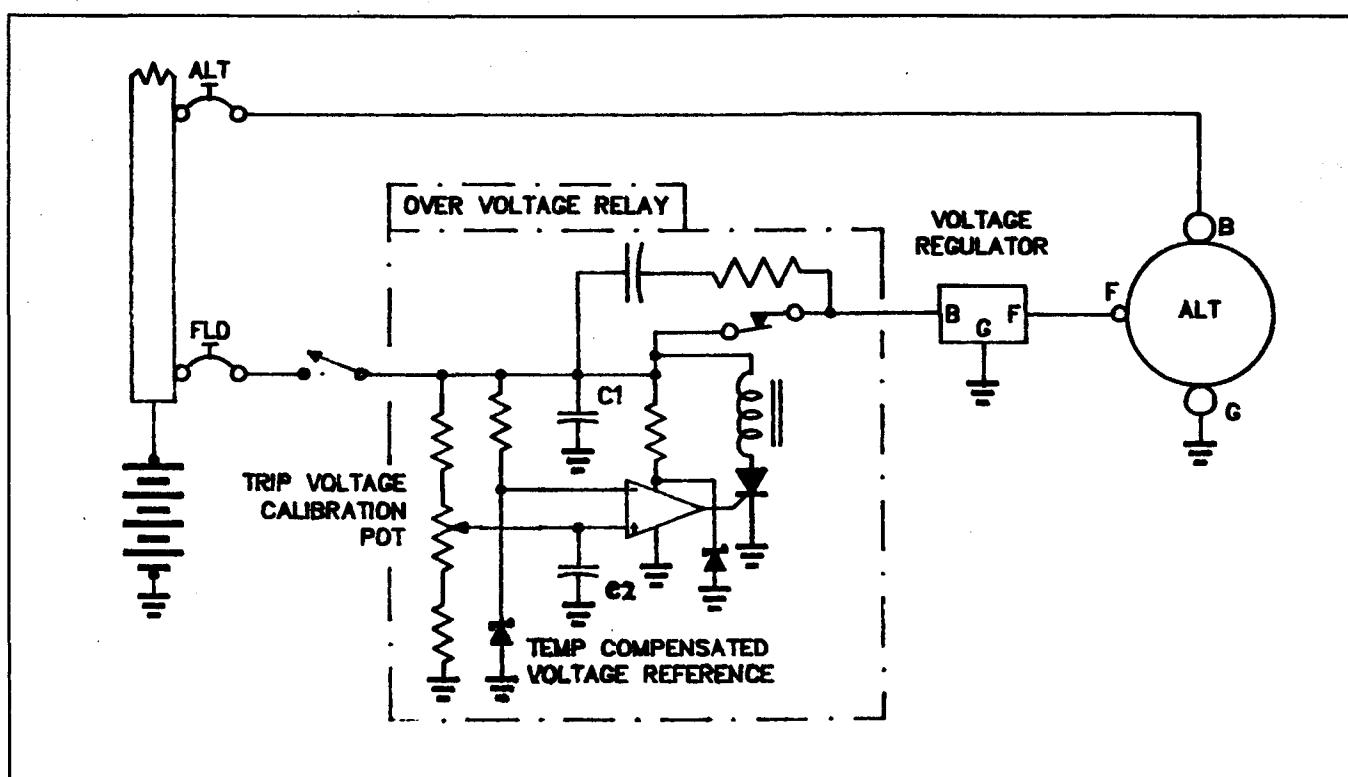


Figure 6-2. O.V. Relay with Electronic Sensing.

to withstand a *spike* of 300 volts in amplitude and 100 microseconds in duration when delivered from a source with a 50-ohm impedance. Without going into elaborate detail, passing this test is a breeze. The *spike* contains very little energy and it is easily negated by the capacitor C1 in the sample circuit shown.

Another paragraph in the spec says a device must be able to withstand *surges* of 40 volts for 100 milliseconds and 20 volts for 1 second periods of time. The spec allows the device to operate in an abnormal manner during the transient, however, the device being tested cannot be damaged by it and must return to normal operation afterward. To comply with this requirement, I simply select components which are rated to operate at 40 volts or more if they are to be connected directly to the airframe electrical system. Example: a 16-volt rating might be sufficient for C1 in normal operating conditions but a 40-volt *surge* would be likely to kill it.

The values 20 and 40 volts, and the times associated with them were selected by the RTCA as being worst case situations. For example, when a voltage regulator fails, a large alternator will begin pushing up the bus voltage in spite of best efforts of the battery to absorb the excess energy. Experience and analysis have shown that the voltage is not likely to rise above 20 volts in less than one second, even with a tired battery, thus giving the O.V. relay time to react and shut down the *faulted* system. Further, if the *fault* occurred with very little or no load on the alternator and with the battery off line, the voltage could be expected to rise more quickly and to a higher value, say 40 volts in 100 milliseconds or less. In the case of O.V. relays, one of the requirements for certification is to be able to sense and contain such a *fault* in 100 milliseconds or less and before the bus rises to more than 40 volts. Here we see the interplay between design to withstand and design to limit. All components certified for flight must be able to withstand this test and the power generation system be designed to insure that these test limits are never exceeded in practice.

For 28-volt airplanes, the test voltages are doubled: a 600-volt *spike* for 100 microseconds, an 80-volt *surge* for 100 milliseconds and a 40-volt *surge* for one second. It is a simple test to make for the products I have certified in the past. First, I make sure an appropriately rated *spike* suppression capacitor is also rated to withstand the *surge*. Then I turn the power supply up to 80 volts for a good count of "two". If my box still works, I'm ready to sell it to the customer.

There is another factor in O.V. relay design that is often addressed badly by some manufacturers. The field of an alternator is an inductive device and capable of storing considerable electrical energy. In order to explain how this happens I will tap your knowledge of another inductive energy storage system, the automotive ignition designed by C. F. Kettering. Bet you never heard of him. Fascinating fellow. His many accomplishments include electrification of the cash register, and designing practical starters and ignition systems for cars. He was also the first individual in the U.S. to have a house cooled by a refrigeration system of his design (Bet you thought Carrier was first!). When its too cold and wet to fly next winter, look Kettering up in the library. His accomplishments have more influence on your daily life than do those of Thomas Edison, however very few people have heard of him.

Figure 6-3 shows the basic components of the Kettering automobile ignition system. Battery voltage is supplied to the primary winding of the ignition "coil" via the closed contacts of what are commonly referred to as the "points". The current flowing in the primary wires sets up a strong magnetic field within the core of the winding. When the points open a curious thing happens. The current in the winding goes to zero and the magnetic field in the core rapidly collapses. The rapid rate of change of the magnetic field induces an electron flow in the many turns of the secondary winding of the coil. This impresses a voltage in the secondary winding on the order of tens of thousands of volts; enough voltage to cause a spark and accomplish ignition of the fuel mixture at the plug.

Figure 6-3 also includes the "condenser" which is an archaic term for a capacitor. Recall that without the condenser, the car runs poorly and the points get burned. The reason for the capacitor has to do with the speed with which the points spread apart upon opening. Remember, the points are opened by a cam which rotates at 1/2 engine RPM and there is a finite limit to cam lift as well as shaft RPM. Air is a pretty good insulator, it will stand off as much as 1000 volts per 1/1000 inch gap. As the camshaft is coming around and the points first open, how big is the air gap between them? The difference between "zero" and "first gap" can be quite small; a very few volts will bridge a gap of micro-inches. As the points begin to open, if there is no capacitor, the current through the secondary of the coil goes immediately to zero. The collapse of the magnetic field has the ability to induce many thousands of volts in the secondary but it can induce several hundreds of volts in the primary as well. This voltage can

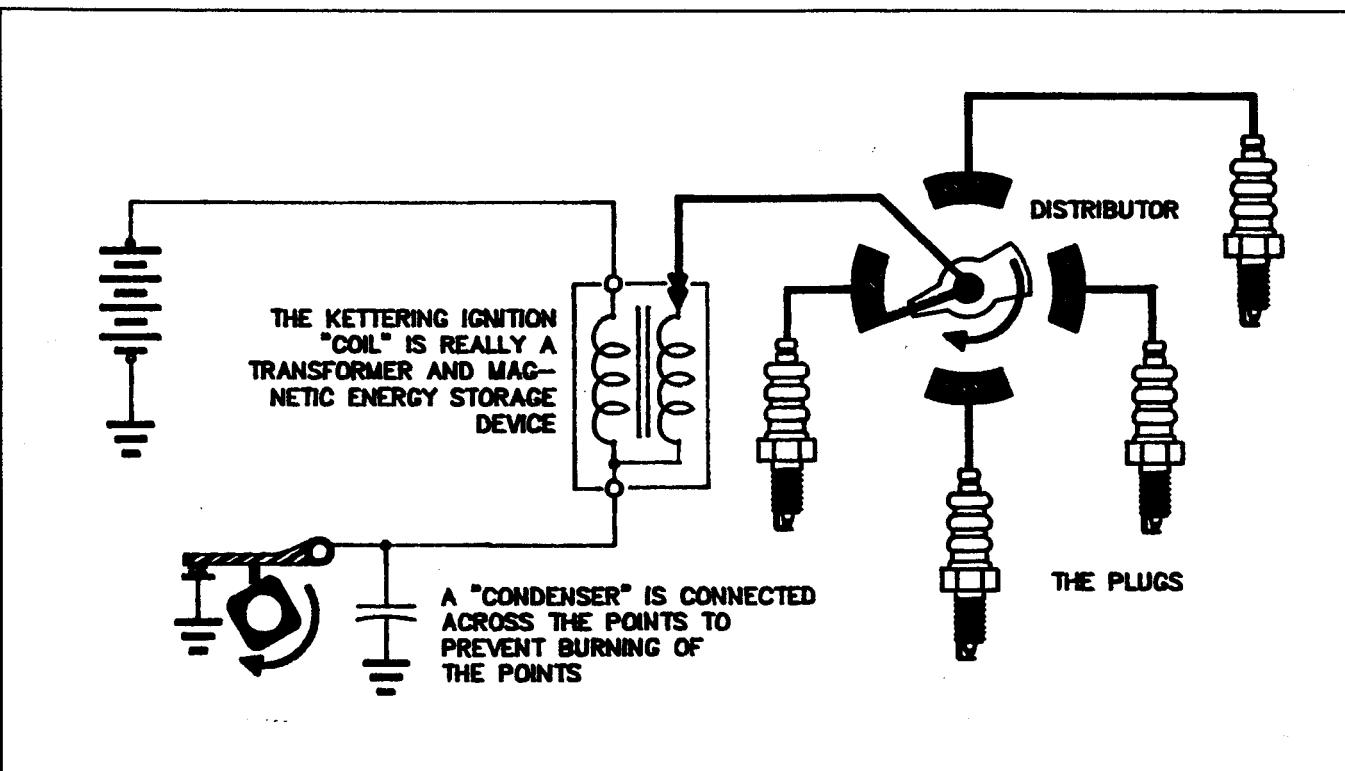


Figure 6-3. Simplified Schematic of Kettering Ignition System.

cause an arc to form across the partially opened points. Once the arc is established between the points, it would continue to grow in length as the points opened further. Energy that would normally be available to cause a spark at the tip of the spark plug is now being lost in heating up the points! Hence poor spark and burned points.

By placing a capacitor across the points, the voltage rate-of-rise (dv/dt for those of you who remember first semester calculus) may be slightly retarded by not allowing the current in the coil to drop immediately. If the capacitor is made too large, the rate of field collapse in the coil will be retarded too much and spark performance will suffer. If the capacitor is too small, it will not prevent an arc from being established between the points as they first open. The electrical size of the capacitor must be adjusted for the best compromise between arc suppression and spark performance. We'll discuss this example in more detail in the chapter on switches and relays.

Going back to the overvoltage relay in Figure 6-2, note the series connected resistor and capacitor connected across the contacts of the relay. The capacitor accom-

plishes the same job for the relay contacts as the "condenser" did for the points in my '41 Pontiac. When the O.V. relay is tripped, and just as the contacts are opening to break the field circuit, the current in the alternator field must be prevented from collapsing so rapidly that an arc is established and maintained across the open contacts of the relay. If the relay selected was marginal in contact spreading velocity (fancy term for how fast they open), the size of the capacitor and resistor could be critical to the survival of the relay contacts. O.V. relays which actually contain relays should not be used with very large alternators (50 amps or more) unless one knows specifically that the relay and associated arc suppression network are adequate to the task. I have reduced many a relay contact to molten, dead-shorts in the process of determining the proper components for an arc suppression network. For smaller alternators and, if you always have a battery which hasn't been overworked, just about any O.V. relay from a certified airframe can be used by the homebuilder.

Now, let us suppose our voltage regulator has just shorted and full bus voltage on the order of 14 volts has been applied to the field. Inductors resist changes in

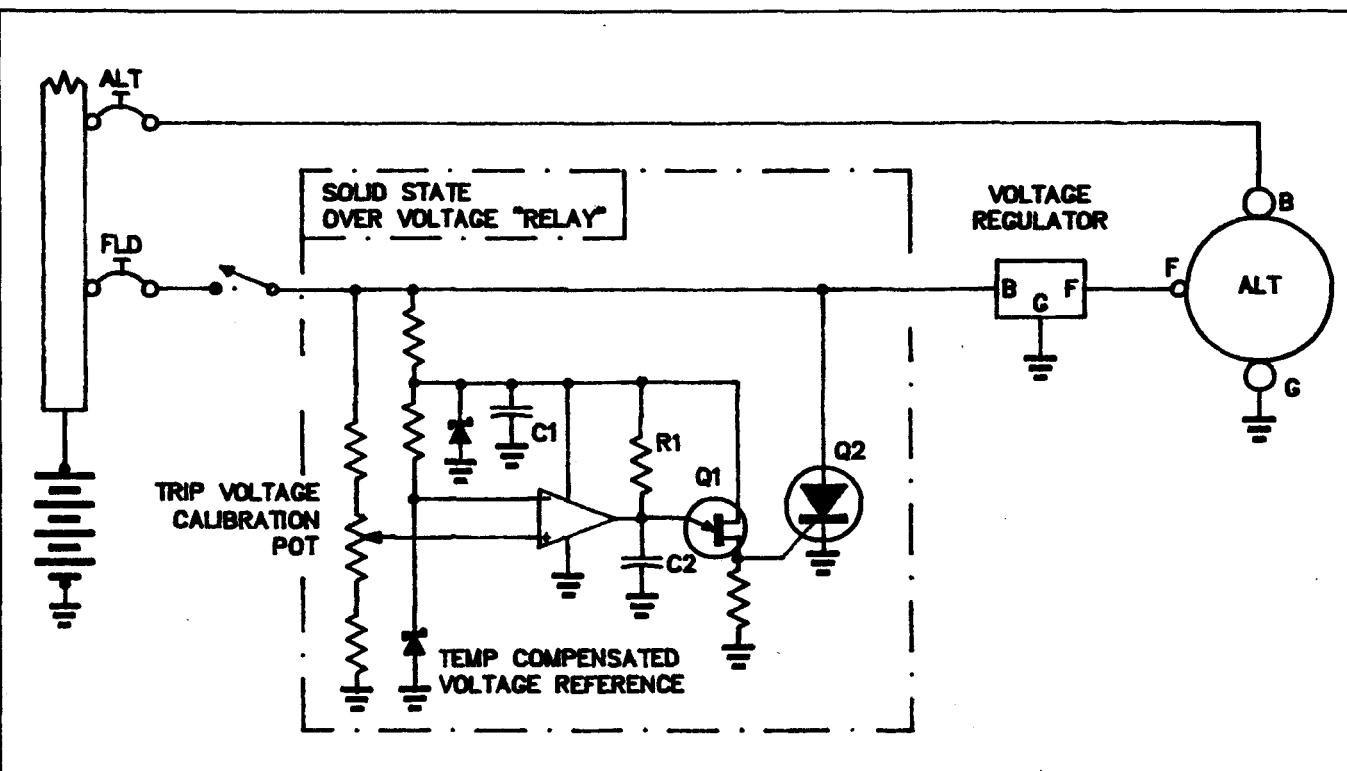


Figure 6-4. The Ultimate Protection, the "Relayless" O.V. Relay.

the current which flow through them. This is true of any inductor whether it is the primary of a spark coil or the field winding of an alternator. The increasing magnetic field in the core of the alternator field causes a counter-electromotive force (or opposing voltage) to be induced in the winding. This is why the "dwell" time on a set of points in the ignition was so important. The points must be closed for a minimum amount of time per spark cycle to allow the coil's magnetic field to build to some minimum level required for adequate spark. This same delay in the build of magnetic field in the alternator prevents an instantaneous rise in alternator output. It rises very quickly but the slope is measured in numbers on the order of 0.2 to 1 volt per millisecond.

The field is connected directly to the output of the alternator via the failed regulator so the process is regenerative. "Regenerative" means the system feeds itself to the physical limits and possibly failure of some component. As the bus voltage climbs, the field voltage climbs causing the bus voltage to climb some more, etc. Were it not for the battery's ability to absorb large amounts of energy for a short period of time, an

unchecked alternator failure could push a 14 volt bus up to 100 volts or more in a few hundred milliseconds.

The task of the O.V. relay is to sense an impending system disaster and bring the alternator under control before something smokes. The trick is to be able to discern the 'normal' *spikes*, *surges*, and *noise* from the *fault*. Then, once a *fault* has been identified, the system needs to be shut down in an orderly fashion with nothing more spectacular than a little flicker of the panel lights. Tens of thousands of O.V. relays have been marketed (a goodly portion of them my designs) which are similar in operational philosophy to the example in Figure 6-2. These were certified designs which currently fly on many a heavy, aluminum bird. Over the 15 or so years that I've been involved in these programs I have evolved three criteria for designing O.V. relays: First, consider any voltage over 16 (32 in a 28 volt airplane) as an indication of impending *fault*. Second, if the voltage stays above this level for more than 5 milliseconds, consider it to be a *fault* which proceeds a voltage runaway. Third, shut down the alternator in the most expeditious manner and, if possible, without breaking an inductive load.

It sounds like a tall order but it is quite simple. For those of you who are interested in the electronic details, Figure 6-4 shows the implementation of this philosophy as it was designed for Voyager. Note the arm of the calibration pot does not have a capacitor to ground like the design shown in Figure 6-2. This allows the comparator to "see" an accurate representation of the bus voltage with no smoothing of the *spikes, surges and noise*. The output stage of the comparator is an open collector transistor which is maintained in a turned on condition as long as the bus voltage is below 16 (or 32) volts. When the voltage does exceed the calibration value, the comparator's output transistor turns off and the collector pull-up resistor (R1) is allowed to charge C2 until it reaches the trigger voltage of the unijunction transistor, Q1. The time interval required for R1 to charge C2 to the trigger voltage is independent of the magnitude of the system bus voltage. The size of the resistor and capacitor are chosen to achieve the aforementioned 5 millisecond 'wait and see' interval.

If the bus voltage drops below 16 volts, at any time before the 5 mS timer times out, C2 is discharged thus resetting the timer to zero. If the timer does make it to timeout, the unijunction fires and the charge on C2 is dumped to the gate of the SCR (silicon controlled rectifier), Q2. Once this guy is triggered, a dead short is placed from the field circuit breaker lead directly to ground. The voltage across the field of the alternator is forced immediately to zero by way of the failed regulator and the impending disaster never grows to fruition. All that remains to happen is the opening of the field circuit breaker in response to what it perceives as a wire shorted to ground.

This type of shutdown technique is commonly referred to as a "crowbar overvoltage protection circuit". The "crowbar" technique complies with Nuckolls' third law of O.V. protection. In placing the short from the field supply to ground, the energy stored in the inductive component of the alternator field is harmlessly dissipated in the resistance of the field wire instead of in the air gap of some poor relay contact. The inductive circuit is never 'broken' but rather tied to ground through the fired SCR. The field circuit breaker does 'break' a current flow. However, it is not an inductive field circuit but rather a simple short to ground; just exactly the kind of situation the breaker was designed to take care of!

I have a story to tell about crowbar overvoltage protection systems. While in the employ of a Wichita based

aircraft components manufacturer, I had been trying for a number of years to get the heavy aluminum bird people to consider the crowbar O.V. protection technique. The usual response to my suggestion was, "What we have now works. It's certified. No customers are complaining. Why change?" It's a damn powerful argument in the certified airplane business and it tends to bury the future in antiquity! One day about eight years ago I received a call from a man in a test lab who was trying one of our production linear regulators with a built in O.V. relay in the mockup of a new system being developed for a single engine turbo-prop. On turbines, the alternator spins at 9,000 to 11,000 RPM in cruise. It seems no production O.V. relay available to this individual could handle this fire-breathing, 70-amp beast in an over-voltage condition. They had a certification requirement that the O.V. relay must catch 50 simulated failures in a row with a bus voltage excursion no higher than 40 volts! All products tried, including ours, had failed after a few O.V. trips. Furthermore, on the few times when successful shut downs were achieved, the bus voltage excursions were something to behold; the panel light bulbs in the mock-up were being replaced regularly in the course of his explorations.

Did I have a deal for him! I modified one of our production units to include a crowbar O.V. system not unlike the one shown in Figure 6-4. I was out to his lab in less than two hours. He connected my prototype into his test setup and prepared to run the first test at reduced RPM, battery on line, and with some electrical loads turned on. I told him, "Nope, crank it up all the way, turn off the battery and kill the loads." He was skeptical but he did as I asked. When he punched the *fault* button, nothing happened! The mockup panel lights barely flickered and he thought his *fault* simulator had failed. I pointed to the now popped field circuit breaker and to the chart recorder which indicated a rise to 32 volts had occurred, just before the system was shut down. I told him to try it 49 more times if he wished, even a hundred, and let me know how it worked out. I needed to get back to my office. I knew the first thing to fail was going to be his field circuit breaker and it was rated for thousands of operations!

He called me later in the day. He said we were a shoo-in for the alternator control system on the new airplane; he'd never seen anything like it. I told him I'd been trying to sell the system into the airplanes across the field from him for years but the status quo was king. He allowed as how their latest-and-greatest would carry our system and perhaps it would trickle

down into the rest of the product line later.

A few weeks later, they canceled the program; no market for the latest-and-greatest. When we had the opportunity to do the alternator control unit for Voyager, one design decision for the system was already made, tried and proven! To this date, I know of no production lightplane flying such an O.V. protection system. However, B & C Specialty Products has produced a couple of hundred LR-1's and LR-2's. You guys know a good thing when you see one! In the construction articles we plan to do a design and provide a source for the etched circuit board for the con

struction of a crow-bar over voltage protection system suitable for homebuilt aircraft.

FAIR GLITCH, WHERE HAST THOU GONE?

The emphasis of certain words in this section was done as an aid to understanding; to plant the seeds of some concepts which will be addressed in more detail in later sections. Notice our whimsical friend "Glitch" received little than a dishonorable mention. By the time we've published on the full range of topics in aircraft electrical and avionics systems, you should have a better handle on bus voltage anomalies than most of the licensed mechanics and technicians I have known

Electrical Systems Instrumentation

MEASUREMENT SYSTEMS

Making accurate measurements of any kind was a real problem during early years of industrial and economic growth. In Philadelphia, during the time of Ben Franklin, one could purchase "a pound" of coffee from multiple merchants only to discover that each purchase was visibly different from the others in terms of quantity. Greedy merchant's scales were balanced with light weights while competitive merchant's weights might be heavier. Sale bills of the time would cite both price and "good" or "fair" measure. The problem was complex. There were sociological issues which could only be addressed by legislation and enforcement of laws.

Before one could craft laws bringing weights and measures into agreement throughout a nation, one needs standards. International trade added further complications: if you were offering to trade "1000 tonnes" of Georgia cotton for "10,000 barrels" of Scotch whiskey, it was essential that both parties agreed on the sizes of "tonnes" and "barrels." The U.S. congress, being comprised of many businessmen, appreciated a need for standards. Early efforts toward national and international agreement on sizes and weights has evolved our present day National Bureau of Standards. Other countries have equivalent offices. The international repository for world standards is in Paris, France. The evolution of physical standards and international agreements built on those standards is a fascinating story; look it up in a library sometime.

We've been doing calculations using volts, amps and ohms, and simply assumed that a means of measurement for these quantities existed. In this chapter we'll lay some groundwork for electrically operated instruments. Building standards and measurement systems for hogsheads, furlongs and stones was relatively easy compared to amps, volts and ohms. The former are things you can touch and see while the latter are observable only in the effects they have on their surroundings.

Aside from gyro and barometric devices, most instruments on aircraft panels may be electrically operated irrespective of parameters they display. These may include but are not limited to ammeters, voltmeters, fuel level gages, pressure gages of all types, temperature gages, position readouts, tachometers, etcetera, etcetera,

etcetera. This chapter seems to be the best place to introduce basic electrical measurement and display devices known as "meters." We'll apply meters to their most fundamental task: measurement of small currents. In later chapters we'll discuss how to adapt small current meters to measure and display lots of other things.

EFFECTS OF CURRENT FLOW

I've previously described current as a flow of electrons and a means for quantifying the flow in units called amps which are proportional to electrons per second. Measurement of electron flow rate and displaying an answer requires a means for detecting flow, scaling a quantity and displaying a result. We'll talk about detection first.

We've already discussed a fact that electron flow manifests itself in a very common phenomenon: temperature rise. When selecting wire size, temperature rise is undesired but we cannot afford the luxury of making it zero. Discussion in a later chapter on wire will describe a concept of "reasonable compromise." For lamps, a hot filament is very desirable so we design with filament materials and enclosures to maximize the heat and light consistent with useful life; another reasonable compromise. Temperature rise is directly proportional to watts of power dissipated which is also directly proportional to current. Over one hundred years ago, some clever fellows figured out how to exploit this phenomenon for the purpose of measuring current.

Figure 7-1 shows schematic representations of a "hot wire" ammeter. A pointer and pulley arrangement are driven by a cable stretched between midpoint of a fine wire and a spring which holds the cable tight. When current flows through the wire, it warms up causing it to expand. Increased length causes the midpoint of the wire to translate upward thus relieving some spring tension. Cable motion over pulley causes the pointer to move upscale. Pointer motion is directly proportional to hot wire expansion which is directly proportional to temperature rise which is directly proportional to current. With a properly scaled mechanism, we may calibrate a scale plate to read directly in amps of current flow through the hot wire.

Variations on this theme were developed over the years but very few found their way onto instrument panels of

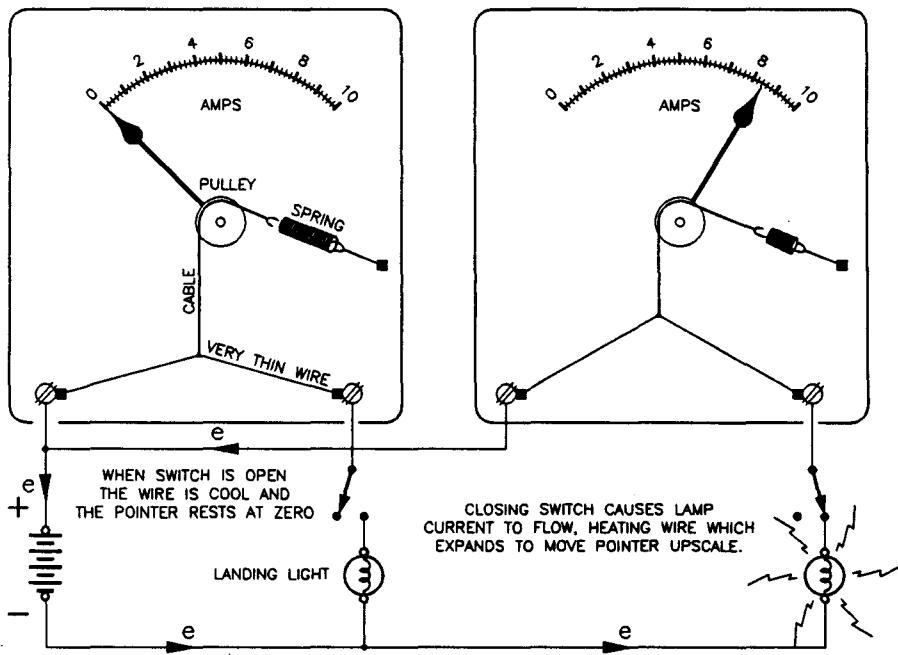


Figure 7-1. "Hot Wire" Ammeters.

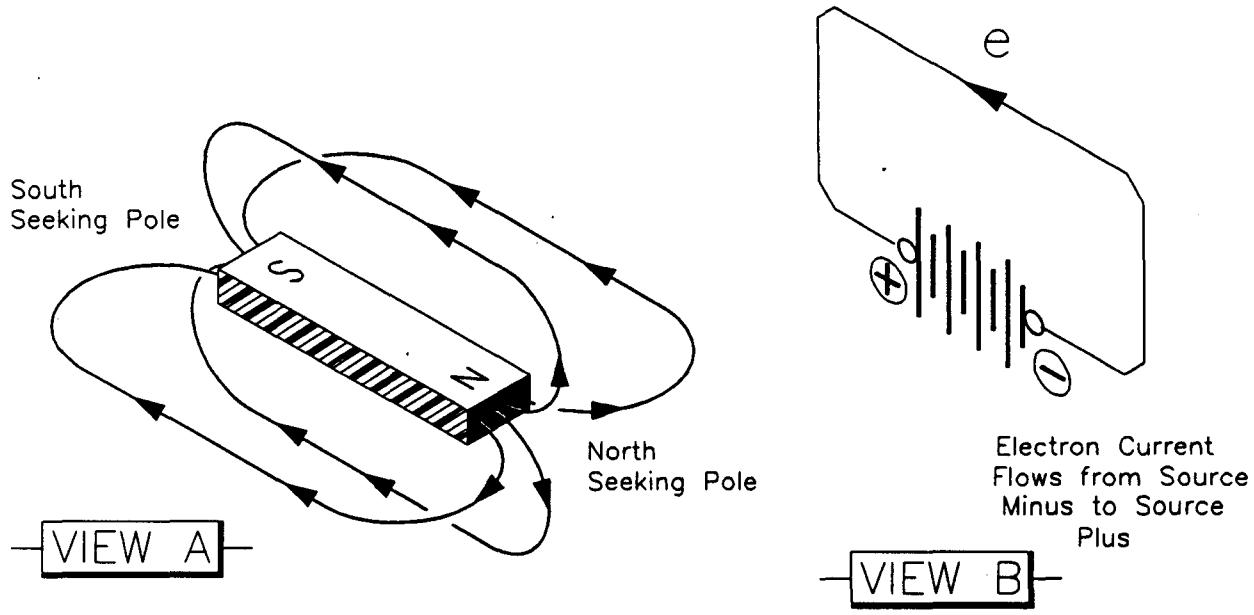


Figure 7-2. Magnetic Lines and Electron Current Flow

any vehicle. I would call your attention to the fact that this metering scheme, because it uses a heating effect, is not sensitive to **polarity** of the current flowing through it. For example, you cannot use a hot wire device as a battery ammeter. It would always read up-scale whether the battery is being discharged or charged! Its lack of sensitivity to polarity makes it equally applicable to a.c. and d.c. circuits.

There is yet another manifestation of electron flow: a magnetic field. Basic groundwork laid here will be utilized in later chapters on relays and motors. Indeed small coils of wire, suspended in a magnetic field inside a meter case, become torque motors to drive pointers up or down-scale depending on magnitude and direction of current flow. Before we can discuss magnetic fields and current flow, we need some language tools to describe them. By defining and using common tools, we may all predict physical behavior and arrive at the same conclusions.

MAGNETIC DEFINITIONS

We all know that a magnetic compass is simply a small magnet free to move on a pivot. One end or pole of the magnet, usually painted or fitted with an arrowhead points to planet earth's magnetic north pole. Indeed, any bar magnet, suspended on a string or pivot will align itself to earth's magnetic field. Let us agree that poles which point north will be marked "N" for "north seeking"; the other will be "S" for "south seeking." Further, let us agree that lines of magnetic force (or flux) move or have polarity arrows which point from north to south *outside* a magnet. This convention is illustrated in figure 7-2.

GOING WITH THE FLOW

For years there was fierce disagreement amongst scientists and practitioners as to the nature and direction of "current" flow. One theory espoused electron current flow and another talked about "hole" flow. A conductor atom, temporarily missing an electron, was said to have a "hole". Therefore, as electrons migrated from one atom to the next along a wire, "holes" were envisioned to be moving in the opposite direction. Electronics and electrical engineering books written before about 1940 have to be read with caution when "current" is discussed. Make sure you know which convention is being used.

"Hole" current began to fall into disfavor about 1900

when vacuum tubes were developed. Electrons were known to move in a perfect insulating space: a vacuum. Therefore, current had to be expressed in terms of electron flow only, no "holes" could exist. In the 1940's, the "hole" staged a comeback! Semiconductor materials, from which transistors are made, come in "P" and "N" types wherein "holes" and "electrons" are majority current carriers respectively.

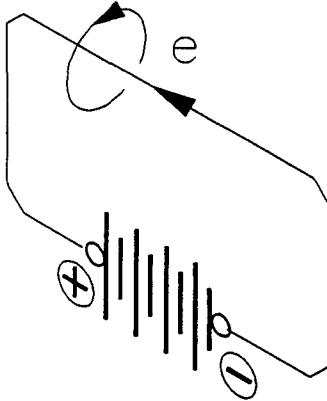
"Current" is commonly thought to move from a battery (or alternator) out through a power distribution system and return through the ground system. Actually, electrons flow out through the ground system and return via the power distribution system! In this work, the word current is used to describe electron flow. So, let us agree that electrons moving through conductors originate at the negative (-) terminal of an energy source and re-enter that source through its positive (+) terminal. I have marked the conductors in figure 7-2 to indicate electron current flow. In this and future figures, a small letter "e" and arrowhead should be interpreted as indicated electron current flow.

THE LEFT HAND RULES . . .

Electron motion in a conductor creates a magnetic field around the conductor, perpendicular to the line of electron flow. Stronger current flows create proportionally stronger magnetic fields. This field can be friend or foe as we will study in later chapters. For now we'll discuss a friendly aspect of electro-magnetism: conversion of electrical energy into mechanical energy.

In figure 7-3, there are two views of conductors carrying a flow of electrons. In view A, a single conductor is shown with a current direction arrow. If you grasp that conductor with your left hand such that the thumb points in direction of electron flow, note that your fingers wrap around the conductor in direction of magnetic flux lines. In view B, a cylindrical coil of wire is similarly marked with current direction arrows. Grasp the cylinder with your left hand, fingers wrapped in direction of electron flow. Note that your thumb points in direction of lines of flux from within the coil; at the north seeking pole.

Some of you may have studied some generator and motor rules in a physics course. Many "rules" have been devised to describe electromagnetic flow, field and force phenomena using extended fingers of both right and left-hand. Due to mixed definitions of current and flux combined with variable assignment of fingers to



Electron Current
Flows from Source
Minus to Source
Plus

VIEW A

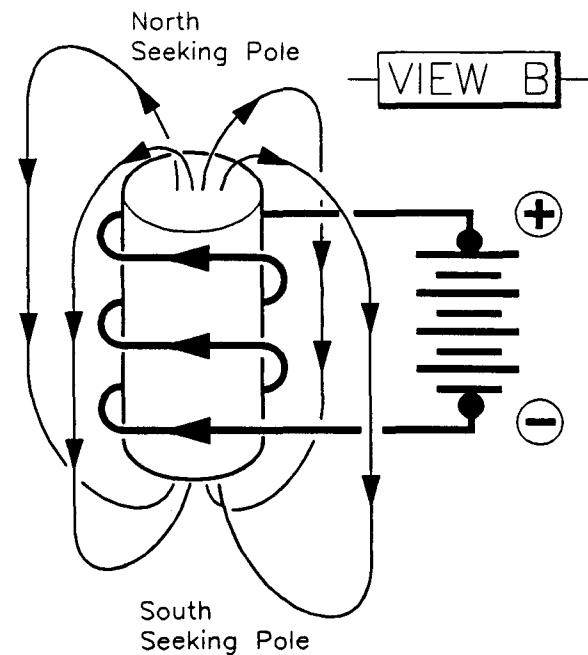


Figure 7-3. The Left Hand Rule for Magnetic Fields.

flux, flow and force, I avoid these so called right and left-hand motor and generator rules for teaching. Remember the left-hand rule as I have described above and you can unravel any flow, flux and force problem as I will demonstrate.

RECIPE FOR SPIN: ONE CUP OF FLOW AND TWO FLUXES STIRRED WELL YIELDS FORCE.

Figure 7-4(a) shows a single pass of wire suspended between north and south poles of a magnet. If you grab the illustrated conductor with your left hand, thumb pointing in direction of electron flow the fingers would wrap over the top away from the south pole and toward the north pole. In 7-4(b) I show a cross section of view A; electrons are flowing into the page.

Note

In this and other figures, an "x" on the end of a conductor denotes the tail feathers of a receding electron flow arrow; a dot in the center would represent an

arrowhead point for an approaching flow arrow.

Flux around the conductor due to flow opposes flux between the poles above the conductor. Flux due to flow reinforces lines between the magnet poles below the conductor. This combination causes a force to exist, at right angles to both flow and flux, which causes the conductor to be pushed downward, away from opposing fields and toward reinforcing fields. This figure illustrates a basic motor rule: when direction of lines and current flow are known, a direction of resulting force may be resolved. Further, the magnitude of force present is directly proportional to current flow multiplied by magnetic field strength.

Figure 7-4(c) shows a single loop or turn of wire suspended between opposite magnetic poles. This single turn conductor could be wire in a meter movement or a turn of wire in a motor armature; it makes no difference. If we apply the left hand rule to this conductor, current induced flux adjacent to the north pole are opposing underneath and current induced flux under the south pole

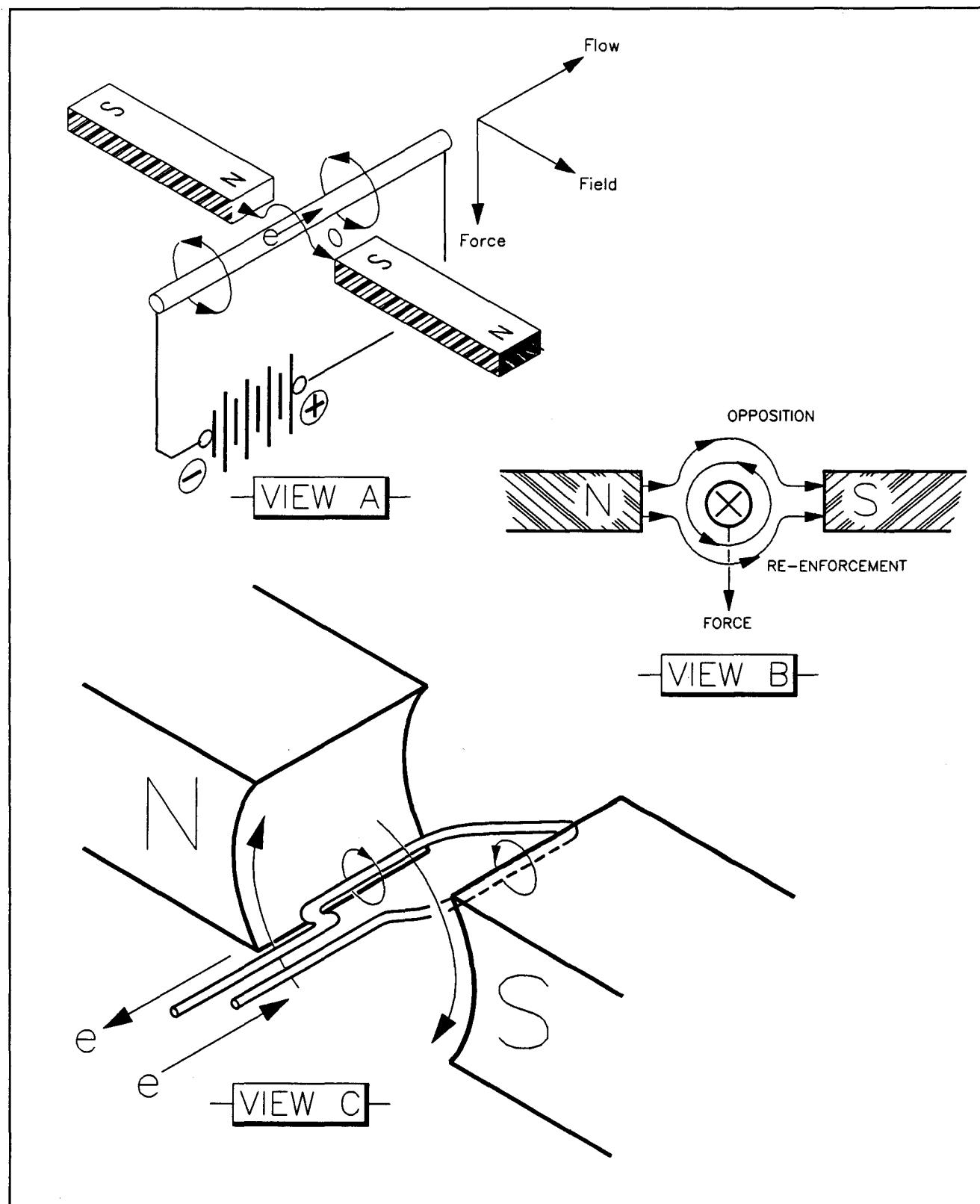


Figure 7-4. The Three F's: Flow, Flux and Force

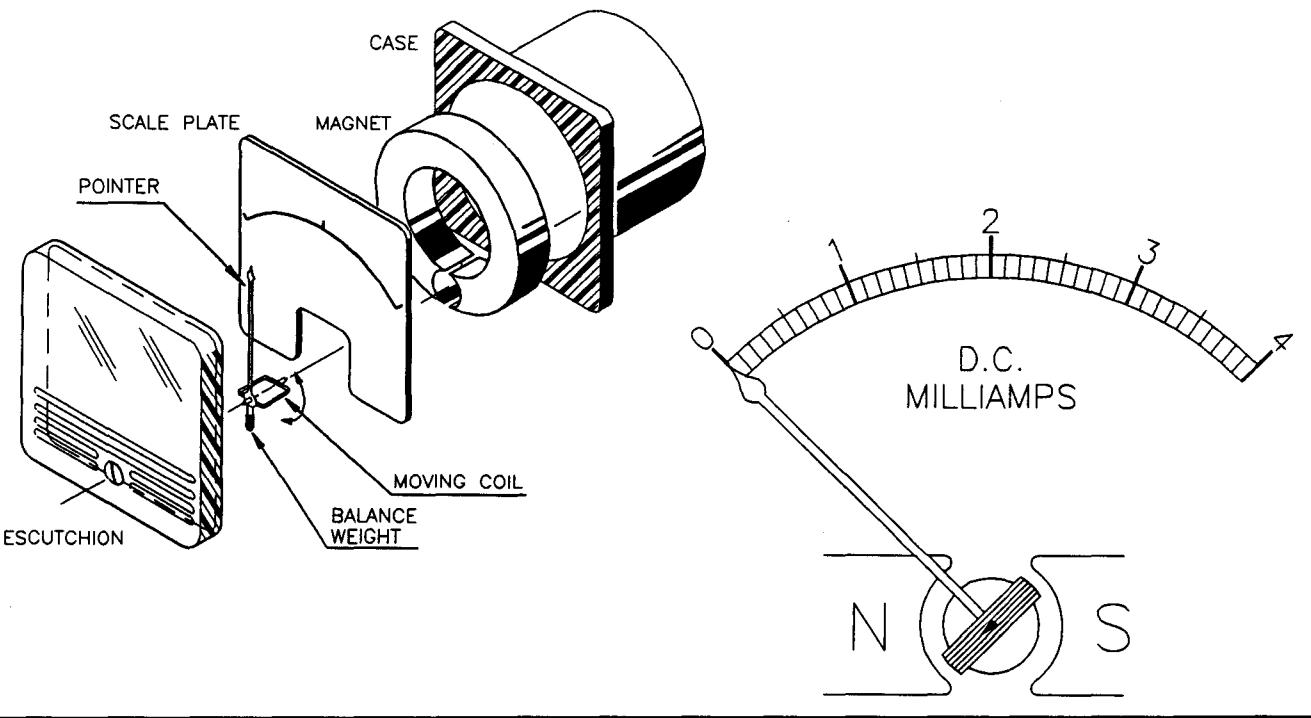


Figure 7-5. The Moving Coil Panel Meter.

are opposing on top. Forces acting on this turn of wire will tend to torque clockwise as one looks into the front.

MOVING COIL PANEL METERS

These fundamental facts of physics allow us to assemble a number of current flow measuring devices. One style of meter is illustrated in figure 7-5. The basic moving coil meter has not changed in fundamental theory or design since 1888 when Edward Weston developed the device we now know as the Weston movement. *[The French call it the D'Arsonval movement after the guy who invented it "first." Don't know who really did it but I thank them both for their enduring products of creativity!]* This occurred some 20 years before invention of the vacuum triode which launched the electronics age.

Two aspects of the original Weston movement have changed with succeeding years. First, development of better magnetic materials and manufacturing methods has produced magnets which can be located inside a moving coil. A steel cylinder around the outside completes the magnetic circuit. This results in a very compact assembly that is relatively immune to interference from external magnetic fields. Second, early designs suspended the

moving coil and pointer assembly on pivots, sometimes equipped with jeweled bearings. A zero-current, pointer restoring force was provided by coiled hair-springs not unlike those found on a balance staff of a clock. Modern movements can be had with a taut-band suspension. A thin, metal twisted ribbon provides both suspension and zero current restoring force. The latter movements are quite rugged, zero friction and very linear in spring rates for restoring forces, however . . .

WHEN THE "BEST" IS JUST TOO GOOD

About 1968, a salesman with a local electronics supply house visited Cessna's engineering department to show us a new multi-meter product he had to offer. It was manufactured by Weston Instruments *[who else?]*. In the act of handing it to me, he dropped the shiny new meter just outside my grasp. The thing hit the concrete floor and bounced! My pucker factor rose to about 110% and I was apologizing for not having had a grip on the thing; he simply grinned from ear-to-ear. He explained: this meter had been purposely dropped for about the 50th time and in spite of its checkered history and dinged up case, it would still meet all operational specifications. It seems the most fragile part of the instrument, the

meter .co

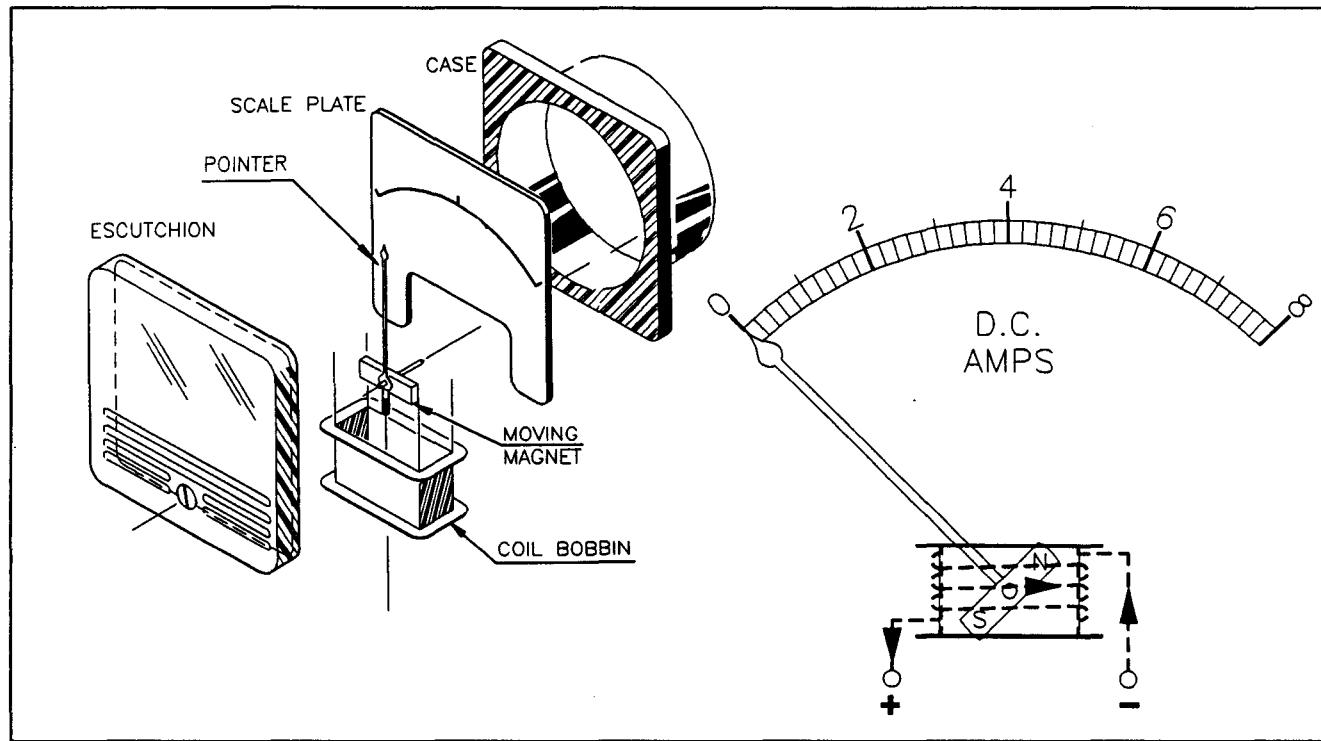


Figure 7-6. The Moving Magnet Panel Meter.

movement, was fitted with the latest and greatest of improvements: the taut-band suspension. We were impressed! He suggested and we immediately agreed that taut-band movements were just the ticket for shaky instrument panels.

Unfortunately, taut-band meter movements proved totally unsuited to aircraft panel installations for two reasons. First, under vibration, taut-band movements allow small excursions in coil and pointer position with six degrees of freedom! I've seen the pointer of a taut-band ammeter in a C-172 jump around like a drunken grasshopper! The other had to do with techniques used to damp meter movements. If one wants a slow, deliberate motion in a pivot-and-jewel movement, a drop of viscous silicon oil on one or both of the pivot bearings would settle the critter right down. No such fix was available for taut-band movements. Remember when searching surplus catalogs for meters or meter movements to use in your airplane, pivot-and-jewel are the only movements suited to aircraft panel mounted applications. Generally, any meter you see advertised will be pivot-and-jewel unless otherwise specified.

THE BALANCING ACT

On most meters and moving coil types in particular, there will be a balance weight applied to the needle shaft below the front pivot point. This balance weight will often be hand adjusted by a skilled operator when the meter is assembled. It is very important to have accurate balance. To check a movement for balance, look at the meter zero reading closely while holding the meter in each of the five positions which one may readily observe the face. The meter should not change reading in any observable way due to orientation. This is not a test to see if the meter will read well while flying upside down! Remember, vibration in your airplane applies artificial acceleration forces in any and perhaps all planes at once. A properly balanced needle will be the most resistant to errors of reading due to vibration OR g-loads from any direction.

MOVING MAGNET PANEL METERS

There is another class of meter; very popular in automo-

tive applications called the moving magnet meter. This type of movement is illustrated in figure 7-6. As the name implies, a bar magnet is suspended in the core of a fixed winding. As current flows through the winding, the core tends to twist so as to become more aligned with the field in the winding. This twist drives a pointer upscale against a hairspring which provides a zero-current restoring force. This style of meter is inexpensive [*notice I didn't say cheap!*], rugged and not terribly accurate. [*Not to worry, if they're good enough for cars, they're good enough for airplanes!*] Indeed, many instrument clusters found on certified aircraft were manufactured by Stewart-Warner and others using pretty much stock automotive technologies. We'll discuss accuracy issues later but suffice it to say that for applications commonly addressed by clustered gages, the moving magnet meter isn't too bad.

HOW ACCURATE IS ACCURATE?

Many products have been sold on features which have little or no relevance to how the product is to be used, panel meters included. Accuracy is something of a buzz-word; meaning that it is held forth as very desirable but without quantifying the term with numbers relative to either the task. There are names for meter performance characteristics which beg illustration. To that end, Figure 7-7 shows three graphs. Y-values on these graphs represent percent of applied stimulus with respect to full scale; X-values are percent of reading with respect to full scale.

Accuracy, is stated as either a percentage of error with respect to full scale or percentage of error with respect to reading. A meter with 0% error would plot with a straight line connecting all like values of X and Y on the graph. This is represented by curve 1 on all graphs in Figure 7-7. Curve 2 in the top graph depicts a meter which reads 5% higher than applied stimulus over its full range. At 95% of full scale stimulus, the meter displays 100%. A meter producing this plot has 5% accuracy.

Linearity has to do with how well a device tracks a varying input. Curve 3 on the middle graph shows a meter that reads "dead-on" at zero, 50% and 100% of applied stimulus. If this meter were checked at only these three values, one might assume it to be very accurate. Detailed investigation of readings over the entire range show the device to read low at about 30% and high at about 75% of applied stimulus. It's stimulus/reading trace makes a sort of s-curve on the graph. Linearity is generally stated as a percentage of full scale. Linearity errors are usually included in an

overall accuracy figure for any given device.

Offset or Zero adjust errors are illustrated by curve 4 in the lower graph. If a panel meter is fitted with a front face zero adjust screw, this type of error is eliminated by re-setting the pointer. Many moving magnet and some cheap moving coil devices are not fitted with zero adjust screws. Some meters without screws may be disassembled and re-adjusted to read zero if needed.

Resolution has more significance in digital instruments than analog panel meters but consider this. If you have selected a meter with a scale length of say 1-1/2 inches to display alternator load amps. Let's further assume that it reads 70-amps full scale. 1.5 inches of scale length divided by 70 is 0.021 inches per amp. Even if the accuracy of the meter is stated to be 2% of full scale; 70-amps times .02 times .021 inches/amp yields an increment of .029" on the scale plate. What is the likelihood you can take advantage of such resolution while observing a 0.030" wide pointer from two feet away? Given the eye's ability to resolve small differences in pointer position, a 5% accuracy meter would probably suffice in such small scale. This begs the question, is such a small meter suited to the task? Yes, because in this circumstance, you are not interested in resolving very small numbers; if the meter displays rather gross conditions of performance then accuracy on the order of plus or minus 5% is sufficient.

One can see that resolution and accuracy, while separately defined, are interdependent. A manufacturer of small meters knows that high resolution scale plates and movement accuracy are not warranted. Limitations of human sight preclude taking advantage of such capabilities in small meters. However, where high accuracy is needed, larger scale plates with longer pointers are needed to display the needed resolution and higher movement accuracy is required.

Repeatability is probably the most important attribute to quantify in small gages, whether used in an airplane or any other vehicle. The fuel gage on most cars is an excellent example of a need for repeatability. After purchasing our latest automobile, a '88 model, I was disappointed to discover the fuel gage was no more accurate than was my '41 model purchased some 32 years ago. However, as with all cars from then to now, I came to know that so many needle widths above empty really meant that x-number of gallons remained. Repeatability is the key feature here. You are all familiar with it in cars and airplanes alike, you just didn't have a name for it! Repeatability simply quantifies how con-

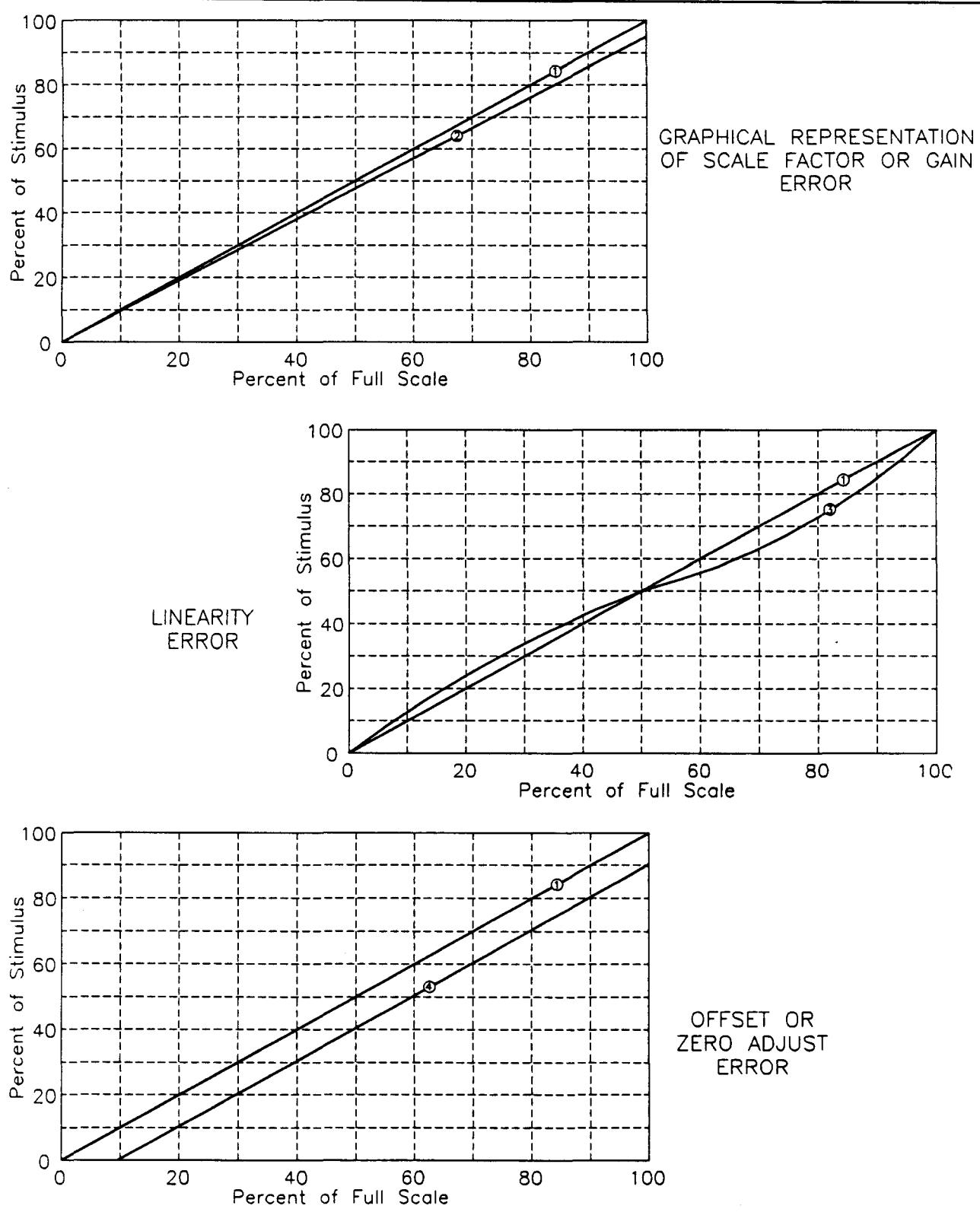


Figure 7-7. Panel Meter Accuracy Issues Illustrated.

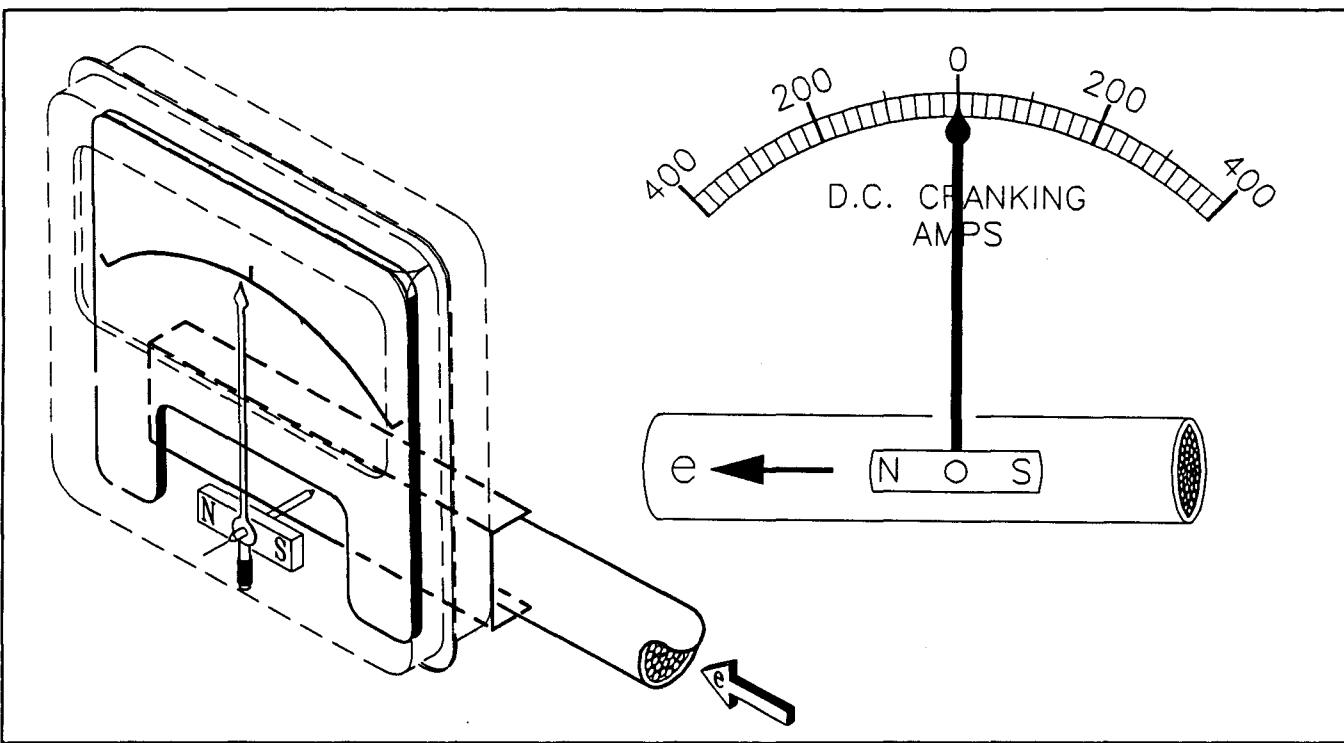


Figure 7-8. Starter Current Test Meter.

sistent the readings will be over long periods of time, irrespective of accuracy or linearity.

Stiction is a contracted combination of "static" and "friction." Stiction is a phenomenon seldom quantified in electrical instrument specs any more. It's usually so small as to be insignificant. Taut band meters have zero stiction because there are no pivots, hence no friction. Stiction manifests itself by displays of intermittent, jerky motion when slowly changing stimulus is applied. Altimeters and rate of climb instruments commonly exhibit stiction on the bench but not in the airplane. This is due primarily to vibration which is conducted to the instrument from the engine. When testing these instruments on the bench, one will see technicians tapping gently on the instrument face before taking a reading. The vibration unsettles the needle drive mechanism allowing it to assume a position as commanded by the movement.

When the first Learjets were built small shaker motors supplied needed vibration to instrument panels. Instruments of the time were used without difficulties on piston airplanes. The Lears were so free of vibration that several instruments produced jumpy readings due to

stiction. Until better instruments were to be had, panel shakers kept them reading properly. Some years ago I worked in a lab where precision measurements were made with large, mirrored scale, pivot and jewel panel meters having 1/4% accuracy ratings. Before making a measurement, instruction manuals suggested tapping the face to shake out the stiction. One day we acquired a new instrument with phenomenal accuracy and resolution, everyone was eager to use the new device. I recall watching a co-worker peering intently into the face of the thing while gently tapping on the bezel. When asked why he was doing that he was suddenly embarrassed to realize that he had been attempting to tap stiction errors out of a digital voltmeter! Old habits die hard.

TEMPERATURE EFFECTS

The meter movements we've discussed so far have been current sensing devices. The wire wound around the bobbin on either a moving coil or moving magnet assembly is usually copper which has a decided positive temperature coefficient with respect to resistance. When copper wound meters are used as low-voltage voltmeters, like when used with a shunt in a battery ammeter circuit, the meter will tend to read higher battery current

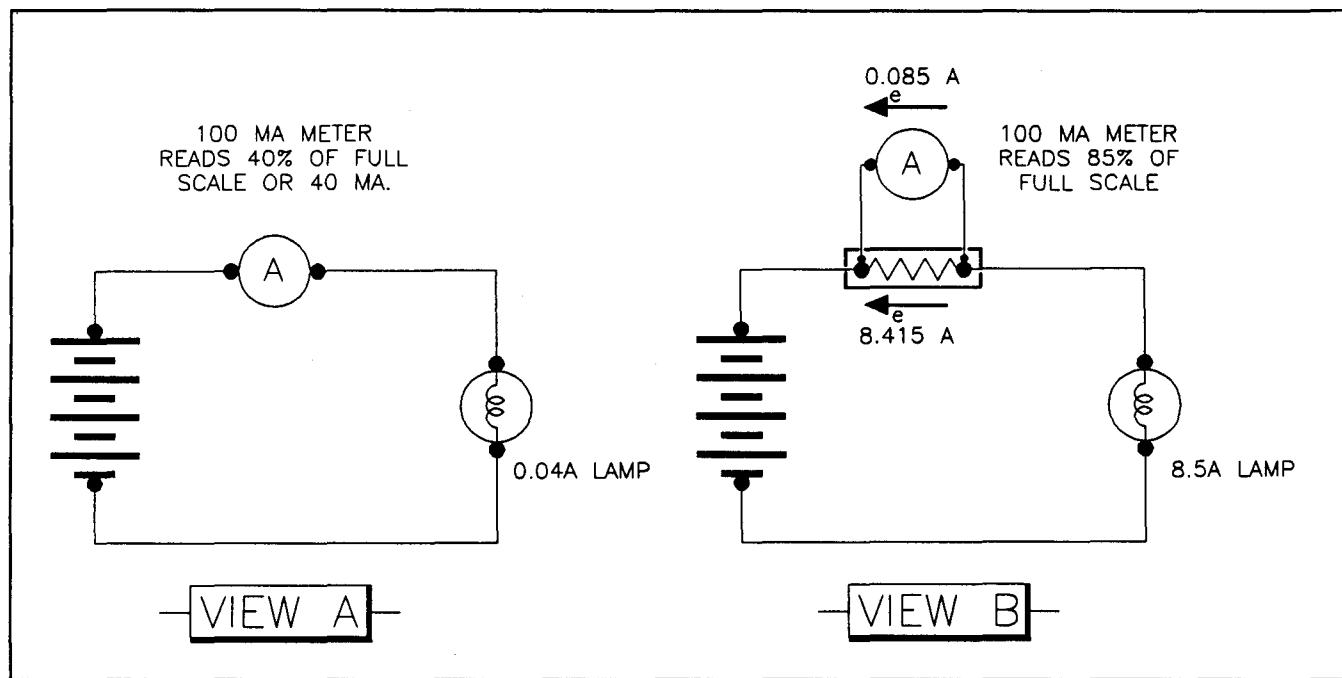


Figure 7-9. Shunting a Panel Meter for Higher Currents.

as the meter cools. This is due to lowered resistance of the copper winding causing current to rise as temperature drops when stimulated with a constant voltage.

Sensitivity usually states the amount of current needed to produce a full scale motion of the meter. Moving coil meters generally fall in the range of 100 millamps down to about 10 microamps. Moving magnet meters are available over a range of 1 millamp up to 50 amps or so. There is a tremendous difference in current range for these two technologies. In fact, moving magnet panel meters are more desirable for some low sensitivity (high current) applications.

One which comes to mind are the alternator and starter testing ammeters sold by automotive tools suppliers. This type of meter is illustrated in Figure 7-8. This is a moving magnet device without a coil bobbin. Instead, a channel on the back is used to position the alternator B-lead or starter power lead in proper proximity to the magnet. I've shown only the polarity of the moving magnet and direction of electron flow. Which way will the meter read, upscale or down-scale? Hint: a magnet free to rotate will try to align itself so that lines of flux

internal to the magnet are coincident with lines of flux from the external field. In this case, the external field is from a single pass of wire across the back of the instrument. Since we're interested in current values from 30-400 amps, this simple device is sufficient. Further, an absolute accuracy on the order of 5 to 10% is adequate. These are diagnostic tools, not calibrated measuring devices.

Many types of vehicles use moving magnet meters as a battery ammeter where full scale sensitivities run from -20/+20 to perhaps -60/+60. Few systems would use smaller than 20 amp alternators and wiring good for 60 amps is pretty hefty! For larger currents, a shunted moving coil meter is more practical. A moving coil meter may be shunted for any desired current range. Figure 7-9 illustrates use of a shunt resistor to produce a calibrated voltage proportional to current flow which is measured by a panel meter. To understand this concept, we have to acknowledge that a moving coil panel meter is also a voltmeter. Wire used to wind the coil must have some resistance so

Just checked in my junk box and found a 1-1/2" square aircraft "loadmeter". A label on the back sez "Use with

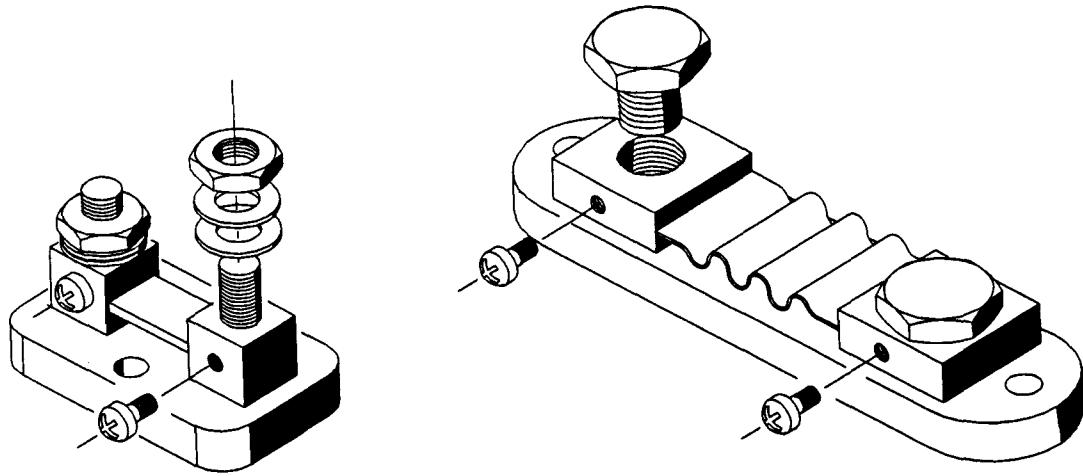


Figure 7-10. Typical Ammeter Shunts.

50 M.V. shunt." The loadmeter is calibrated from 0 to 1. I measured its internal resistance at 105 ohms. *amps equals volts divided by ohms*. So 0.05 volts divided by 105 ohms yields a full scale sensitivity of 476 microamps for this panel meter. That's less than 1/2 milliamp! We can use this meter to indicate any desired full scale quantity. I suspect meters like this are used to indicate loading as a percent of full output on 400 amp generators on King Airs. Let's see, *ohms equals volts divided by amps* so 0.05 volts divided by 400 amps yields 125 micro-ohms, a low resistance indeed! The example in Figure 7-9 shows a shunt used to bring a relatively small panel meter's full scale current reading up to 10 amps.

Use of ammeter shunts is desirable when one wishes to avoid running heavy current lead wires into the vicinity of a panel meter used to display current values. A shunt is absolutely necessary when working with large currents. You simply cannot buy a meter, moving magnet or otherwise, to measure say 1000 amps, however a 50 millivolt, 1000-amp shunt is a catalog item. Ammeter shunts are very specialized resistors. First, they must carry relatively large currents without changing value due to heating. Consideration must be given to the difficulty of making very low resistance connections to a device which is also very low in resistance.

THE 4-WIRE CONNECTION

A high current shunt may be designed to provide an accurate resistance measured in micro-ohms while resistance of wire fittings mashed together by threaded fasteners may have resistances measured in milliohms! Figure 7-10 illustrates two styles of ammeter shunt found in airplanes. The smaller style will be used for ranges from 5 to 60 amps, the larger is typical of 50 to 200 amp shunts. Note the heavy end posts, usually brass, which supports the resistance material between. Current to be measured passes through the shunt by way of the heavier connections. Smaller screws elsewhere on the end post are provided for panel meter connections. Figures and schematics in this publication will always depict an ammeter shunt as a four-terminal device.

BATTERY AMMETER REVISITED

In the battery chapter, I spoke of "battery ammeters." I also suggested, if you plan only one electrical system instrument, make it a battery ammeter. Battery ammeters are a zero center panel meter which indicates present value of current flowing into or out of the battery. Readings left of center indicate battery discharge; right of center indicate charging. A zero to small positive readings indicate system equilibrium. The battery

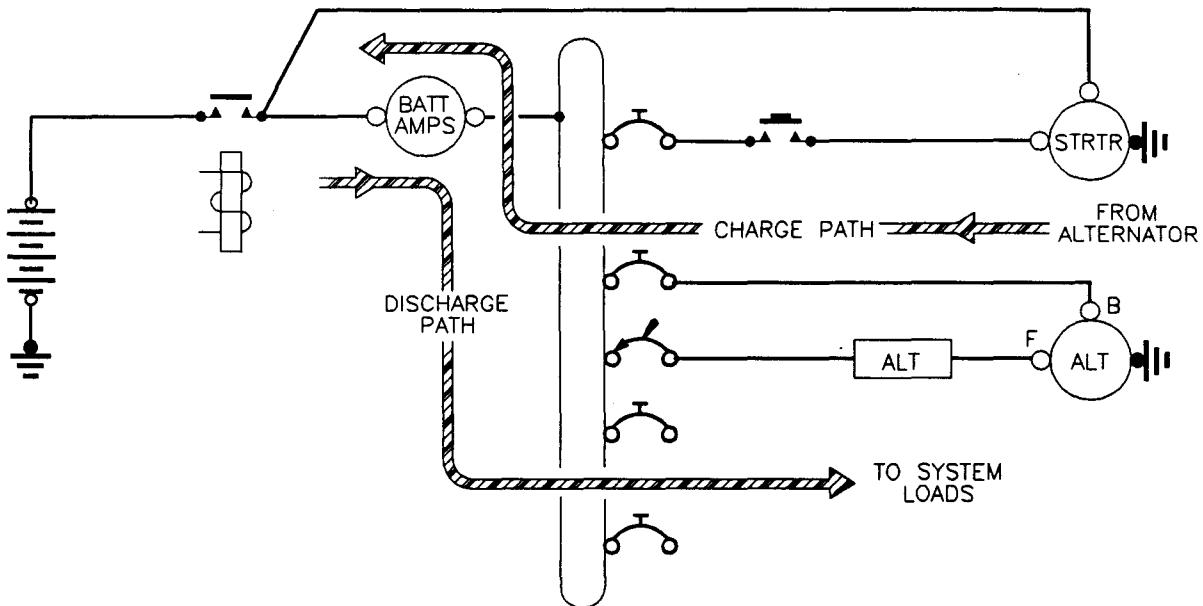


Figure 7-11. Classic Battery Ammeter Wiring.

is charged and the alternator is carrying all system loads.

A battery ammeter must be inserted into the system so that it can measure both charging and discharging currents. Figure 7-11 shows the classic battery ammeter interconnection. Note that energy to charge the battery and carry system loads is conducted through a breaker at the power distribution bus bar. *[Yes, I know the arrows point out from the plus terminal of the power source; but there's no little "e" on them either.]* With this interconnection scheme, ammeter wiring is relatively simple; the ammeter is conveniently located near the power distribution bus on the panel. This configuration allows you to use a relatively low cost, moving magnet or internally shunted panel meter rated to carry and indicate current flows up to the alternator's rated value. This scheme has been used for years and works well but I offer an alternative for your consideration.

In Figure 7-12, I show the alternator B-lead wire routed to the starter main power terminal. Note that charging energy now flows directly to the battery via the starter supply conductor. This shortens a large conductor which used to run from alternator B-lead to the bus bar. The large starter cable can now serve two purposes; starting and charging. This change takes advantage of the bat-

tery's superior capability for reducing alternator noise on the system. Instead of conducting alternator noises to the battery by way of the bus bar, noises are shunted to battery on shorter, fatter wires.

On canard pushers with battery and engine on opposite ends of the cabin, a considerable amount of heavy wire has been eliminated. On tractor airplanes with the battery on the firewall, alternator wiring is reduced to a very minimum and battery adsorption of alternator noise is maximized. This isn't a something for nothing trade-off; now the ammeter wiring is rather unhandy. The ammeter has to be inserted into a conductor which also carries starter current as shown. If the meter is a -60/0/+60 amp device, 200-amp starting currents will whack the needle pretty hard. Further, we don't want to route 2-gage wires to the panel just to accommodate the battery ammeter. Hence, architecture in Figure 7-12 would never be recommended as an method of interconnection.

There are several alternatives. (1) It is perfectly okay to choose not to install a battery ammeter. A voltmeter is second-most desirable as a single electrical system gage; we'll discuss them later in this chapter. (2) We may install an ammeter shunt as shown in Figure 7-13, or (3)

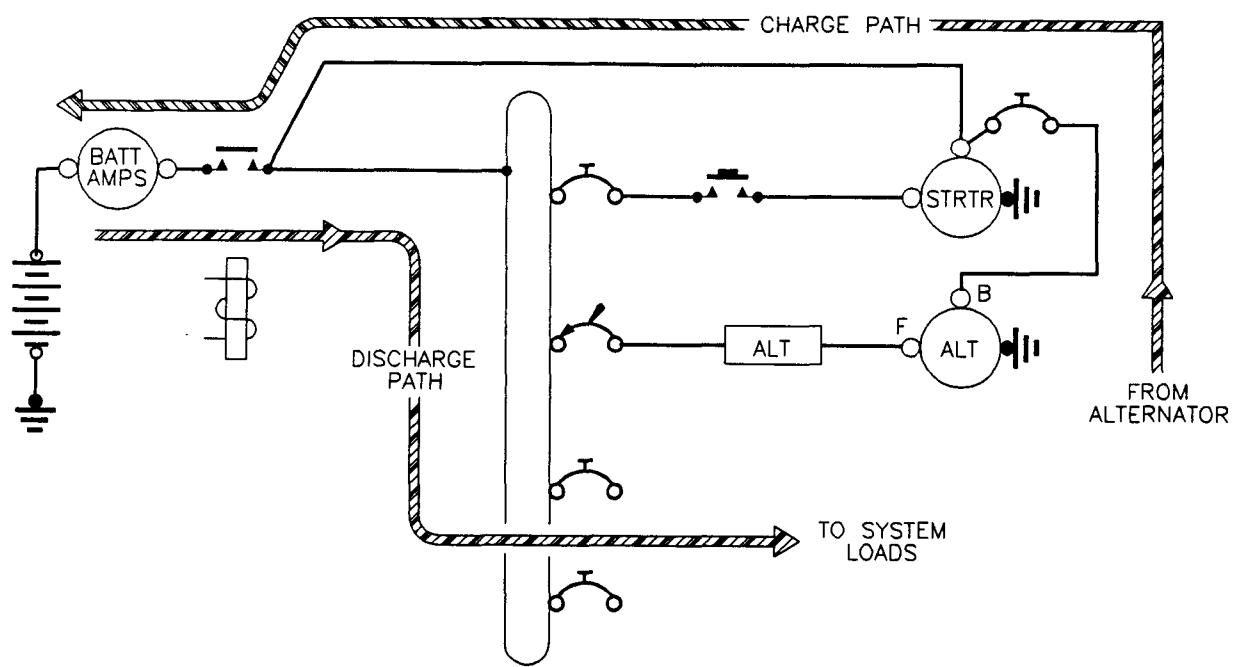


Figure 7-12. Using Starter Cable to Carry Charging Current.

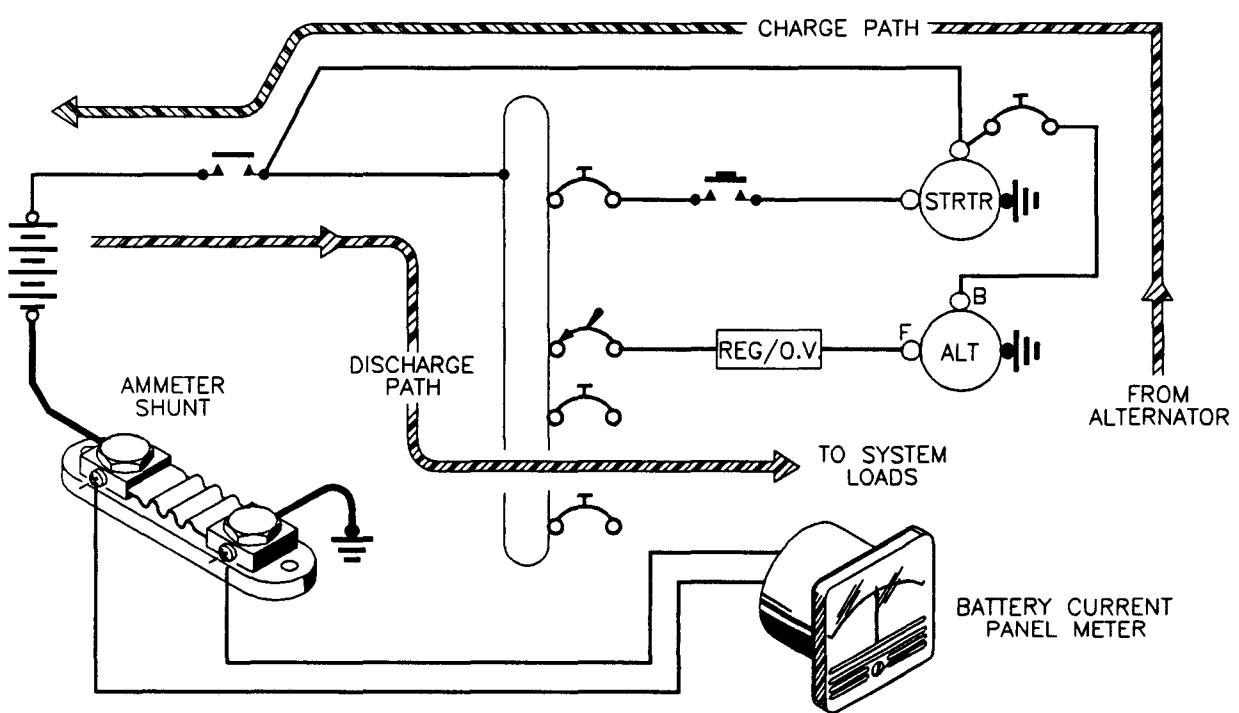


Figure 7-13. Battery Ammeter Shunt in the Battery Lead.

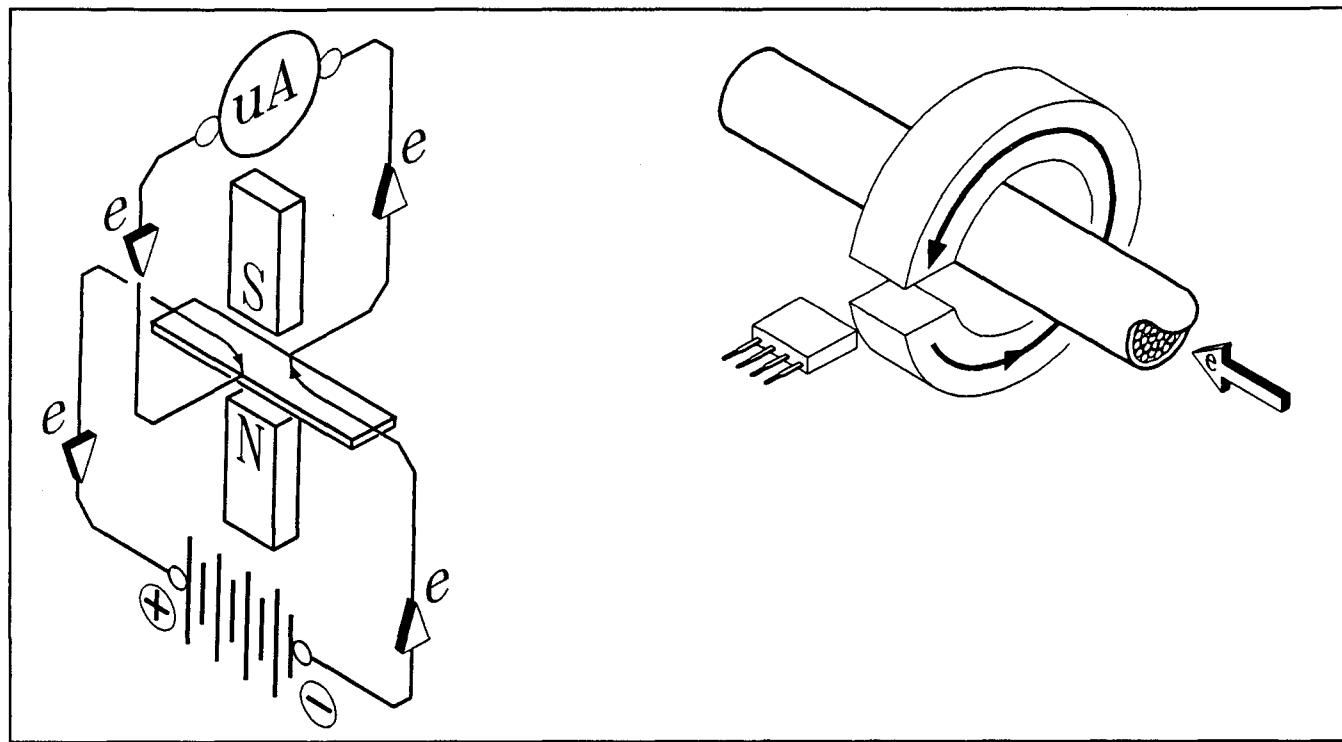


Figure 7-14. Hall Effect and Hall Effect Devices.

we may measure current in the battery wiring with a non-contact sensor like a Hall-effect current transducer illustrated in 7-16. Let's look at the options:

BATTERY AMMETERS WITH SHUNTS

A shunt permits breaking the heavy current conductor in a location remote from the panel meter location. On very large airplanes, a hundred feet or more in wire may be used to connect a panel meter in the cockpit to a shunt buried in the guts of an airplane. Figure 7-13 shows a shunt installed in the battery cable. This is a practical way to meter battery current but it requires some special considerations. First, I would recommend using a 100-Amp, 100 mV shunt in place of a 50-Amp, 50 mV shunt. Both shunts are the same resistance, 1-milliohm. However, the 100 amp shunt will not be damaged by 150-250 amp cranking currents as this represents only a 1.5-2.5 times overload and only for a few seconds. For a 50-Amp shunt, these same cranking currents would represent a 3-5 times overload. Secondly, while cranking, the ammeter needle will be pegged on the discharge side. It may even hit the peg with an audible "click." This action will not damage a well built meter but it does sound bad. Recall that my junk box meter had a full

scale sensitivity of less than 500 microamps. Applying a 2.5 milliamp current for a short time is not going to burn it out.

ABOUT SHUNTS IN GENERAL

The ammeter shunt is a simple, elegant way to measure large currents in remote locations with small meters. Keep in mind that the wires leading to your panel meter have the same voltage with respect to ground as the wire which carries the big current to and from the shunt. When shunting a battery ammeter, I recommend placing it in the ground lead to the battery. All wires connected to the shunt will then be at ground potential. If you decide to put a shunt in any "hot" lead, be sure to include 5-Amp fuses to protect the 22AWG wires between the shunt and panel meter. Check out air parts supplier catalogs for off-the-shelf shunts. Empro Manufacturing (see Appendix-A) also builds standard and custom shunts.

BATTERY AMMETERS WITH NON-CONTACT SENSORS

There is yet another practical way to measure current in

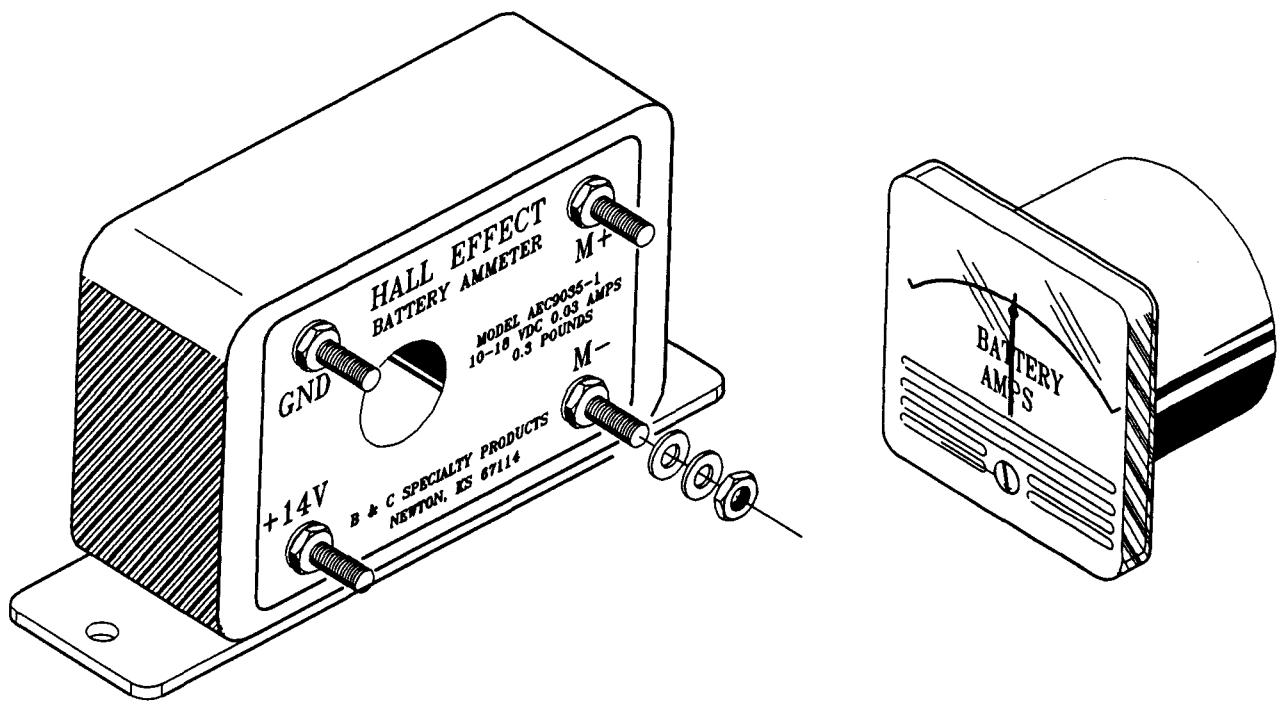


Figure 7-15. Major Components of a Hall Effect Battery Ammeter.

a conductor using what is known as a Hall effect device. Like the starter current ammeter we discussed previously, this device measures the strength of magnetic field around the conductor without actually breaking into it. The Hall effect has been known for many, many years but it was the early 60's before commercial quantities of practical devices were available. Our friends at Micro Switch developed a line of devices to replace mechanical limit switches. These were a plastic encapsulated integrated circuit device used to detect the presence of a magnet on a mechanism and actuate relays to stop or start motion.

Electron flow current appears to move through a conductor at the speed of light. I say "appears" because when you shove an electron into one end of a wire, an electron becomes available at the other end very quickly, however Suppose you had a pipe, 1/2" inside diameter and 1000 miles long. Let us further suppose that the pipe was full of marbles. If you pushed a marble into one end, you would instantaneously get a marble out the other end. The marble you inserted traveled only 1/2"; the "current" traveled 1000 miles in an instant. Electron flow in a conductor is very similar but more random yet. An electron has hundreds of adjacent atoms to jump to

throughout the mass of a conductor. If you could paint an electron red and put it into the end of a conductor 1000 miles long, I dare say you could run a d.c. current through the conductor for a very long time and may never see the "red" electron come out the other end. If you were using alternating current, like that which comes out of the wall socket, then the migration of a single electron through a conductor is further hampered because it is constantly reversing direction!

So, while a current travels very quickly, individual electron motion is relatively very sedate. Figure 7-14 illustrates principals of the Hall device. Suppose you have a long flat conductor suspended in a magnetic field with a source of electrons (battery) connected between the ends. The electron current flow may be high but individual electrons are stumbling around like drunken sailors in a strong breeze. They flow generally in the right direction but their path is subject to other influences too. If you apply your left hand rule to the general direction of flow and consider the field formed between ends of the two bar magnets, then electrons tend to migrate toward one edge of the conductor as shown. If given a means to leave the edge and travel to the other edge where there is a dearth of electrons, then they will do so. In this

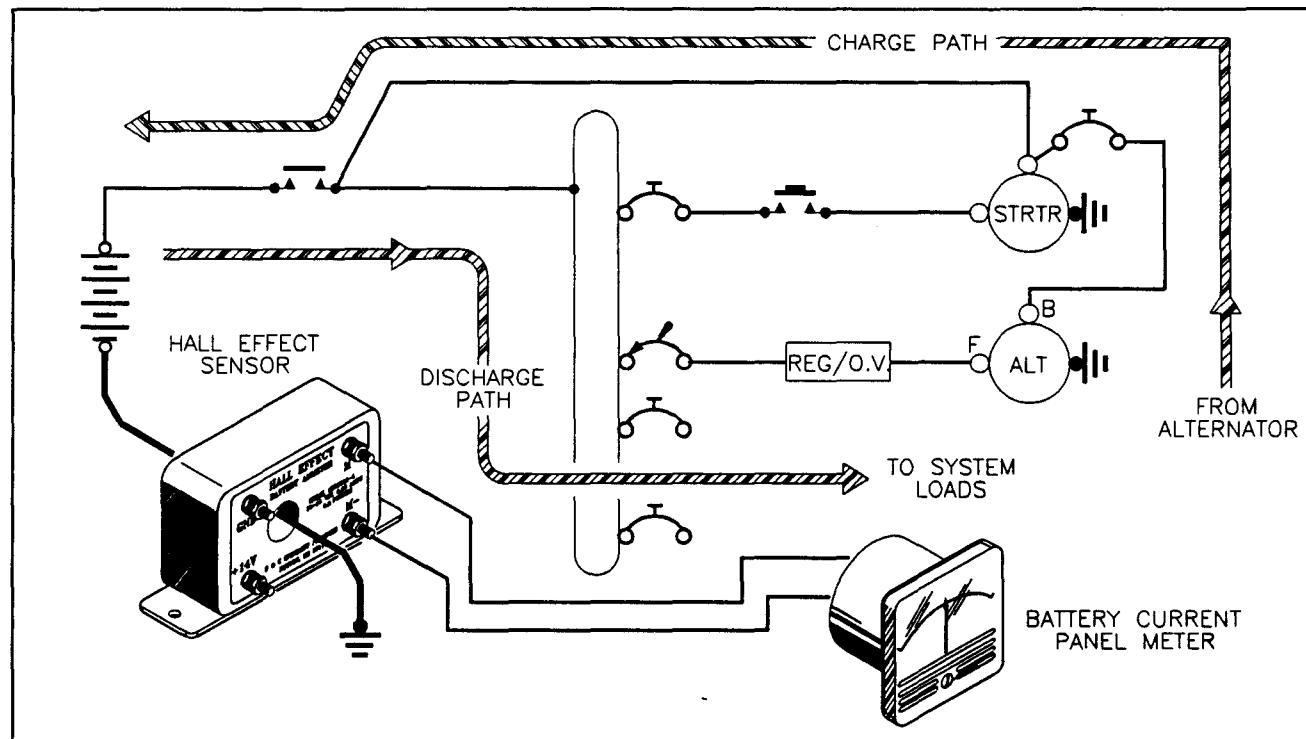


Figure 7-16. Application of Hall Effect Battery Ammeter.

example I have shown a micro-ammeter inserted in a conductor which connects the two edges. The microammeter will indicate a current flow. It is a small one but a very important fact should be observed. The Hall effect current is proportional to the product of bias current multiplied by magnetic field strength.

In Figure 7-14 I show a toroidal core of magnetic material which has been opened with a small air gap. If you run a conductor through the toroid and cause a current to flow, magnetic lines of force created by that flow will be concentrated in the toroid and appear across the air gap. A Hall sensor may be inserted into the gap. If supplied with appropriate bias, amplifier and means for displaying the value, this scheme allows us to measure d.c. or a.c. current in the conductor without even touching it. We've seen snap-on ammeters used by electricians and air-conditioner repair personnel. These also sense magnetic fields external to wires and convert the readings to current. However, these are iron core transformer devices; useful only on a.c. current. The Hall device will measure either a.c. or d.c. current.

A complete Hall effect ammeter would consist of a power supply, a Hall transducer, some form of amplifier or signal conditioner, and a panel meter. These four

items are part and parcel of many other instrumentation systems which we'll discuss in a later chapter on airframe systems instrumentation. Figure 7-15 shows a typical Hall effect battery ammeter system approximately full size. The sensor assembly contains power supply, transducer and signal conditioning. The sensor assembly is mounted near the battery or battery contactor. Leads are run from the sensor assembly to a companion panel meter calibrated to appropriate full scale values. The system illustrated will appear in Appendix K. Like all such gadgets described herein, a short kit of parts OR a completely assembled and tested system will be made available through B & C Specialty Products. A number of manufacturers build similar devices. They show up in surplus catalogs on occasion and are always available new. A Hall effect battery ammeter installation is illustrated on foldout distribution diagrams in Appendix-Z and in Figure 7-16.

VOLTMETERS

Having completely thrashed the topic of panel meters, we can now discuss and appreciate the second most important electrical system instrument on the panel: the voltmeter. The battery ammeter, if properly interpreted, can

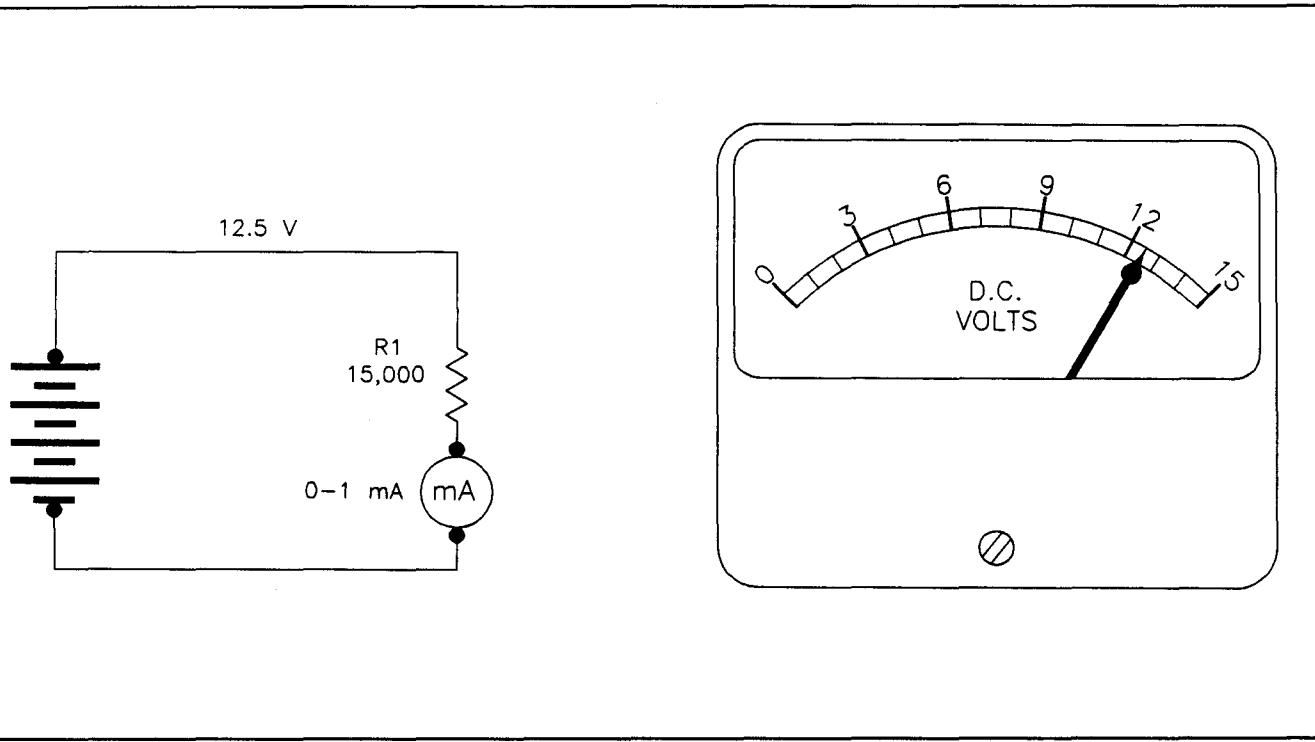


Figure 7-17. Basic Voltmeter.

warn of several classes of system difficulty. The voltmeter is more specific. When the alternator is functioning properly, a voltmeter will indicate system voltage which must be interpreted with consideration to battery temperature. When the alternator has been shut off or has failed, the voltmeter will present an indication of present battery condition and warn of impending discharge as the voltage begins to fall more rapidly.

AMMETER + RESISTOR = VOLTMETER

Figure 7-17 illustrates a schematic for basic voltmeters. In this form, one simply decides what value of voltage will produce a full scale indication, use *ohms equals volts divided by amps*, and divide by the full scale sensitivity of the meter. Therefore a 1 milliamp basic movement requires a resistance of 15,000 ohms to produce a full scale reading at 15 volts. When working with very precise meters it is necessary to adjust a series resistance value to compensate for the meter's internal resistance. Suppose the meter had a resistance of 200 ohms, then externally we would want to add 15,000 minus 200 equals 14,800 ohms. In this case, error introduced by not accounting for internal resistance would be $200 / 15,000 = 0.013$, or 1.3 percent. On a small meter (scale length of 2" or less) this is a needle

motion of 0.026" or less; not worth worrying about.

EXPANDED SCALE VOLTMETER

The problem with basic voltmeters in airplanes is that most of their scale range displays voltages of little interest to us. For example, if our meter reads 15 volts full scale on a 14 volt system, we would expect normal operations to produce readings of 13-15 volts depending on battery temperature [*assuming we have a temperature compensated voltage regulator*]. With a failed or shut down alternator, readings of 10 - 12.5 volts are of interest; anything below 10 volts represents a rapidly failing battery. Readings below this are not significant.

There is an interesting way to produce offset and rescaling of a basic voltmeter to secure an expanded scale. This is illustrated in figure 7-18. First, we need a stable reference voltage against which we will compare system voltage. This is easily obtained by biasing up a precision zener voltage regulator through a resistor (R1) as shown. This zener can be any voltage from say 4 to 8 volts. Let's go through a quick calculation for the resistors:

First, let's say the zener is rated at 6.0 volts with an

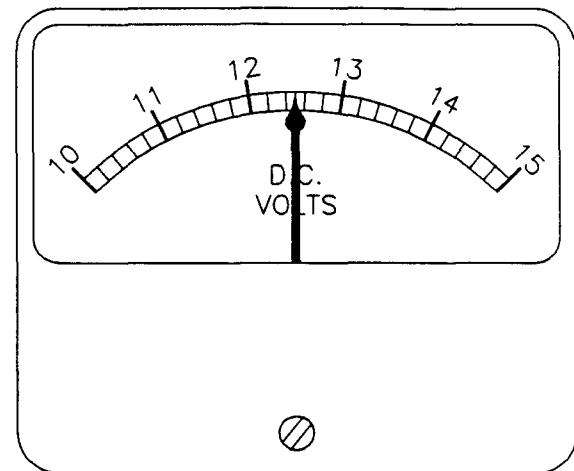
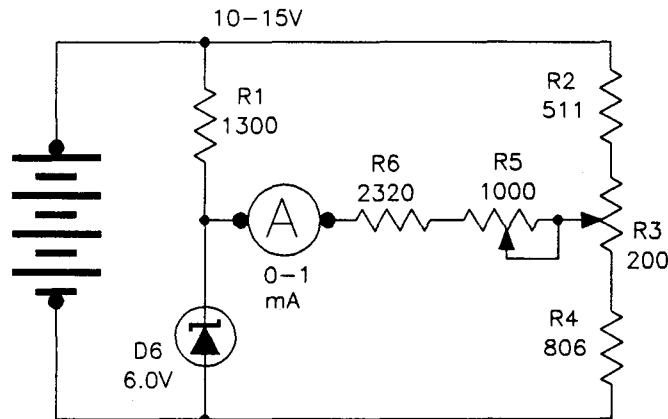


Figure 7-18. "Differential" or Expanded Scale Voltmeter.

operating range of 1 to 10 millamps of bias. Let us choose to operate it at 3 millamps when the bus voltage has fallen to 10 volts. So, 10 volts minus 6.0 volts is 4.0 volts across R1. *ohms equals volts divided by amps* so 4.0 divided by .003 yields 1333 ohms. 1300 ohms is a close standard value so we pick $R1=1300$ ohms. Now, what wattage? If the bus voltage rises to 16 volts (full scale on our expanded scale meter) then we have 15 minus 6.0 = 9 volts across R1. *Watts equals volts squared divided by ohms* so 9 times 9 divided by 1300 = 0.062 watts or 62 milliwatts. Our common 1/4 watt resistors will be quite adequate.

Now, we want our meter to see zero current when the bus is actually at 10 volts so the voltage divider consisting of R2, R3 and R4 needs to produce 6.0 volts when the bus is at 10 volts. Lets pick a bias current for the divider of approximately 10 times the full scale meter current or 10 millamps when the meter is full scale (15-volts on the bus). This means our total divider resistance must be 1500 ohms to produce a 10 millamp divider current at 15 volts. We also know that the ratio of $(R2 + R3 + R4)/(R4 + .5 \times R3) = 10/6.0$. Let us pick a 200 ohm potentiometer for R3. Now we have two equations and two unknowns:

$$(1) R2 + 200 + R4 = 1500 \text{ ohms}$$

$$(2) 1500 / (R4 + 100) = 10 / 6.0$$

simplifying (2)

$$(5) 1500 / (R4 + 100) = 1.666$$

$$(4) R4 + 100 = 1500 / 1.666$$

$$(5) R4 = (1500 / 1.666) - 100$$

$$(6) R4 = 800 \text{ ohms}$$

plugging value for R4 into (1) we get

$$(7) R2 + 200 + 800 = 1500$$

solving for R2:

$$(8) R2 = 1500 - 800 - 200$$

$$(9) R2 = 500 \text{ ohms.}$$

Okay, how about wattage? At worst case, we have 10 millamps flowing in the divider at 15 volts bus voltage.

15 volts times 10 milliamps is 160 milliwatts total for all three resistors. Again, 1/4 watt resistors will be quite adequate. Stay with me folks, we're almost there. . . .

Let's now look at the resistors required to make our meter read full scale when the bus is at 15 volts. The voltage divider is set up for a division ratio of 10/6 so when the bus voltage is 15.0 then the voltage divider tap will be at:

$$(10) \quad 15/E = 10/6$$

Solve for E:

$$(11) \quad (15 \times 6)/10 = E$$

$$(12) \quad E = 9 \text{ volts}$$

Our little meter is reading a difference between the zener at 6.0 volts and the divider tap at 9.0 volts. So, Our meter must read full scale (1.0 milliamps) at 3.0 volts difference. Therefore, $R_5 + R_6 + \text{Internal Resistance of Meter}$ must be $3.0/0.001$ or 3,000 ohms. Say the meter has a resistance of 155 ohms then $R_5 + R_6$ will have to be 2845 ohms. Let's pick a 1000 ohm pot for R_5 and assume it is centered at 500 ohms. This leaves 2345 ohms for R_6 .

Referring to the resistor tables in any of several catalogs from Appendix-A we find that standard 1%, metal film resistors are available with values of 806, 511 and 2,320 ohms. We use precision metal films here to get long terms stability. The values need not be dead on to computed values because we're going to calibrate the meter using potentiometers R_3 and R_5 . Apply 10 volts to the assembly and adjust R_3 for "10" on meter, apply 15 volts and adjust R_5 for "15." This needs to be done only once; the adjustments are not interactive as long as you set R_3 first.

With the foregoing exercise we have, (1) spread only the range of interest over the same scale for 3 times better resolution, (2) independently calibrated to insure accuracy, and (3) used stable components secure repeatability. Moral: Most of the cute little voltmeters advertised to homebuilders are offered by folk who don't understand what the voltmeter is supposed to do for you. A simple meter reading 15 volts full scale in a 1-1/2" package is probably NOT worth putting into an airplane. The meter lacks sufficient accuracy or resolution to measure charging voltages to plus or minus 0.1 volt values we'd like to measure.

DIGITAL PANEL METERS

When it comes down to accuracy and resolution, the digital panel meter (DPM) beats the analogs hands down. Many of the catalogs listed in Appendix-A will offer digital panel meters; Figure 7-19 illustrates two common configurations. The two most common display technologies are liquid crystal [*like your wrist watch*] and light emitting diode or LED [*Most digital alarm clocks use LEDs*]. Neither display is preferred over the other; both have their unique drawbacks. LEDs wash out in sunlight so mounting in a shaded spot on the panel is recommended. Liquid crystals need backlighting at night and they get very slow to respond when cold, some will not indicate at all below freezing temperatures. For accuracy and resolution, they are equal. The same type of electronics will drive either technology.

A single digital display might be considered for multiple parameter measurement applications. For example: We might install a rotary switch beside a digital panel meter and use the same instrument to read amps, volts, OAT degrees F, OAT degrees C, etc. Parameters selected for display on a single instrument would be those which do not generally require constant, independent monitoring. Decimal points on DPM's may be positioned from outside and basic 100 or 200 millivolt devices may be externally rescaled to read any desired value. Major downside of DPM's is limited pilot ability to quickly perceive and interpret trends. Things to be shown digitally should be selected with this limitation in mind.

With digital resolution in a battery ammeter, for example, one may check all external lights for proper operation in daylight and from the cockpit. Each system can be turned on and its current draw measured to within 0.1 amps. Variations in normal readings will quickly flag failed devices. If there is much interest in pursuing digital technologies for panel displays, let me know about it. We'll work it up in Hot Flash issues or update this chapter as appropriate.

REHABILITATING THE "IDIOT" LIGHT

When warning lights began to replace gages in some cars during the early 50's there was a great hue and cry from the purists who claimed a desire to "know what was really going on." Aftermarket gage kits could be purchased in any parts store. To some extent their protestations were justified. Mostly because the warning lights had poorly defined operating parameters. For example, oil pressure switches for some cars didn't turn the light on until pressure dropped below 4 psi! From my own

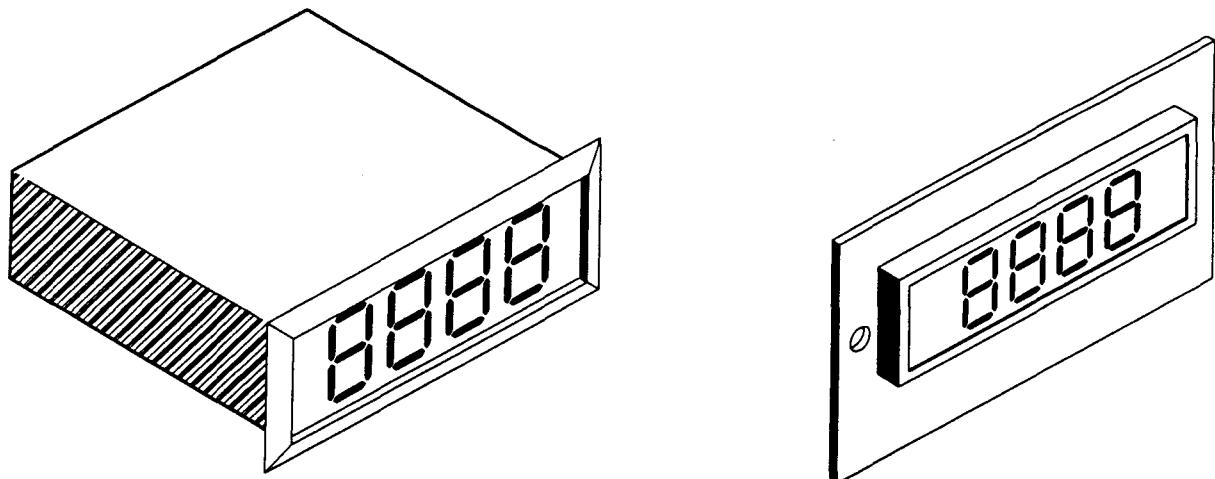


Figure 7-19. Typical Digital Panel Meter Modules.

experience I recall visiting a Chevy dealer in the mountains of New Mexico just before closing time. I had a bad regulator replaced before heading out onto the desert. I had installed a battery ammeter of my own design and fabrication which told me I had a problem long before the warning light came on.

There's nothing "idiot" about a light if it's operating parameters are useful, predictable and understood. For many airplanes running small permanent magnet alternators, a "genius" light may adequately serve all electrical system instrumentation needs. For example, an under-

over voltage warning light (see Appendix-K) would serve to warn of a failed alternator or regulator. The device I refer to will illuminate a steady light if bus voltage falls below 12.5 which it will quickly do if the alternator has failed or is off line. The light flashes if voltage exceeds 15.5 volts thus warning the pilot to shut the system down.

This chapter has served to introduce electrical system panel instrumentation and get the physics explained. In later chapters we'll use panel meters to do many other display jobs.

Wire Selection and Installation

The concept of using wires to provide a path for electrons to flow from a source to some remote load where the work is to be done is pretty well understood. The following discussion on wire will cover the selection of wire sizes, wire forms, and appropriate types of insulation for various tasks.

THE ANATOMY OF A WIRE

A trip through the wire catalogs will reveal a plethora of wire sizes and types as well as cables made up from bundles of individual wires. There are hundreds of military specifications written for the purpose of describing and obtaining special and perhaps not so special wires for specific tasks. Wire has experienced a myriad of evolutionary stages over the last 50 years. Actually, the basic wire is pretty much the same but the insulations which cover the wires have evolved a great deal. Indeed, insulation is still the arena where great strides will be made in reducing the size an electrical system installation. Weight will not be greatly improved upon; the copper conductor is already the major proportion of the weight and there is simply no practical way to do with less copper with current technology.

Most wire used for interconnection in a vehicle will start with a core of pure copper. The metal is relatively cheap compared to materials which conduct better than copper. Silver is probably the only pure metal that is equally suited mechanically and conducts better than copper. If anyone is really interested in wiring their airplane with silver wire, I can put you in touch with a manufacturer who would be delighted to sell you what you need! For the rest of us po' folk, copper will remain the material of choice. There is no material more economical than copper for any given wiring task.

Some brief flirtations have been made with aluminum conductors for wiring in both the aircraft industry and in wiring houses with mixed results. Aluminum is less expensive than copper but it does not conduct electron flow as well as copper. However, even when the size of the conductor is increased to compensate for the higher resistance of aluminum, the weight of the installed aluminum conductor is still less than for its electrically equivalent copper counterpart. This tantalizing fact has prompted a number of engineers to use aluminum battery cables in airplanes manufactured by both Piper and Cessna. I am aware of no such at-

tempts at Beech or Mooney but I'm sure that they have at least considered the possibilities.

The majority of factory installed aluminum cables have now been replaced and for one basic reason. Aluminum suited to the manufacture of wire has to be very soft. Soft aluminum will readily "work harden" when stressed beyond its elastic limit causing it to become brittle and subject to cracking. The connectors that are crimped onto the wire cause the metal to be upset in compression and the first beginnings of material work hardening take place. This makes the terminations sensitive to both vibration and corrosion. In a few cases, the aluminum wire installations were not adequately supported along their installed length and vibration began to work harden the conductors during the airplane's first flight hour. The hassles of maintaining good termination quality and preventing conductor failure under vibration has proved to be not worth the effort for the few ounces of weight savings. The metal airframe itself has proven to be the only conductor of electrons that could be suitably made from aluminum.

FABRICATION FOR SURVIVAL

The form the copper takes may vary from a single, solid strand to a twisted combination of many fine strands of wire. Most houses are wired with solid wire, while the wire used in the cord for a hand tool like a drill motor or electric iron is finely stranded. The reason for this is FLEXIBILITY. Along with flexibility comes a resistance to breaking from being flexed. The logic for this can be understood better by looking at Figure 8-1. I have shown two diameters of copper wire wrapped 360 degrees around a quarter-inch diameter rod. The larger strand of wire is 10 gauge wire having a diameter of 102 mils (102/1000 of an inch or 0.102"). The smaller is a 22 gauge wire having a diameter of 25 mils or 0.025". When you bend any material, the side of the material that faces the inside of the bend is in compression while the side that is outside the bend is in tension. The stresses in the material are variable. As you move inward on the bend radius, tension stresses go down until at some point inside the core of the strand, the stress is zero. The stress changes to compression from this point and rises in magnitude until the maximum compression stress is encountered on the inside of the bend where the strand is in contact with the rod. In the scenario depicted, let us assume that the stress in the 10 gauge wire is zero exactly in the

center or 0.05" off the surface of the 0.250" rod. The circumference of the circle through the center of the wire is π times 0.350" or 1.01" inch. The circumference of the rod is π times 0.250" or .785". The circumference of the circle at the outside of the wire is π times 0.450" or 1.414". In this example we have taken 1.00 inches of wire and caused reduction of length in compression of 23% on the inside and a 41% extension of length in tension on the outside. Copper is a very ductile material. The initial formation of a piece of 10 gauge wire around the quarter-inch rod will result in very little loss of structural integrity in the copper. However, copper too will work harden. If you bend and unbend the strand a few times, the ductility goes down and cracks will begin to appear in the surface. A few more bends and the cracks will go all the way through and the strand fails. Let's suppose we wanted to make an equivalent wire in an electrical sense by twisting say, 19 strands of a smaller wire together. Why 19? I'll get to that later. It so happens that if I combine 19 strands of 22 gauge wire in a bundle, I will have about the same cross sectional area of copper as a 10 gauge wire. Suppose we bend a 22 gauge, 0.025" diameter wire over the same quarter-inch rod. This yields circumferences of .785", 0.864" and 0.942" respectively. This means that a 0.863 inch piece of wire has been compressed inside the bend for a 9% reduction and stretched outside the bend for an elongation of 9%. As you can see, a reduction of wire strand diameter produces an approximately proportional reduction of stress in the wire for the same bending scenario. The ultimate example of flexibility and resistance to breaking from flexing can be found in welder's cable wherein large effective diameters of wire for several hundreds of Amps of load are made from hundreds of strands of fine wire.

Now that the utility of stranding wire for flexibility and resistance to breakage has been established, let's talk about that number "19". If you take a compass and a sheet of paper and draw groups of equal diameter circles around a central circle, you find that six circles will just fit around the one in the middle and that every circle is exactly tangent to any adjacent circle. This illustrates the first common value of "7" for the stranding of wire. Continue to add circles around this array and you will find that twelve more circles fit neatly around the first seven for a total of nineteen. This is the next higher number found in the wire catalogs for stranding. This discussion has been illustrated in Figure 8-2. The exercise can be carried out many more steps but for our purposes, 19 is enough. The smallest wire used in airframe wiring applications is 22 gauge

which is made up from 7 strands of 30 gauge or 19 strands of 43 gauge. Of the two, the 19-strand wire is much preferred over the 7-strand wire.

Okay, our best choice for wire thus far is to make it from copper and to have at least 7 strands in its make-up. The next layer up on our construction project is the plating of the wire. Many automotive wires do not bother to plate the individual copper strands before twisting them together. If you cut away the plastic insulation from the middle of an old battery cable (some distance away from the corrosion caused by migration of the acid under the end of the insulation) you will note that while the wire is basically intact, it may be a far cry from the bright copper that was used to make up the cable. There are several reasons for this.

First, copper is a very active metal. By 'active' I mean that it reacts very readily with oxygen in the air combined with moisture and the nasties that float around in it. A copper tea kettle sitting in the open air of a kitchen will last but a few weeks before needing another pass with the copper polish. Second, when you strand a wire, there is no practical way to totally seal the air circulation from between the strands. Third, most plastic insulations are not perfect barriers for the protection of wire from the environment, especially when hydrocarbons are present. The design life of an automotive system is something on the order of 7 to 10 years. We build airplanes for much longer life spans so using a plated wire under our insulation is in order. Tin is the metal of choice. It is easily applied and much more resistant to chemical activity than bare copper.

KEEPING THE "JUICE" INSIDE THE "PIPE"

The next layer up is the insulation. Here is where we find the most striking evolution in construction over the past 50 years. If you think vehicle systems present some tough design situations, find a book in the library on the laying of the first transatlantic cables. These cables were laid by combination steamer/sailing ships that burned wood or coal. Oil and the by-products thereof were not around yet. Designing a conductor for both electrical characteristics and mechanical strength was difficult enough; covering the wire to protect it from the salt water at thousands of feet of depth was entirely another matter. The fibers available were organic as were the sealers. Many layers of tars, jute-like fibers and shellac in varied combinations were tried. Millions of dollars of 1890's money were literally dumped into the Atlantic ocean before the first really

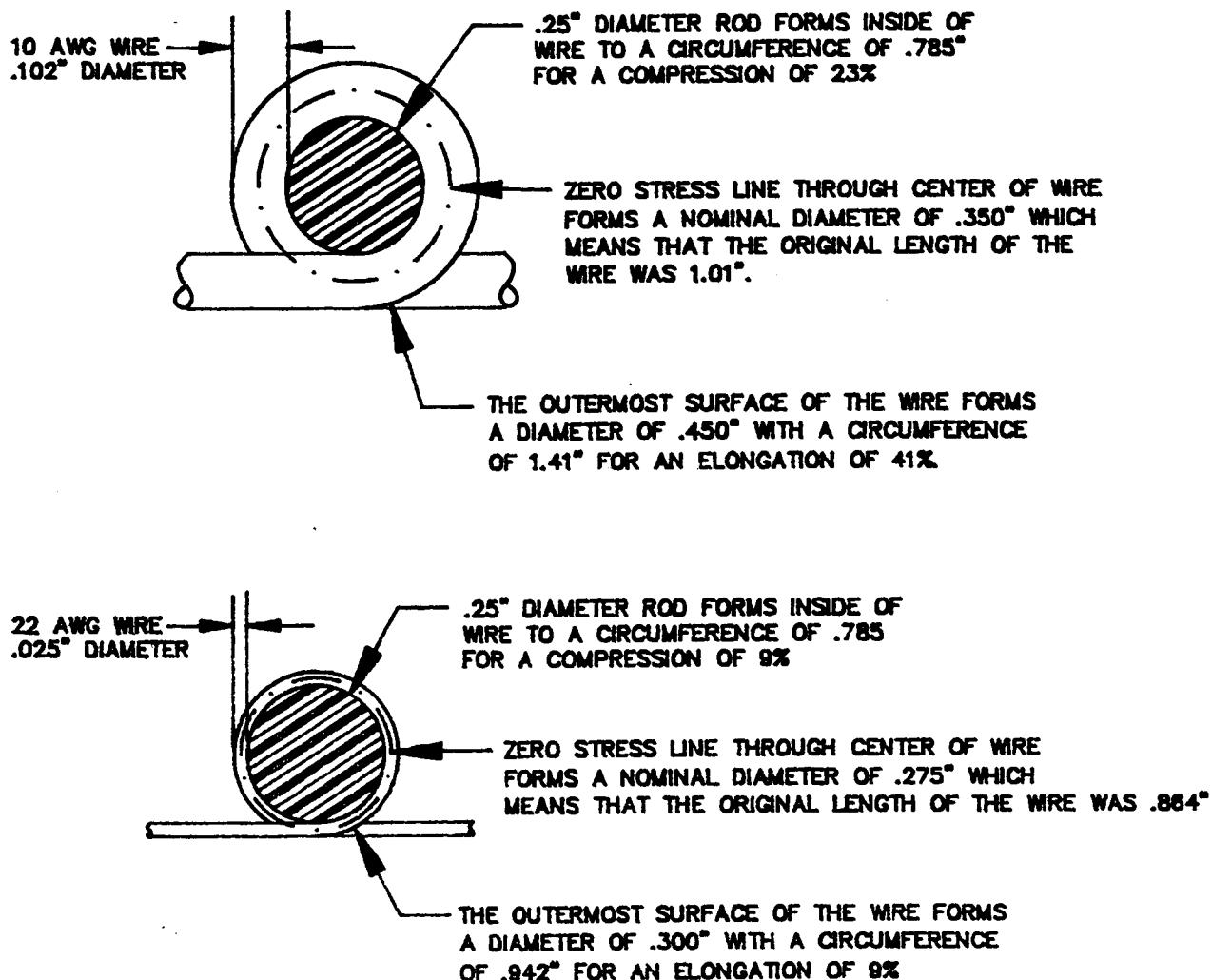


Figure 8-1. Wire Stresses Versus Wire Diameter.

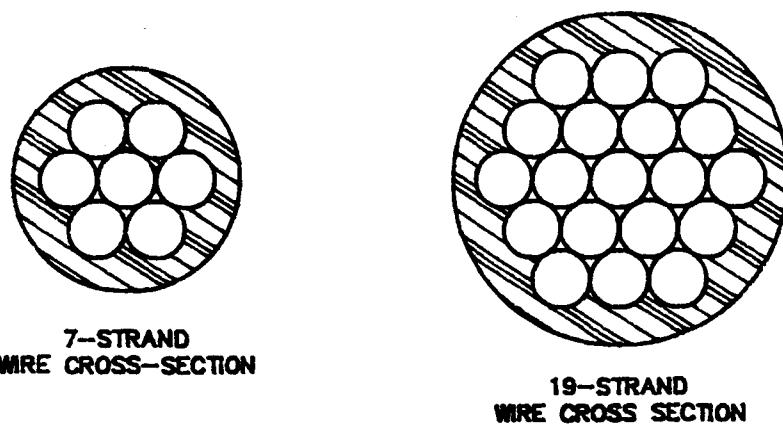


Figure 8-2. Common Layup Configurations for Stranded Wire.

successful cables were built and laid. I found the story of the fabrication and laying of the first transatlantic cables fascinating; I recommend it to you for times of poor flying weather.

The wires that are found on the early airplanes are a product of the 20's, 30's and 40's when rubber was extruded over the twisted strands. Cotton was braided over the rubber and then sealed with a kind of shellac. If any of you have been involved in the restoration of a 1940's airplane or automobile, you have had a first-hand experience with this stuff! Any of this wire still in place today has become brittle and insulation may fly off of the wire in little pieces when the wire is flexed. The cotton over rubber insulations had another disadvantage. Being organic, fungi liked this stuff a whole lot! Military equipment of the period had to be treated with special fungicides to prevent death by athlete's foot. The 50's and 60's brought us the petroleum based plastics for insulation; much more stable with age and they gave the fungi heartburn. Derivatives of these materials are still around today in the form of PVC plastics used in most appliance and automotive wiring insulations. In the 60's, the wire of choice was insulated first with PVC and then a thin jacket of nylon was extruded over it. This combination had a service life of

5 to 10 times longer than the cotton braid over extruded rubber. Military aircraft wire of this era might include some synthetic fiber over-braids either as a top layer over the PVC or perhaps between the layers of PVC and nylon. This type of treatment provided additional abrasion resistance.

I made a statement about plastic insulations not being a 'perfect' barrier for the protection of the wire inside. A good example of the phenomenon can be experienced firsthand: a piece of fish dropped into a ziplock baggie can be detected by the nose from outside the bag after a few hours of containment. Of course the nose is a pretty sensitive instrument; it can detect concentrations of some odors in concentrations down to a few parts per billion. Another example of the 'porosity' of plastics can be found in laboratories where precise amounts of some chemicals are to be dumped into the otherwise healthful environment in a cage of critters. A plastic tube containing the nasty stuff is run through the sealed environment. If one knows the make-up of the chemical and the plastic tube the migration rate of the chemical through the walls of the tube is very predictable. The dosage of the nasty stuff given to the hapless critters is known and controllable. This is the reason for the phenomenon I mentioned

previously: unplated copper wires will corrode in spite of an intact layer of PVC plastic insulation!

Another breed of plastics was brought into the marketplace about 1960 and they all started with "TEF". The first was teflon and it was truly an amazing advancement. The stuff stayed flexible and soft down to the big minus temperatures and would not melt in 400-500 degree F environments either. The major disadvantage was its abrasion resistance in that you could dig into the material with your thumbnail. However, because it was so slick, it was easily bundled inside pvc jacket for general abrasion protection of multiwire avionics harnesses. It was (and still is) expensive wire, partly because of the need for silver or nickel plating the copper before extruding the teflon over it. I'm not sure of the exact reason but I believe it involves a reaction between tin and hot teflon in the process which extrudes the insulation onto the wire.

So much for history. If you were going to pick a wire insulation for a new or restored airplane, the choices are really rather few and happily so. But let's review the requirements that we want to place on the wiring insulation for an airplane. The most obvious application of insulation is to keep the electrons from getting out of the wire before they get to the other end! So the first requirement is to prevent the wire from coming into undesired contact with conductors of electric current which includes other wires or metalic parts of the airframe. The next requirement is that the insulation must be durable to a suitable degree. A properly installed wire should not be subject to much mechanical abuse but just the act of installing a wire or wire bundle can inflict damage to a poorly insulated wire. Insulation creep-back or melting while soldering a wire is undesirable. The insulation must have a reasonable characteristic at temperature extremes. When subjected to the lowest expected operating temperature, the insulation must remain flexible enough so as not to crack under stress; at the upper extreme, it must not melt, deform or lose so much strength that the wire migrates within.

Wire migration inside an insulating jacket is a rare phenomenon but I have seen it happen. We had a rash of OMNI antenna failures in a series of aircraft at Cessna back in the early 60's. The problem centered on shorted coaxial cables used to interconnect the antenna on the vertical fin with the receiver on the instrument panel. The cable routing called for a particularly tight radius bend of the cable through some structure. This bend caused the center conductor of

the coax to put a stress on the insulation such that with time, vibration, temperature cycles, etc. . . . the wire slowly moved from its nominal center within the center of the cable outward to the braided shield until it finally penetrated the insulation and shorted. The process took two to five years to occur. A change of the material from which the cable was made combined with a rerouted installation path cured the problem. Most coaxial cables today use a stranded center conductor which is very unlikely to migrate.

The last requirement is that the insulation should have some longevity in the environment to which it is exposed. This relates back to the design service life and ideally your airplane should last forever, right? Well, perhaps not but a goal of 20 years is not unreasonable. There are few variations of environmental extremes within the airplane itself. Wires routed through spaces not in the engine compartment experience temperature extremes ranging from the coldest to the hottest that the weather and the sun can produce. Minus 40 to plus 180 degrees F is a reasonable range to consider for these spaces. Wires in the engine compartment are subject to radiation and conduction heating from engine components that may take a wire to 300 degrees F or more! However, it is usually not difficult to preclude the possibility of this upper extreme. Resistance to chemical attack is a factor as well. Wires can be subjected to the effects of fuel, oil, hydraulic fluids, deicer fluids, products of combustion, topped off by cleaners and solvents used to remove dirt and oil. An especially reactive addition to this recipe is ozone which creeps out of the fitting on the ignition system.

PICKING THE WIRE SUITABLE THE TASK

The wire of choice today is insulated with a material called "tefzel". The wire is put up for the military under specification MIL-W-22759. Tefzel is a close cousin to teflon. It proved to be preferable to teflon for most applications due to its superior abrasion resistance; you cannot dig into it with a fingernail like you can with teflon. Its temperature rating is, I believe, somewhat lower than teflon but there should be no routing for wire in an airplane that will push tefzel even close to its limits! MIL-W-22759 wire may be available to you in assorted sizes and lengths from avionics shops. However, MIL-W-22759 is not the only wire suited to aircraft applications; it just happens to be the wire of choice. Let's look at some options:

PVC insulated wires can be used quite satisfactorily in most areas except the engine compartment. There are

two common types of PVC insulation available. One is rated at 80 degrees C. The other, having been exposed to intense radiation during manufacture is rated at 105 degrees C. The lower temperature wire is not quite as tough and "creeps" away from a soldered connection rather badly. If you plan to use only crimped connections, the lower temp stuff is okay. If you want to use soldered connections (see section on wiring interconnections) then the irradiated, higher temp variety is recommended. Teflon wire may also be found at reasonable prices through surplus dealers. Teflon insulation is a little tougher to strip neatly. This job is greatly facilitate by purchasing a pair of strippers with blades specifically designed for stripping teflon.

Some extra care should be used in installing either PVC or Teflon wires to prevent abrasion or localized pressures on the insulation. Adequate support and additional overwrap in potential abrasion areas will take care of the first hazard. Localized pressure is a condition that is not so well understood. Most plastics, if kept under a constant pressure above a certain value, will flow over time to relieve that pressure. The pressure can come from some obvious source like bending a wire bundle around a corner. Even if the bundle is immobilized, a constant unrelenting pressure can cause the insulation to flow from under the pressure point and cause one or more wires to become uninsulated. If that corner happens to be some aluminum structure in a metal airplane, then the system supported by the compromised wire will cease to function when the breaker pops. Abnormal pressure can come from other sources; some are pretty surprising. I have seen string ties and the plastic tye-wraps applied so tightly to a bundle of wires that the insulation on the wires was extruded sufficiently to expose the conductors within! Use some care and judgment when "immobilizing" your wires lest you strangle them as well!

EXPLORING THE "UNKNOWN"

Suppose you have a spool of good looking wire in your hot little hands and you would like to use it in your airplane. The spool bears no markings that would tell you what the wire's pedigree is. You can tell some things about it for yourself. First, strip back the insulation and check the interior stranding. Is it 7 strands? Okay. Is it 19 strands? Great. Is it a plated wire and not bare copper. Is the wire indeed made of copper? It may seem to be a silly question but if you shop around military or industrial surplus outlets you should be wary of unmarked or otherwise unidentifiable materials; people have had all sorts of special weird wires

made. Now about the insulation. . . Tin the strands of the wire with a soldering iron and some solder. Does the insulation crawl back from the hot end or drip? If it doesn't melt with normal soldering procedures, try touching the iron directly to the insulation. If it doesn't melt then the wire is probably insulated with one of the "TEF's". Soak a piece in Avgas or Mogas for a week; does the insulation swell up or get soft?

If the stuff is obviously not teflon or tefzel, but all the answers to the foregoing questions are ones you like, then it's probably okay for everything except the hottest spots under the cowl. I'll never forget an experience about 23 years ago when I was moving with a pregnant wife from Pittsburgh, PA, back to Wichita in the dead of winter. I figured I'd do a tune up on the old '57 Chevy before we left just as a precaution against ignition problems. Went down to the parts store and bought the usual goodies. Then I saw "it"; a display of beautiful red transparent ignition wires. What the heck, the old harness WAS a couple of years old. . . .

About a 100 miles down the road the car began to run badly and smell worse! We nursed it into a little town in West Virginia and opened the hood. The insulation on the pretty red harness was dripping onto the exhaust manifold, causing much smoke and letting all of the sparks out of the wires too. Bought a new (and very expensive) harness made of the ugly ol' black stuff; got to install it in front of a parts store in the dark and in the rain! Moral: If you don't know what kind of product it is then find out before you put it on your airplane.

Wires come in made up assemblies too. You can buy spools of multi-strand cables with a jacket extruded over the whole bundle. It's handy to be able to pull a smooth bundle of wires that are already protected from abrasion though the netherworld of structure under the floorboards of an airplane as opposed to a hand made bundle that is all lumpy with string ties or tye-wraps! You can almost never find exactly the bundle you want; made up from say, two 14 gauge wires, three 16's and eight 22's. There is a way to make use of these pre-bundled cables which I will describe later in this section.

SIZING A WIRE TO THE TASK

There are two factors to consider when selecting a wire size. To most folk, the first is pretty obvious. One must consider the CURRENT that the wire will carry. The second and not so obvious is the VoltAGE DROP in

the length of wire required for a specific task. Example: 14 AWG wire used in house wiring is supplied from a 15-Amp breaker. The implication here is that this size is adequate for supplying loads up to the rating of the breakers: 15 Amps. But suppose you wanted to run a 1500 Watt electric heater in your hangar and the hangar was 250 feet from the house. The heater will draw 1500 (Watts) divided by 115 (Volts) which equals 13.1 Amps (See equation 4 in Figure 1-3 and solve for Amps. While we are at it, let us solve for the resistance of the heater. Use equation 5. Plug in 115 Volts 1500 Watts and solve for Ohms. I get 8.82 Ohms. More on that later.) Ha! let's go get a box of 14/2 Romex house wire and run it out to the hangar, it will carry 13.1 Amps with no problems. . . .

Looking at the wire data table in Figure 8-3 we see that 14 AWG wire has a resistance of 2.53 Ohms per 1000 feet. It is a 500 foot round trip to the hangar and back. Then perhaps we need to add another 50 foot round trip from the outlet on the back porch to the breaker box. Let's see. . . . 550 times 2.53 divided by 1000 is 1.39 Ohms. Adding that to the figure of 8.82 Ohms for the heater, we get a total circuit resistance of 10.2 Ohms. Using equation 2, with 10.2 Ohms and 115 Volts plugged in, we can solve for a new circuit current of 11.27 Amps. Using equation 1 again we can calculate that the Voltage across the heater is 8.82 Ohms times 11.27 Amps or 99.40 Volts. Using equation 4 we can calculate that the heater with 99.40 Volts at 11.27 Amps dissipated in it will generate only 1120 Watts. There is 115 minus 99.4 Volts or 15.6 Volts dropped in just the wiring! Using equation 4 again: 15.6 Volts times 11.27 Amps is 175.8 Watts of power (or 13% of the total) lost in the wire in spite of the fact that the wire is not being overloaded!

Let's assume for this example that we were willing to lose 5% of our energy in conducting it from house to hangar. Looking at equation 6 in Figure 1-3, we note that power is the product of Ohms times Amps squared. If 5% of the total energy in the circuit is allowed to be dissipated in the wire then we can say that Watts dissipated in the heater is 19 times greater than the Watts dissipated in the wire. Using equation 6 twice, we can say that 19 times the wire Ohms times the square of the Amps of current is equal to the heater Ohms times the square of the Amps. Divide both sides by Amps squared and we are left with: Heater Ohms is equal to 19 times the allowable wire Ohms. Solving for wiring Ohms we get $8.82/19 = 0.46$ Ohms.

If our 550 foot run of wire can have a drop of 0.46 Ohms then a 1000 foot run of the same wire would have: 0.46 divided by 550 times 1000 or 0.84 Ohms. Looking in the table again we see that an 9 AWG wire is smallest wire that will yield a resistance of 0.84 Ohms per 1000 feet or less. 9 AWG is not one of the commonly stocked sizes so we would probably have to buy 8 AWG. In short runs inside a house, 8 AWG wire can be loaded to 40 Amps! But because of Voltage drop considerations, we need to use 8 AWG wire to supply a 13 Amp load at the remote hangar location. There is another lesson here. . . suppose we were to run 230 Volts to the hangar instead of 115. Would 14 gauge wire handle a 1500 Watt heater with less than 5% loss of power in the interconnect wiring? Does this exercise suggest why a 28 Volt electrical system might have some advantages over a 14 Volt one?

Remember the example of Voltage drop in the landing light circuit in Section 1? The same reasoning was applied to that case as the one we just did on the hangar heater. Let's look at the wire table again and see what it has to tell us. The first column is the AWG No. which stands for American Wire Gauge Number. Don't ask me why the 0000 and the 000 wires are in the table that way. One would think that they could have made the four zeros guy equal to AWG 0 and then moved all the rest of the numbers down accordingly. . . zero, zero, zero what kind of number is that? Especially for a BIG wire! Any how, the next column is the diameter of the wire in Mils or 1/1000th of an inch. The next column is the area in "Circular Mils" (??????) Here's another toe stubber. Note that the circular mill area is the simply the square of the diameter value in mils. Just to make life easier for someone, somewhere, they decided that the area of a wire didn't have to be expressed in real area by including pi in the equation; just squaring the diameter would yield a number that was PROPORTIONAL to the real area. Good enough for the purpose of those who would learn to speak "wire-ese" and confuse the rest of the world. The fourth column is based on the real cross sectional area of the wire and states the resistance of a strand in Ohms per 1000 Feet. The last column is also based on real world area and gives Feet per Pound.

Note that the numbers for diameter apply to a solid, single strand of wire. However, for a stranded wire to be rated as 22 AWG it must have the same electrical characteristics as 22 AWG solid wire. The total cross

Wire Table						
AWG No.	Dia-meter Mils	Area Circular Mils	Ohms per 1000 Feet	Feet per Pound	10 Deg C rise current	CMA per Amp
0000	460	211,600	.049	1.56		
000	410	167,800	.062	1.97		
00	365	133,100	.078	2.48		
0	325	105,500	.098	3.13		
1	289	83,700	.124	3.95		
2	257	66,400	.156	4.98	100A	664
3	229	52,600	.197	6.28		
4	204	41,700	.249	7.91	72A	579
5	182	33,100	.313	9.98		
6	162	26,250	.395	12.6	54A	486
7	144	20,820	.498	15.9		
8	129	16,510	.628	20.0	40A	413
9	114	13,090	.792	25.2		
10	102	10,380	.999	31.8	30A	345
11	91	8,230	1.26	40.1		
12	81	6,530	1.59	50.6	22A	296
13	72	5,180	2.00	63.8		
14	64	4,110	2.53	80.4	15A	274
15	57	3,257	3.18	101		
16	51	2,583	4.01	128	12.5A	206
17	45	2,048	5.06	161		
18	40	1,624	6.39	203	10A	162
19	36	1,288	8.05	256		
20	32	1,022	10.2	323	7A	146
21	28	800	12.8	400		
22	25	642	16.1	514	5 A	128
23	23	509	20.3	648		
24	20	404	25.7	817		

Figure 8-3. Wire Table for American Standard Wire Gauges

sectional area of the strands must have a circular mil area (CMA) of 642 or perhaps a little more. This means that the resistance and weight of the stranded wire will be the same as for the solid wire. The only thing that is **not** the same is the diameter. A stranded wire will be slightly larger in diameter than its single strand cousin.

Here are some other things to note about the wire table. First, every three steps in wire gauge corresponds to a factor of 2 in the CMA of the wire. 13

AWG wire is one half the CMA and twice the resistance of a 10 AWG wire. 19 AWG wire is one-half the resistance and twice the CMA of 22 AWG wire. Second, note that 10 AWG wire is almost exactly 1 miliOhm per foot. And last, note that 10 AWG has a diameter of .1 inch. With these three facts committed to memory, you now have a wire table in your head! Suppose you were trying to figure the suitability of 16 AWG wire for some application. Since it is six steps from 10 AWG its resistance will be four times that of 10 AWG wire or .004 Ohms per foot. If you are trying

to figure a problem involving 18 AWG wire you know that 19 AWG is nine steps from 10 AWG. Take one half for every three steps. . . . 1/2, 1/4, 1/8 the CMA and 8 times the resistance of 10 AWG or 8 miliOhms per foot. Drop down about a third of the interval between 19 AWG and 16 AWG resistance and you have about 6.66 miliOhms per foot for 18 AWG. Referring to the wire table again we read the real number to be 6.39 miliOhms per foot. . . . 6.66 miliOhms is good enough for estimating; amaze your friends by appearing to have memorized the wire table!

Now, for picking a wire size I can tell you that no airframe system wire should be smaller in cross-section than 22 AWG just as a practical matter for ease of installation and mechanical durability. 22 AWG wire may be loaded as heavily as 5 Amps. Therefore, the breaker feeding a 22 gauge wire should be 5-Amps or less. Figure 8-4 shows a graphical depiction of the continuous load ratings for temperature rises of 10 degrees C and 35 degrees C of a single strand in free space. I have taken the numbers for selected gauges from the graph and included them in the data in Figure 8-3.

TWICE AS BIG DOES NOT MEAN TWICE AS STRONG

Lets explore the term 'capacity'. A close look at the numbers in the charts and graphs will show that just because a wire has twice the cross section of another wire, its capacity does not double. We know that no wire has zero Ohms resistance, therefore, some energy is lost as the flow of electrons run down the wire. The energy lost comes off in heat. The ability to reject heat is a function of the surface area of the wire which grows in direct proportion to the diameter. The apparent ability carry current grows with the area of the wire which is proportional to the square of diameter. So as a wire gets larger, its ability to reject the heat generated within does not go up as fast as its apparent ability to carry current. Hence the circular mils per Amp loading of larger wires is larger than small wires because the ultimate limit on a wire is its insulation and environmental surroundings which are temperature limited.

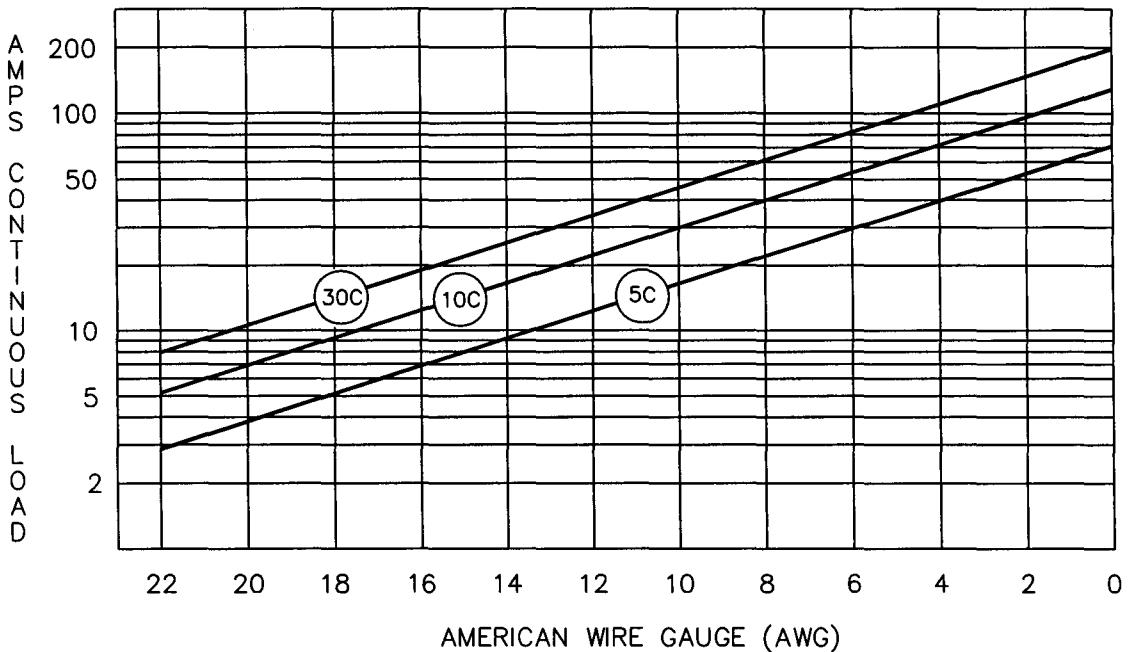
When the heating is tolerable, the wire does no damage to its own insulation when operated at rated capacity in its rated environment. PVC's are rated to 105 degrees C, "tef" types to 300 degrees C. The numbers are valid for a single wire supported in still air. Now, if we bundle some wires up such that some

wires buried deep in the bundle are pushed to near their maximum ratings, we might find it necessary to de-rate the wire further to avoid exceeding insulation temperature limits. Figure 8-4 also shows a derating curve for a 10 degree C rise in wire temperature. For bundling wires the free air temperature rise current ratings are often used to insure that the wire does not overheat when buried inside a bundle of other wires. Note that the rated capacity of a wire has only to do with the safety issue of wire protection and does not address any performance issues. Homebuilders may indeed have to de-rate a wire to insure that sufficient energy is conducted to the far end to insure proper performance of the powered device.

WHEN IS AN OVERLOAD NOT AN OVERLOAD?

Now that we've laid out the "rules" we can discuss how and why they are sometimes broken. If you were to run 10 Amps through a length of 22 gauge wire, does this imply that you are going to come spinning out of the sky trailing black smoke like the victim of a dog-fight? No, specially if the wire is short for low energy loss in spite of overload, well ventilated to control temperature rise, or is subject to an overload for only short durations. In fact there are specific cases where short term overloading is designed into an aircraft system and the excess losses are considered tolerable. The starter cable in an airplane is generally not sized to present an ideal situation with respect to energy lost in the wiring. The starter cable carries current for only a few seconds per flight and most designers will allow the losses in this wire to be "excessive" by normal standards. As a rule of thumb, I would consider a drop of 1.5 to 2 Volts in starter system wiring to be a livable situation if the cables are long and a weight savings can be realized. Looking at the numbers for this situation, suppose that the battery can deliver 200 Amps at 10 Volts and we'll say that a 2-Volt drop is to be experienced in the starter wiring at this level of current draw. This leaves 8 Volts for the starter to run on which will probably get you a successful start in all but the coldest weather. A two-Volt drop out of 10 means that 20% of the energy available from the battery is lost in wiring. Another 20-25% is being lost internal to the battery itself! Remember from earlier discussions that the battery is chemically a 12-Volt device and its inability to deliver 12-Volts under heavy load is due to internal resistance (read internal losses).

Necessity has been called "the mother of invention" but I suggest that compromise is "the father of success". The point of this discussion is that the rules are not



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Figure 8-4. Wire Current Capacity Versus Wire Guage and Temperature Rise.

carved in stone and you as the system designer can make some intelligent decisions as to when the rules are bendable.

SPECIAL WIRES FOR SPECIAL APPLICATIONS

I haven't mentioned shielded wire yet and I won't go into details in this section because shielding is part of the topic on electrical noise to be thrashed severely in a later section. As a portent of things to come I will have you ponder this statement in the interim: "The magneto wires are the only airframe electrical system wires worth shielding and in their case, the shield will be used in an unorthodox fashion. Only selected avionics and instrumentation wires require shielding and these should be disclosed to you in the instructions of the manufacturer of the product to be protected." More on this later.

WIRE BUNDLE FABRICATION AND INSTALLATION

Looking though the airplanes at Oshkosh, one can find many examples of ways to wire (or not to wire) an

airplane. Some projects show up with neatly sculptured wiring while others look like the web of a drunk spider created in a hurricane. Both techniques are obviously functional, at least to the extent that both airplanes made it to Oshkosh! And to some extent, the spider web is easier to modify: every wire is mostly visible and accessible. But there are at least two good reasons for taking the time to do it up tight. One is that it simply looks better. If you have a hand-crafted finish on your airplane that you are particularly proud of, there's no reason not to have neat wiring to go with it. The second reason is more important. Consider the fact that a single 22 gauge wire hanging in space between two points is free to move with g-forces and vibration. A single strand of wire is not especially strong by itself when hung out in the breeze and is more vulnerable to accident. A formed and secured bundle of wires yields strength in numbers. A half inch diameter bundle of wires may be made up of many strands of different gauge wire, no one strand of which is very rigid. However, the sum total of the wires is quite resistant to flexing and individual strands are much less subject to being snagged and damaged by accident.

MAKE YOUR MISTAKES ON PAPER

In planning the various issues of The 'Connection, there was a section to be devoted to the discussion of schematics, wiring diagrams and general tips on wire installation. Many of you are working on the electrical systems installations now. So, what follows is a preview of the material to be presented in greater detail in follow-on issues of The 'Connection.

The first step in wiring your airplane is planning. Certainly if you can make detailed drawings of your intended installation, by all means do so. Perhaps no drawings are needed if you can plan out the system in your head but some sketches would be helpful to most of us! Your wire drawings are most helpful in this planning effort. I might make a distinction here between schematics and wiring diagrams. Figures 7-7 and 7-8 are examples of the contrast between the two kinds of drawings. A schematic is the kind of drawing used most often in this publication; types of components and their interconnections are depicted without regard to the placement with respect to each other or the airplane. The wiring diagram is most useful for installation information while the schematic is the best for acquiring an understanding of how a circuit functions. You should make both types of drawings in planning your electrical system and its wiring. A set of schematics are planned for a later issue but for now, begin with a loose leaf binder and make a schematic for every individual system you plan to install beginning at the bus. For example, you should end up with a single page to describe the connections for the landing light beginning with the landing light circuit breaker, through the switch and to the fixture to ground. Show any intended disconnects in the wires such as a wing root connector to permit removal of the wing. Another separate page should be used to describe the alternator system with its two breakers, field switch, Voltage regulator and o.v. relay. Still another page might have the battery and battery master switch wiring. By depicting each system on its own page, any one schematic is relatively simple and one may be revised or replaced without messing up a big, single sheet drawing. Until schematics are published in The 'Connection, look though a service manual for a single engine Cessna or Beechcraft. These are good examples of what a book-form schematic should look like.

After each schematic is done, pick wire sizes and appropriate breakers for each circuit and give each wire segment a number on the drawing, even if you choose not to number them in the airplane. It is a good

idea to number the actual wires as well; close to where they terminate at each end. The Digi-Key Catalog lists rolls of narrow tape with the digits 0-9 for marking wires.

Begin a wiring diagram over a top view sketch of the airplane. For this you need a big piece of durable paper, the 24" wide Kraft or butcher paper works well. If your airplane plans are large, but less than 36" wide, consider having roll sized Xerox copies made at a blue print company. The wire routings can be made directly on actual views already provided by the designer. The wiring diagram needs to be fairly large because a lot of detail is squeezed into the area around the wire bundles.

Planning the wire bundle routes is something like planning major streets though neighborhoods. The object is to decide where the bundles will allow short fan-outs of the leads to individual components and instruments. The wire route decisions are also driven by support and access considerations. That is to say, you don't want long lengths of wire, bundled or not, hanging free in space. Further, wire routes must follow paths that are accessible to you after the airplane has been assembled. Some designers build wire routing considerations (like conduits and extra holes) into their airframes. When areas are likely to become inaccessible after assembly, they will have you route wires or perhaps install conduits during the airframe fabrication process.

ALL ROADS MAY LEAD TO ROME BUT ALL WIRES LEAD TO THE BREAKER PANEL

I would start wire routing plans at the circuit breaker or fuse panel. Every electrical device in the airplane has wiring that connects to the bus. Major routes to the engine compartment and any remotely mounted avionics components must be decided. In many designs, the battery is installed on opposite ends of the airplane for weight and/or volume considerations. If a conduit system such as I have described in the previous section on grounding has been used, the major wire routes are already established.

Once the major wiring highways are mapped in your airplane, how does one get started? The heavy iron bird builders make their harnesses on harness boards that are evolved and fine tuned over the first few production runs of an airplane. Since you are probably in a "production run" of one only, your wire bundles will have to be developed in place on the finished

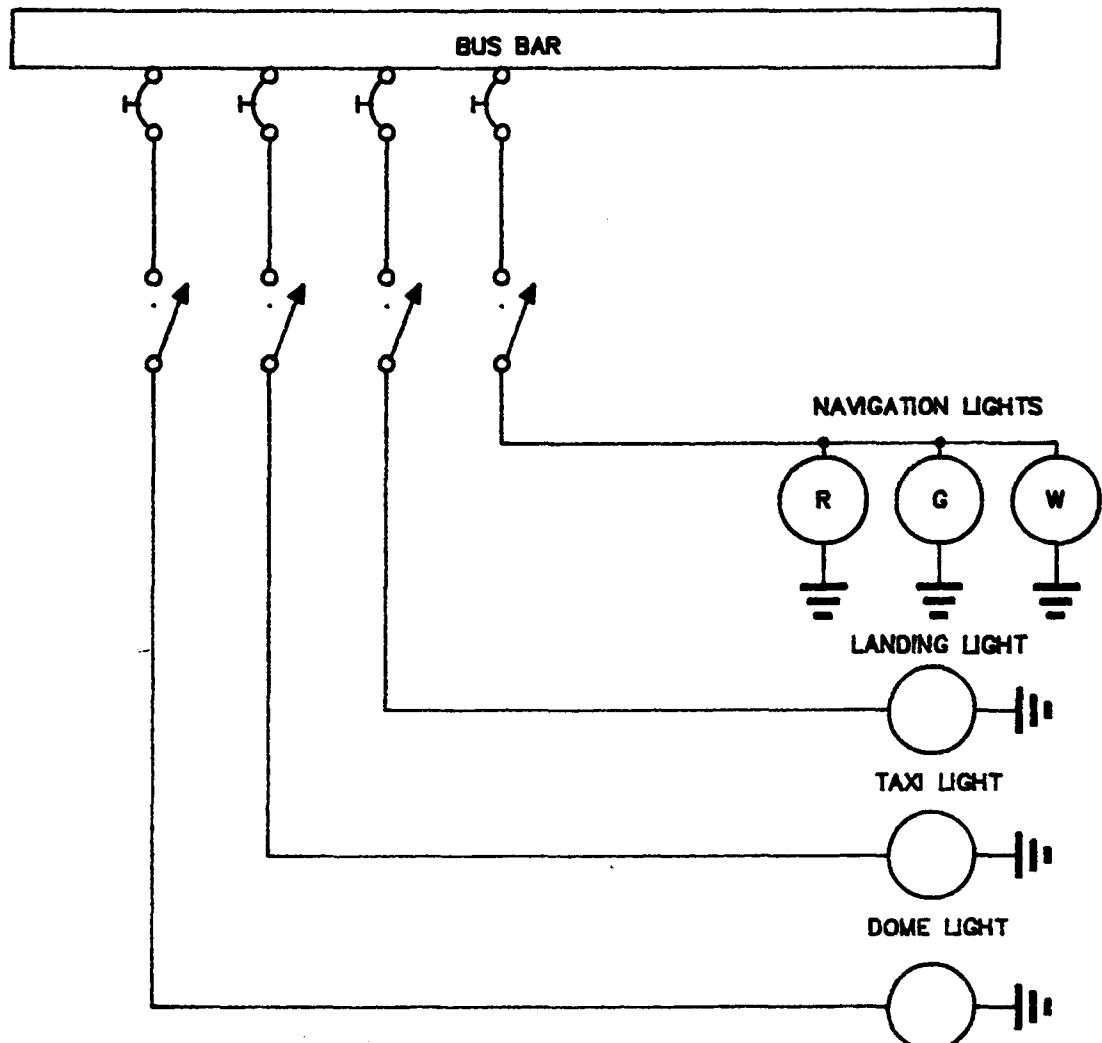


Figure 8-5. Schematic Diagram, Lighting System

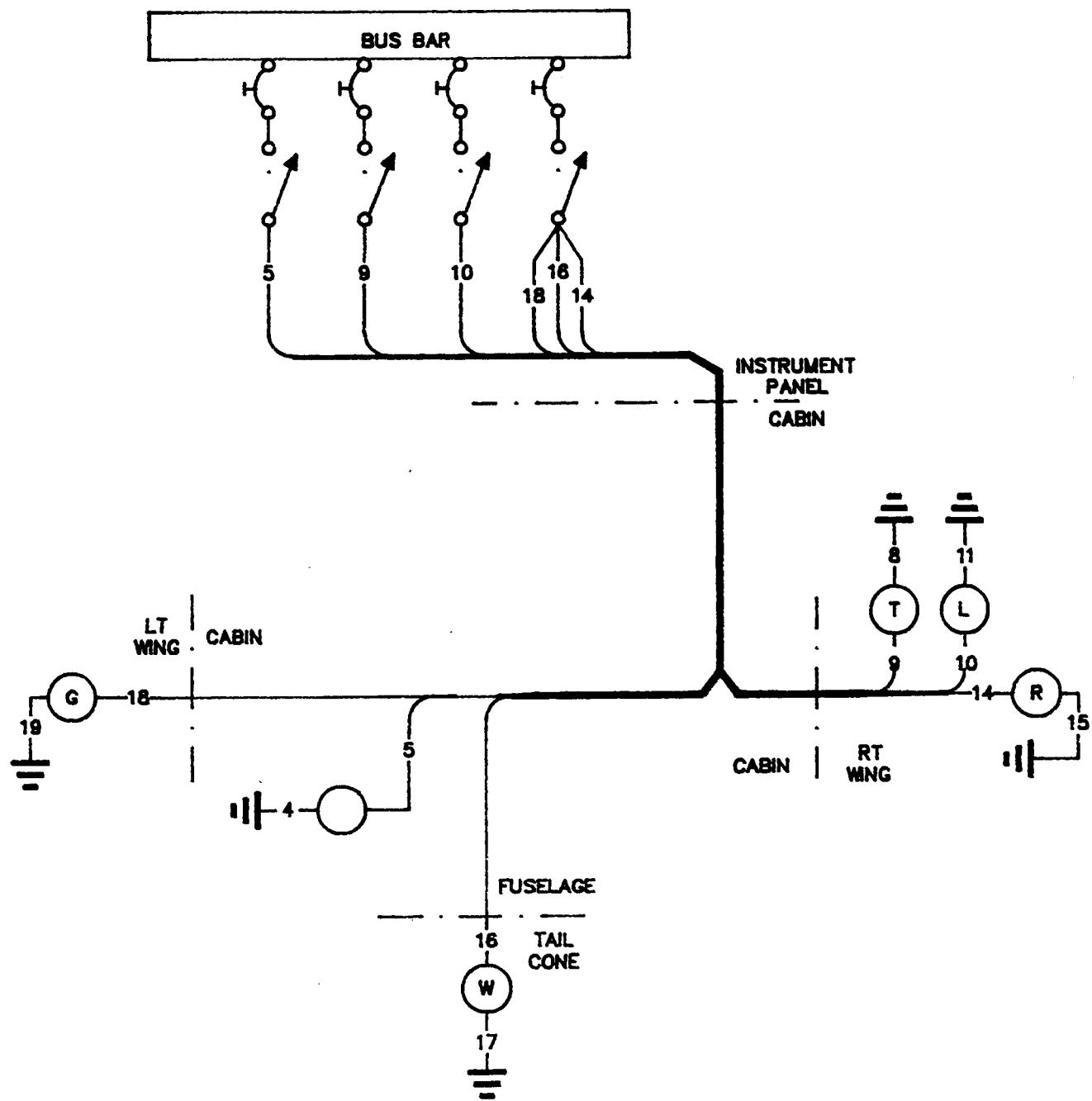


Figure 8-6. Wiring Diagram, Lighting System.

product. The first strand of wire laid into place is not likely to stay by itself! Nor the second, or third Until a number of strands are tied together, the 'highways' may be more like wandering streams, very poorly defined. There are a few simple tools that make it easy: string or cable lace, tye-wraps, and masking tape. String specifically designed for lacing cables is made by a number of firms. The stuff is usually made of Dacron and is waxed. It is often supplied in a thin, flat form. For temporary tying while building a wire bundle, ordinary cotton string will suffice. If you plan to use string as the major bundle tie material, the synthetic cable lace is called for.

There is another wire tying product in the form of a flat plastic strap with a sort of ratcheting buckle on one end. These devices are single-shot in that once they are installed up tight, they cannot be loosened. Tye-Wrap is a trade name for one of the major manufacturers of these things but many people in the Wichita aircraft industry refer to all brands of plastic ties as Tye-Wraps. These may be found in several of the catalogs listed in Appendix A. Masking tape is another temporary fastening device that will be useful in routing wires.

CONSIDER THE PREASSEMBLED WIRE PRODUCTS

I mentioned pre-bundled cables earlier. These materials are widely used in the communications and control industries. It is not unusual to find large spools of multi-conductor cable in surplus houses. Most multi-conductor cables you will find in surplus come from situations where 22 or 20 gauge wires are used in quantity. First, if you find a bundle of 20's, a 20 gauge wire can be substituted for a 22; there is no prohibition for making a wire larger than necessary except for weight considerations, which in this case are minuscule. The 20 gauge wire which replaces a 22 gauge wire may also be protected with a 5 Amp breaker. As a hypothetical case, let us assume that you need the combination of wires I mentioned earlier to run from the switch panel to the engine compartment of an Eze: two 14 gauge wires, three 16's and eight 22's. Looking into the wire table, we find that a 16 gauge wire is four times the CMA of a 22 gauge wire and a 14 gauge is seven times the CMA of a 22 gauge. Two 14's will require fourteen strands of 22, two 16's will require eight more and the eight 22's bring the total to 30. In my trusty wire catalog I find that cables having fifteen pairs of 22 wires can be had in an outside diameter of just over 0.5 inch! The wires in the prefab cable are color coded to

facilitate assembling the multiple 22 gauge wires into equivalents of their larger cousins. Paralleling of strands into larger combinations assumes two things: first, the wires must be very close to the same length (no particular problem when they come prebundled) and second, the joints at the ends are of very good electrical quality (to be covered in detail in the next section).

If you are using conduits, pull wires into these first with plenty of overhang at each end for later connection. Don't make conduit routed wires into tied bundles, just pull (or push) them through all at one time. It is much easier to do this than to try put the last wire though a conduit that already has 15 or 20 wires already in place! This same admonition applies to situations where conduits are not used but the routing is long and difficult, like down the fuselage of a Long-Eze. In this case, bundle up the portion of the wires that runs through the airplane's netherworld and pull it in one whack. Then beginning with the breaker and switch panel, route wires from this most densely populated area out to the equipment to be powered.

While the bundles are first taking form, combinations of string, tape and tye-wraps may be used to hold them near their final configuration. I often put tye-wraps pulled up tight on a wire bundle to hold it in shape and cut them off later as more wires and new tye-wraps are added.

KEEP 'EM DANCING TOGETHER

Once your bundles are complete they should be mounted to the airframe often enough to prevent them from flopping around. There are various techniques for accomplishing this. A classic wire retainer is the "Adel" clamp, named in honor of the company that used to make most of the wire and tube clamps used here in Wichita. They are supplied to the military under specification MS21919. These are metal strap clamps lined with rubber or plastic. An example is shown in Figure 8-7. These clamps are available in 1/16th inch increments from 3/16 up to sizes larger than you'll ever need for wires. The size is depicted in their part number by the last digits. A MS21919DG6 is for gripping wire bundles 6/16" or 3/8" in diameter; an MS21919DG12 is for 3/4" jobs. These clamps are designed to be used directly on a wire bundle or piece of tubing without need for additional protection of the bundle or tube from the clamp's metal structure. Check the catalogs and the Fly Market in Oshkosh for these critters. You've got to learn to love these things!

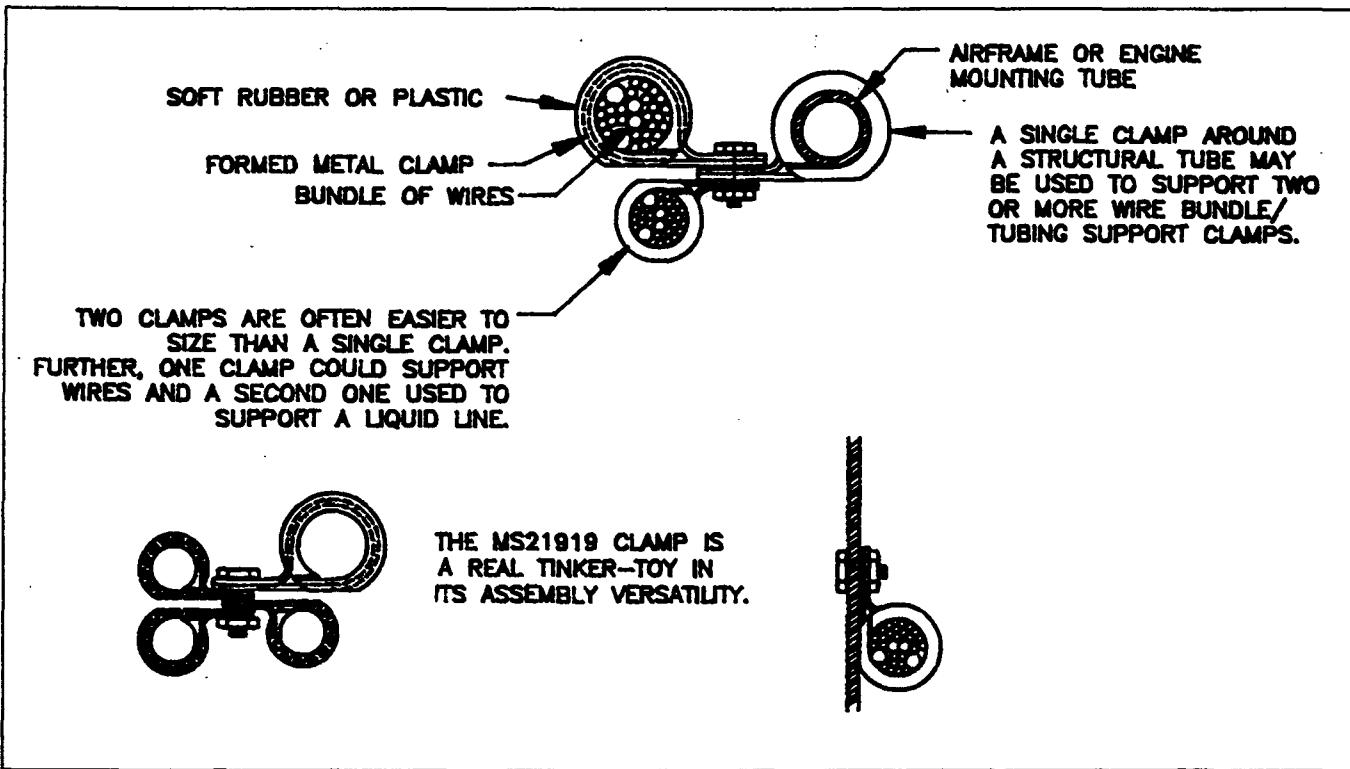


Figure 8-7. Applications of the MS21919 Padded Clamps.

If the clamp is properly sized to the job, it takes three hands to hold one closed with a pair of duckbill pliers, insert the screw from one side and put the nut on the other. I don't know how many screws I have launched into oblivion when the duckbills slipped! However, they are an excellent product and worth learning how to use.

There are also wire bundle clamps made of plastic which are acceptable everywhere except the engine compartment. As a general rule, I wouldn't use plastic clamps in any area of the airplane that is not periodically looked at and touched. Wire routings with inaccessible or seldom inspected locations should use the padded metal clamps.

A major tenet of wire bundle immobilization states, "Never support a bundle of wires in a manner that presses the primary insulation of the wires against the structure or a metallic clamping device". In a welded tube airplane or in the engine compartment, it is perfectly acceptable to string tie or tye-wrap a bundle along a structural tube. At each tie point, a

buffer between the clamping device and primary insulation of the wires must be provided.

Consider using heat shrinkable tubing available from many of the sources listed in appendix A. Slip a short piece of heat shrink over the wire bundle for each tye-wrap location and shrink it down in the proper location as you install the tye-wrap or clamp. You might even want to use two pieces of heat shrink per location. Pick a larger size for the second piece if necessary; two layers of tubing will provide enhanced abrasion resistance.

If you are using a prefabricated cable material discussed previously, the extra protection is already in place and these bundles may be tied directly to structural tubes. Caution with those strings and tye-wraps: just snug 'em up, don't strangle the bundle.

In a fiberglass airplane laid up over foam, I have successfully used rivnuts installed through the plies as though they were sheet metal. The resulting threaded hole then provides mounting support for wire bun-

dles. Speaking of rivnuts, the term "rivnut" is the trademark of the manufacturer that pioneered the technology, the name escapes me at the moment. Since the orgininal products were brought onto the market, many similar products have appeared. Most are quite good but beware of cheap imitations. I have personally tested some of the offerings at the Fly Market and found them lacking. In general, don't use any rivnut that is made of aluminum unless you have a reputable manufacturer's application data for the product and you adhere to it. The best rivnuts are made of mild steel.

Common practice dictates that you do not tie wires up with any liquid lines such as brake fluid, primer lines, oil pressure or fuel pressure gauge lines. The prohibition against this is simple: a wire burning in two from some electrical fault could cause a leak of a flammable liquid and ruin your day completely. The likelihood of this scenario is extremely remote. Your wires are will be protected against burning by proper use of breakers and fuses. Most installations I have seen by homebuilders have liquid lines in more danger of leaks from abrasions due to poor support than from electrical faults! Were it my personal airplane, I would have no problems with tying the liquid lines into the wire bundles that run down the sides of airplanes like Long-Eze's if it will ensure the mechanical security for both the wires and tubes. Of course, if you are using a conduit ground system, you don't want to run the liquid lines down the limited conduit space. In this instance the conduit may become a structural support for liquid lines. As always, use clamps, tye-wraps and or string to hold liquid lines to the outside of the conduit. Use the same care with liquid lines as with wires; use a buffer wrap or padding to prevent the liquid line from chafing on the conduit at the support points.

As an aside on this topic, the only liquid line that runs up the side of a Long-Eze containing a really dangerous fluid is the tubing used to plumb up the engine primer. Consider an electrically operated primer like the Beech Skipper (and possibly others).

This system uses a small electrically operated valve in the engine compartment to connect the pressure side of the electric boost pump into the primer system though a small orifice. Therefore, primer lines are not brought into the cabin. The engine is primed by a few seconds operation of the valve while the boost pump is running. I like that concept whole lot!

A CONNECTOR ADDS THREE NEW "JOINTS" TO EVERY WIRE

There are a number of popular designs for circuit breaker panels and switch panels that can be preassembled on the bench. Many use stub pendant cables terminated in plastic connectors with crimp-on pins to facilitate later installation in the airplane. Personally, this is a mixed bag. Every connector introduces three joints in each wire passing through the connector. One for each crimp to a pin and a third where the two pins mate with each other. If properly applied, connectors can be a great help; the automotive world has been using wire bundle connectors for many years to facilitate prefabrication for later installation on an assembly line. However, if the connector installation technique is marginal, then many possible points of failure have been introduced. In the next few sections we will discuss wire termination techniques and the design of circuit protection systems.

LAST MINUTE HOT FLASH BEFORE GOING TO PRESS ..

Many of you have indicated to me by phone and mail that the Mil-W-22759 wire can be found in avionics shops but only in sizes used in avionics installations. The larger airframe sizes, particularly the large ones used for starter and battery cable are more difficult to find. Consider using electric welding cable available from most welding shops. It is only slightly heavier than the aircraft grade wire but it is quite flexible and easy to work with. Furthermore, its outer jacket is specifically designed for nasty environments!

Wire Termination and Connectors

I have been putting off writing this section until last; having difficulty coming up with the best words to describe some things that really need to be shown in pictures and/or demonstrations. We spent some of your subscription money last week on an accessory for our cameras; a bellows attachment that let us do some really close up photography on some small subjects. We're planning a series of slides for the seminars at Oshkosh '89 to show HOW TO and HOW NOT TO terminate wires. The needed details are beyond our present illustration capability and we're not set up yet to include photographs in this publication. So, until the photographic update of this section is in print, we'll take a whack at it with our best command of the King's English. . . .

The act of reliably connecting a wire to another wire or to an electrical component is probably the easiest task to accomplish in your wiring installation. But until you understand what you are trying to accomplish and master a few techniques for doing it, it's easy to make joints that come apart; usually at inopportune times! There are three requirements for making the lasting connection: first, the connection must be electrically sound. Second, the joint must be mechanically secure. Third, unless the metallic conductor exposed in the process of making the joint is located in a very benign environment it must be protected from the environment.

All of you have probably seen the crimp on terminals that are sold in virtually every hardware and automotive store. A plastic case containing an assortment of terminals along with a crimping tool can be had for a few dollars. And, if you understand how they can be properly applied, even these el-cheapo tools and their terminals may have application in your electrical system installation. You may also find yourself faced with terminating a bundle of wires into a connector of one or more pins that mates in turn with one of your system's components. Strobe light power supplies come to mind as an example. Certainly, your avionics black boxes will have multi-pin connectors on the rear which you will have to deal with. Many times these units will come with some verbal or illustrated instructions for the application of connectors, but more often they do not. They were originally marketed to the aircraft manufacturers and fixed base dealers who, after they had fotted up their first few installations, presumably learned how not to fotch up the rest of

them. Since many of you are only going to want one shot at this, let us see if we can do it right the first time!

The one thing you never do is wrap the end of a stripped wire around a threaded shank and mash it down under a nut or head of a screw! This may meet the intent of rule #1 for awhile but it misses #2 badly. I had a boss who told me once that ten "attaboy's" in a row would get me a raise but that one "awshit" would wipe out all of the "attaboy's" you had saved up and you had to start over. So in keeping with the spirit of collecting only attaboy's, let's make connections that don't break off under stress and vibration a month after the airplane is all buttoned up.

RING TERMINALS FOR SINGLE STRANDS - SOLDERED

The only way to go to any threaded post with a wire is with a ring terminal soldered or crimped on the end. Solder? Did I say solder? I remember my first lesson in soldering. I was spending the summer fresh out of the third grade with an uncle who possessed an electrical engineering degree and was an employee of the local power company. He empathized with my interest in electronics although it was a long way from his particular field of expertise. I remember looking at a construction article, I think it was a one-tube radio in one of the Boy Scout publications; a merit badge project. I had been scrounging parts (albeit some incorrect or defective) and I was short the tools and skills to solder the stuff together. Uncle Bill got out his trusty 250 watt electric iron (about the size of a policeman's billy club) and a roll of solder. The solder was about the size of 10 gauge wire. He showed me a text book he had on the subject; the pictures gave step by step instructions for splicing and insulating house wiring and wires on power poles! We spread out on the basement floor and proceeded to stick the things together. It didn't work when I finished it but it didn't matter. Uncle Bill seemed satisfied enough with my performance that he allowed me to use the tools solo. Thus began my experience with a new technique. It was many years later before I truly understood the stuff and became really proficient with it. I now possess at least six different kinds of soldering tools and three or four different kinds of solder. Let me share some of what I have learned with you here and perhaps we can cut several years off of your learning curve.

Soldering, unlike welding, is a means for making a metallic joint between two metals made up of possibly different alloys using still a third alloy, the solder itself. Solder obviously melts and flows at temperatures much below the melting point of the metals being joined. Welding involves heating the two parts to be joined up to their melting points and then filling the gap with a filler rod of the same material. Solders are available in a variety of alloys for specialized tasks but the solder we are going to need is made from tin and lead. If you visit a well stocked solder supplier, you can find solder in bars, sheets, wire ranging from cat whisker thin to perhaps 1/2" in diameter and powdered. The ratio of tin to lead may vary from 5 percent tin/95 percent lead to perhaps 70 percent tin/30 percent lead. You may even find special solders with a little silver, bismuth or antimony in it. That just covers the metal aspect of solder, then we get into fluxes. Flux is used to break down the oxides (rust or corrosion) of the metals to be joined to make clean bare metal available to the molten solder. Fluxes also are used to coat the surface of the molten solder and keep it from oxidizing too. All metals react more readily with the air as their temperatures are increased in the soldering procedures. There are dozens of fluxes for soldering of various materials in as many different applications.

Now, just what is it that the solder does? It is not a glue or adhesive. Nor does it make connection by simply surrounding and gripping the materials to be joined. Solder achieves connection by actually dissolving a small quantity of the base material into itself. Think of solder as a solvent for solid copper. If you were to make a micro cross-section of two wires twisted together and then soldered you will get a situation which is depicted in Figure 9-1. Note that in the interface between the tin/lead solder and the copper wire, there is a region where a small amount of the copper has actually become dissolved into and alloyed with the tin/lead solder. This layer isn't very thick because as the copper migrates into the solder, it alters its alloy and raises the alloy's melting temperature. So, the hotter the iron you solder with, the deeper the copper penetrates into the solder but at most the interface is only a few molecules thick!

Let's look at the topic of melting point for a moment. Figure 9-2 shows the nature of solder's melting point as its alloy is varied. The figure also depicts another characteristic of the various alloys of solder. Notice that an alloy of 63% tin has the lowest melting point of all the tin/lead solders. Note also that with all solders

other than 63/37 there is an intermediate plastic phase between the liquid and solid phases. This 63/37 ratio is known as a eutectic alloy; it has little or no plastic range in the transition from liquid to solid upon cooling. Ever heard the term "cold solder joint"? What is being described is a joint wherein the solder has a dull gray crystalline appearance; is weak and almost literally crumbles when stressed. The way that the joint got that way was because of two factors: First, a non-eutectic alloy of solder was used. Second, the joint was moved while the solder was in the plastic range as the joint was cooling. Solution to the problem? Use the right kind of solder. For most of your applications, an electronic grade solder of 63/37 alloy, 0.062" in diameter and having an active, non-corrosive flux is recommended. Spend the few extra bucks and get a good name brand, my own personal favorite is 63/37 Kester Resin "44" in an 0.032" diameter. It might seem expensive at about \$8 per pound but a pound will last you a long, long time and the quality is unquestionable. I've used the Ersin Multi-core electronic solders with pleasing results too. However, whichever solder you choose 63/37 is the MAGIC number to insist on.

The melting point figure also illustrates the phenomenon I mentioned earlier about the alloy shift raising the melting point as the copper molecules begin to dissolve into the molten solder. Note that as the alloy shifts away from eutectic, not only does its plastic range grow wider, its melting point increases as well. A little bit of copper causes the melting point in the solder/copper interface to take quite a jump thus preventing the wire from dissolving completely into the molten solder. Neat, huh? What are all the other kinds of solder for? Well, in my younger days it was a big deal to remove all the chrome from your car and fill in the molded channels with a material called body solder. In this case, the body man needed a very wide plastic range so he could sculpture with it. A 30/60 alloy was more to his liking. Eutectic solder would have been totally useless for this application! Here is an opportunity for a high tech practical joke, slip a bar of 63/37 into a body man's tool box. He'll go nuts trying to mold the stuff into any kind of shape! Just about the time it starts to soften it'll fall on the floor.

Now, as you make perfect joint after perfect joint with the right kind of solder, you can imagine all those little molecules of copper swimming out into a rapidly thickening quagmire of molten metal. You'll also know that the probability of a "cold" joint is almost zero as the joint cools.

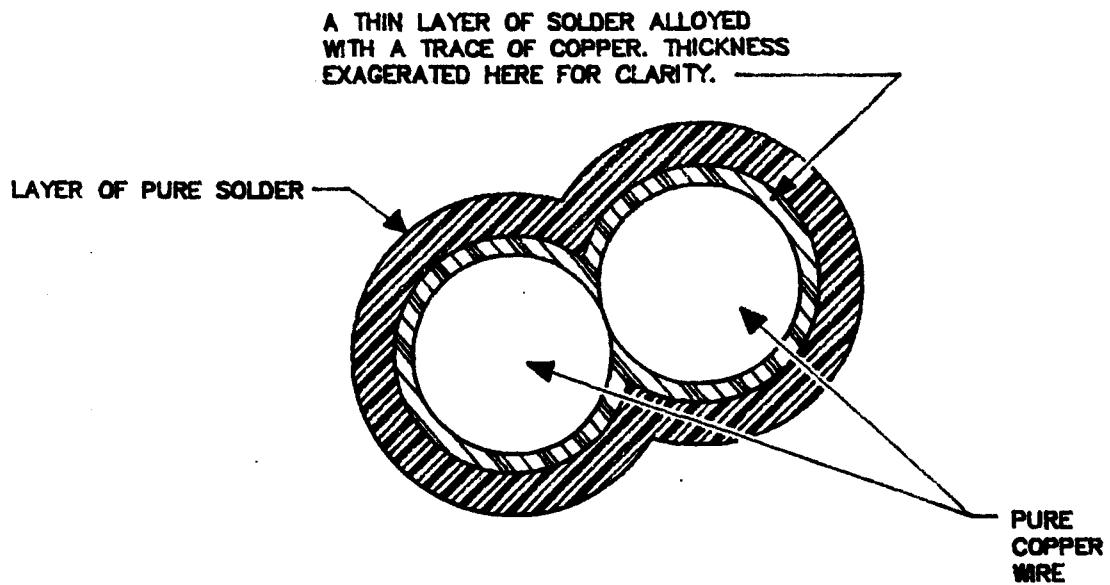


Figure 9-1. Anatomy of a Soldered Wire Joint.

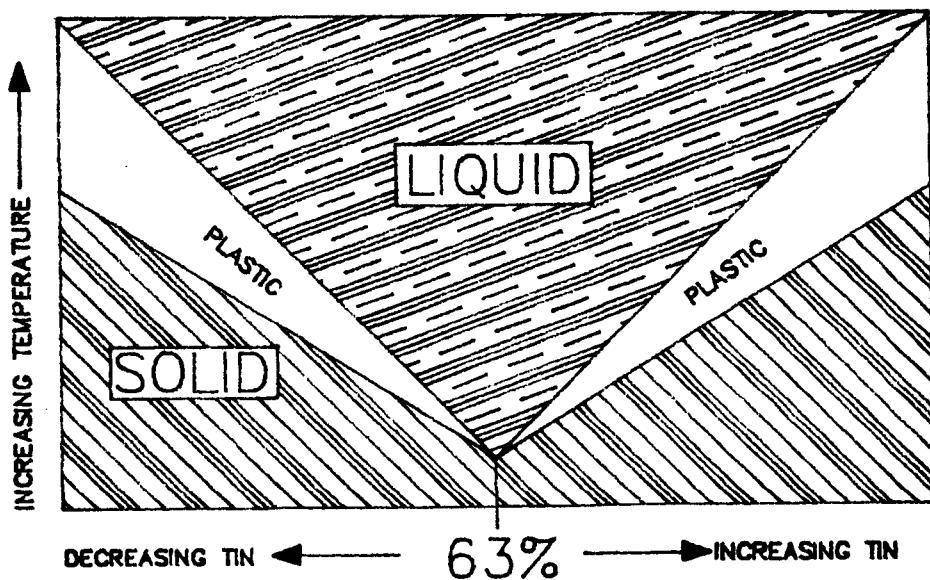


Figure 9-2. Solder Characteristics Versus Temperature and Alloy.

Once the alloying process is understood, the need for clean metal and a good flux is more apparent. Oxides of the metal do not alloy with the solder and indeed prevent alloying by the good metal underneath. The flux helps carry away small amounts of oxides that have formed since the metal was last cleaned. If you follow the rule in the previous section about using only tinned wire, cleaning will not be a serious issue for you. Tin is a very stable material compared to copper and a freshly stripped, tin plated wire is ready to solder with no further concerns about cleaning.

The reason for all this discussion about solder is because when properly applied, soldering is a very versatile, low-cost method for terminating wires. Figure 9-3 shows a solder lug available from electronic supply houses that has a shape of particular interest to homebuilders. The unsymmetrical, dog-bone shape lends itself very nicely to being soldered to the end of a wire and then having the joint protected by a length of heat shrink tubing (see the Digi-Key Catalog). The shape allows the shrunk tubing to get a good grip on the assembly and provides coverage for some distance either side of the solder joint. If you would rather not invest in crimp on terminals and associated tools, this method of terminating wires in ring type terminals is most acceptable, perhaps even preferable, for use in airplanes!

RING TERMINALS FOR SINGLE STRANDS - CRIMPED

The tradeoffs between soldering and crimping are not terribly compelling to the homebuilder. Crimped terminals are the product of choice for factories. There is no heat involved so careless applications of soldering irons to paint, plastic, carpets and upholstery is not a problem. Crimped terminals are also a bit more compact and look better than their soldered and heat shrink covered cousins. But, they are more expensive, they perform no better and they require proficiency in another kind of skill.

Hand tools for applying crimped terminals range from \$10 to \$200. The differences in them lie in the quality of the end result. Expensive crimp tools have precision dies which are brought closed against hard stops thus insuring the proper upset of the metals in the terminal/wire interface. These tools also feature ratchets in their mechanisms that insure that the tool is operated through a full crimp cycle thus preventing inadvertent under-crimping. I own several such tools.

I also own some of the \$10 variety and over the years, I have acquired the skill and knowledge needed to produce adequate crimps with these tools as well. It takes a bit of practice and some knowledge as to proper application which we'll get into now.

If you are going to use crimped terminals, consider the AMP Preinsulated, Diamond Grip (PIDG) products in the Digi-Key catalog. There are also some lower cost ring terminals in the catalog by the 3M company. These are roughly equal to AMP's Plasti-grip line of insulated terminals. I don't recommend these but I would prohibit them only in the engine compartment. Here's why: when crimping any preinsulated terminal on a wire there are TWO crimps to consider. The first is about one third of the length of the insulator back from the ring end of the terminal. This crimp forms the metallic barrel of terminal down onto the exposed wire, the second crimp is about two thirds of the way along the insulator from the ring and it forms the insulation of the terminal around the insulation of the wire. Mind you that the second crimp does not have to get a death-hold grip on the wire like the first crimp does. All you are needing to do with the second crimp is immobilize the wire behind the first crimp so that vibration doesn't put additional stresses on a wire that you have just stressed by mashing it!

If you look in the wire end of a new PIDG terminal, you will find a thin copper liner inside the plastic insulation grip. The plastic portion of a preinsulated terminal forms rather nicely around a wire at room temperature but at elevated temperatures found in an engine compartment, the plastic tends to return to its original BC (before crimping), round shape! The support for the wire is thus degraded or lost completely. The PIDG terminal has a metal sleeve in its insulation grip that prevents the terminal's wire grip from digressing due to temperature extremes. The terminals sold in automotive stores are almost assuredly of the pure plastic form of insulation grip. I won't tell you not to use them but I don't like 'em for airplanes.

Now about these low cost tools. The dies shown on the tool in Figure 9-4 are of the type that are used on the preinsulated terminals. These jaws are shown on the opposite side of tool's pivot from the handles but I have seen tools where these dies are on the inside of the handles; it doesn't matter. Do not use any crimp tool that penetrates the side of the terminal. There are a number of low cost tools for crimping uninsulated terminals that punch a sort of indentation on the side

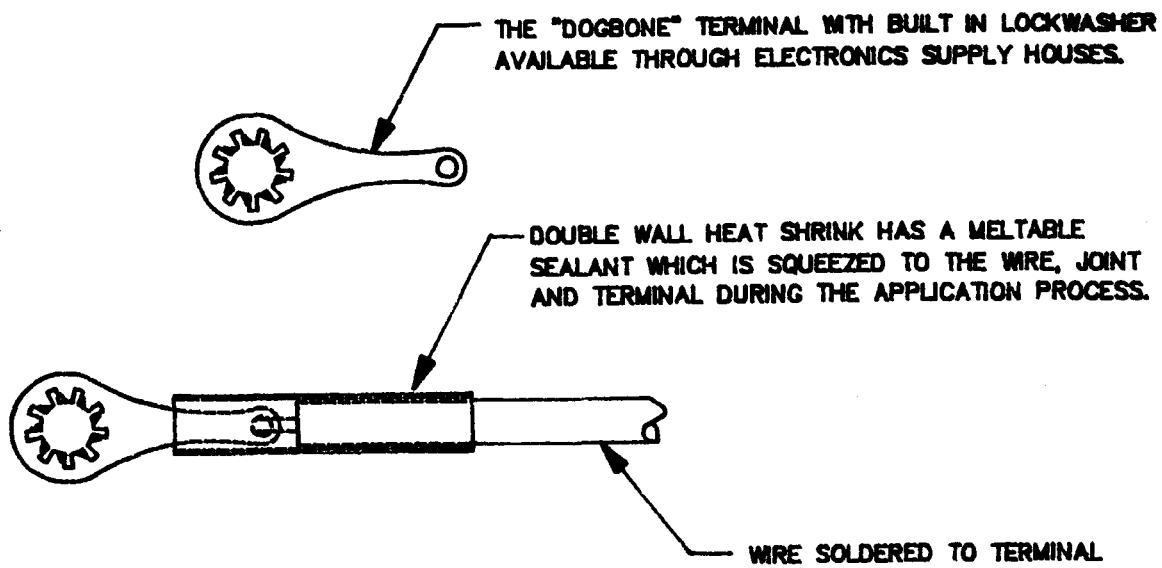


Figure 9-3. The "Dogbone" Terminal for Soldered Wire Terminations.

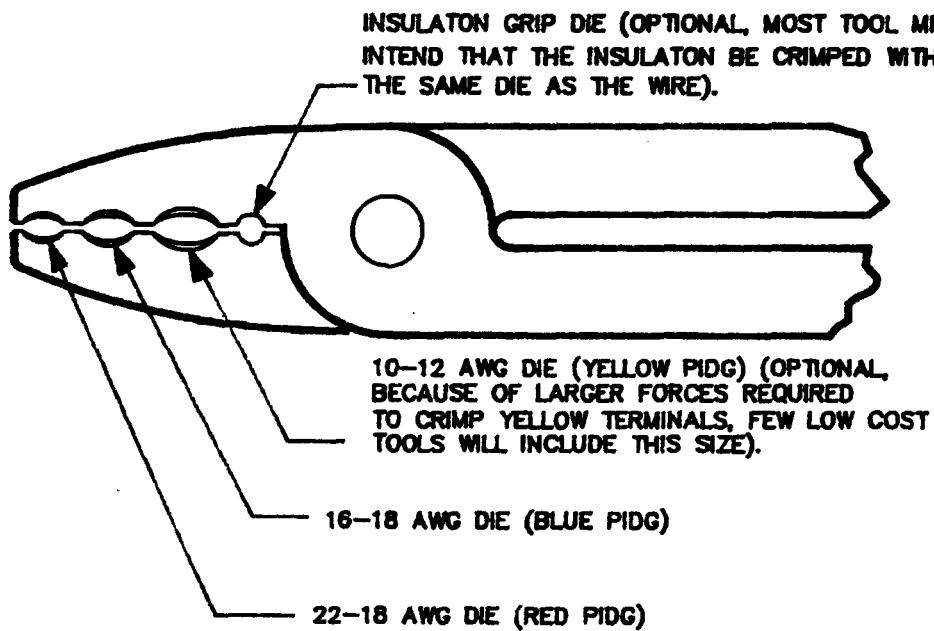


Figure 9-4. Tooling for Preinsulated Ring Terminals.

of the wire grip of an uninsulated terminal. Neither these tools nor the uninsulated terminals should be used on an airplane.

First, study the terminal you are about to crimp on the wire. It is the right size for the wire? A red insulator on a PIDG terminal indicates an 18 to 22 AWG wire range, a blue insulator is for the 12 to 16 AWG wires and a yellow is for 8 to 10 AWG wires. Are there dies on the jaws of your tool marked to suggest which die is appropriate for the terminal? Insert the wire into the terminal; the insulation should bottom out against the back of the wire grip portion of the terminal and inside the insulator such that the bare strands just barely emerge from the ring side of the wire grip. Study the situation for each type of terminal you use and learn the proper strip length for each.

Now, with the wire firmly bottomed out in the insulator, grip the terminal in the crimping tool with the tool centered over the wire grip and with the jaws parallel to the plane of the ring. Put a squeeze on it. Relax the squeeze a little and try to pull the wire out. Put a 5-pound or so pull on it. If the wire pulls loose, you didn't squeeze hard enough. If the wire stays in, take the terminal out of the tool and look at your crimp. Did the plastic extrude out from under the tool so that any metal is exposed? Did the plastic crack down the sides? Does the thing just look squashed? If so, you squeezed too hard! Cut the terminal off and try again. The object is to "calibrate" your squeeze to the task; it's not difficult but it does take some practice and a little critical observation of your results. There is a wide range between too little and too much for our purposes.

Once the wire grip crimp is mastered you are 95% of the way there. Next, using the next smaller die opening or perhaps a special die designated on your tool for the purpose, put another crimp on the terminal's insulator to close it snugly down around the insulation of the wire. Now look at the finished terminal installation. Are the two crimps nicely spaced on the insulator and are they both parallel to the plane of the ring? This isn't a critical issue but it is one of craftsmanship. In airplanes that would otherwise have taken show honors, I have seen the good PIDG terminals applied with a pair of Vise-Grips. Were I on the judging committee I have the errant builder go wash and wax the winner's airplane and then we'd talk about the rework needed to make his own airplane's electrical system reliable as well as neat.

TERMINALS FOR THE BIG GUYS

The red, blue and yellow PIDG terminals will take care of most of your wire-to-stud terminations but how about those big honkers that run from the battery to the starter contactor? There are PIDG terminals for these wires too but even the production hand tools for these wires is a hydraulic actuated ram! Consider getting these terminals installed for you by a local FBO or perhaps an electrical contractor. I've seen these tools and terminals for big wires used by many wire installers in the various buildings I have been employed in. Just cut your wire to exact length required; allow for the addition to length when the terminal is added. I suspect that a local contractor could provide and apply PIDG terminals (or their equivalent) for a few dollars per end. There is a home brew alternative to the PIDG terminations.

You can make custom terminals for big wires by selecting a drill just larger than the bundle of stripped wire strands. Cut a 1" piece of 1/2 or perhaps 3/4-inch soft copper tubing and mash it flat in a vise with the shank of the drill inside. You'll find it not difficult to pull the tubing down tight over the drill stem mandrel thus forming a flat shape with a tubular passage down one side. Drill an appropriately sized hole in the flat to go over your contactor terminal. Use a spotfacer and/or get a good grip on the thing with a vise or Visegrips when drilling. The copper is soft and likes to snag on the drill. A spotfacer makes a nice hole with much less tendency to snag.

Strip the cable back 1" and put the flag terminal on it. Use a large iron (200 watts or more) or a low flame on a propane torch to solder the terminal to the wire. "What !!!!", you say, "What about insulation support?" In these bigger wires, adequate vibration protection can be achieved by supporting the wire against structure close to the terminal. A PIDG terminal would be nice and do it all in one whack but a homemade flag terminal is just fine too and very inexpensive.

Years ago my first mobile ham radio installation was in a 6-volt, 1941 Pontiac coupe. My transmitter was in the trunk of the car and used a 600 volt dynamotor to produce the necessary high voltage for the output stage vacuum tubes. The dynamotor draw was just over 40 amps (with a 25 amp generator, I didn't get into long-winded transmissions, especially at night!). I remember using soft copper tubing to fabricate flag terminals that were soldered to the cable that ran back to the

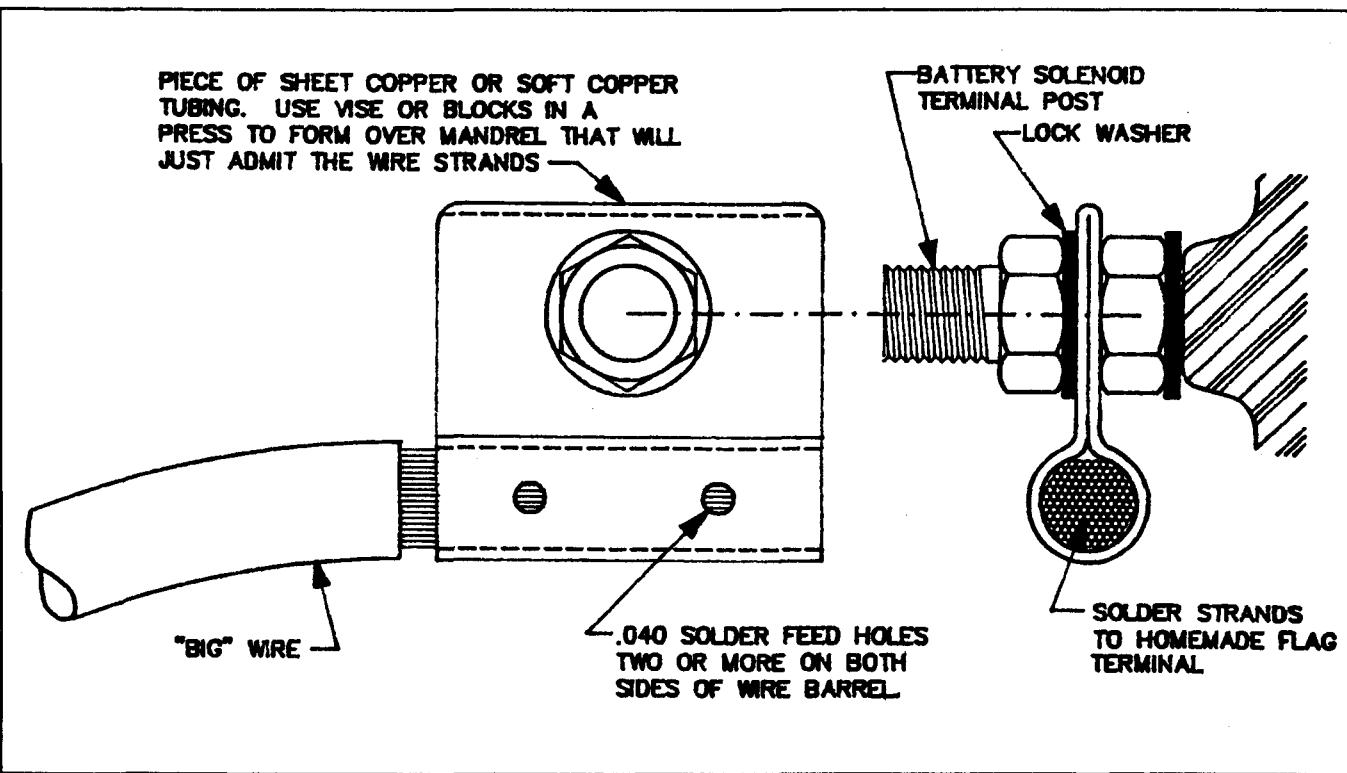


Figure 9-5. Home Made "Flag" Terminals for Big Wires.

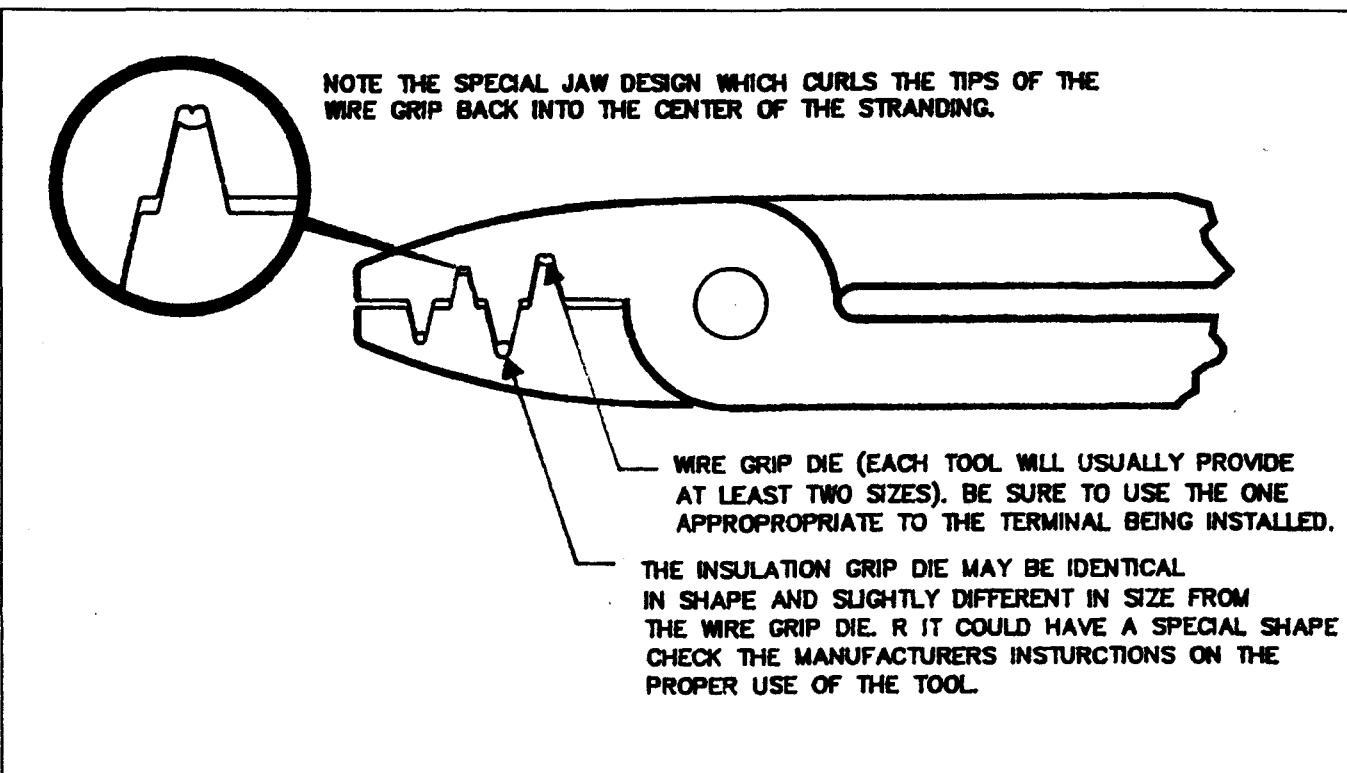


Figure 9-6. Tooling for Sheet Formed Pin and Socket Connectors.

trunk. When your system only runs 6.9 volts to begin with, a few hundred millivolts drop was a significant percentage of total system voltage. Let's see. . . 4 AWG wire is 6 AWG steps from 10 AWG that means 1/4th milliohm per foot. 12-feet from battery to trunk yields 3 milliohms of wire. 40 amps times 3 milliohms was 120 millivolts drop in that wire. In 1960, I hadn't the foggiest notion of how that analysis would come out. Furthermore, I didn't have any instruments accurate enough to see how bad the drop was. It is interesting to note 28 years later that the 4 AWG wire (the biggest I could find at the Boeing surplus yards) had been a pretty good choice!

MULTI-WIRE CONNECTORS

It is almost a sure bet that you will have to deal with some multi-wire connectors at some point in the completion of your airplane. Many of the avionics products will have connectors which pass multiple wires from the airframe systems into the interior of the black boxes. The Whelan Strobes use AMP Mate-N-Locks. You might also find it expedient to use a multi-wire connector at say, the wing root for convenient opening of a wire bundle when removing a wing. Cessna starting using the AMP Mate-N-Lock series plastic connectors while I was in their employ in the late 60's. Many eyebrows were raised, mine included when we saw these sheet metal, crimp on pins supported in plastic housings. Up to that time, wires bundles needing occasional breaking were fabricated with mil standard metal shelled connectors with soldered pins or a perhaps a sleeved knife splice (See the Digi-Key catalog PIDG listings) was put into every strand in the bundle. More often than not, the wires that ran out to removable portions of the airframe, like a wing, were run in unbroken strands. The poor guy in the field had to deal with cutting and splicing the wires if he removed a wing.

Cessna, like the automotive industry, was finding it more efficient to install wire bundles in the assembly stations for the various pieces of structure and some economical but reliable form of connector was needed. The Mate-N-Locks filled the bill nicely. Digi-Key stocks these connectors along with the Molex brand multi-wire devices. They also have low cost tools for terminal application. The dies for these tools are illustrated in Figure 9-6. These are very different from the dies for a PIDG installation. Note that the pins for both the Mate-N-Locks and the Molex connectors are formed from hard copper sheet. The pins have both insulation and wire grips. The funny looking dies are shaped so that during the crimp, the sheet metal tabs on the wire grip are rolled back into the center of the wire strands. The same form is applied to the insulation grip. Another nice feature of these types of plastic connector is that the pins are installed by simply pushing them into the back side of the housing until they "click" into place. Furthermore, they may be removed for replacement of damaged pins by means of extraction tools which are also handy if you have "clicked" a wire in to the wrong hole!

Until we can give photographic coverage to the proper installation of the sheet metal pins in the Molex and Mate-N-Lock type connectors, experiment with them a bit. They are inexpensive enough that you can afford to sacrifice a few housings and pins in your education. Take some scraps of wire and put some pins on them. Look at your results. Two grips; one for the wire and one for the insulation. The pins are listed as different part numbers for different sized wires. Make sure that you observe the limits on these and don't try to use the wrong size pin on a wire. It is possible to put two or even three wires into a single pin on these connectors; just pick a pin that has enough wire and insulation grip capacity to get its 'arms' around all the strands and their insulations.

Circuit Protection

Circuit protection is a generic name for fuses and circuit breakers. These devices are used to keep an unlikely event from precipitating an unhappy disaster. Fuses and circuit breakers are included in an electrical system to accomplish one thing: keep the wiring from creating a fire hazard in the event that the wire becomes overload.

FUSES VERSUS CIRCUIT BREAKERS, WHAT'S THE DIFFERENCE?

Fuses predate circuit breakers by many years. I have lived in houses built in the early days of electrical distribution that used a device called a "plug fuse" than really didn't plug but rather screwed into a threaded socket identical to the ones used to hold household light bulbs. I can also recall the infamous penny fix wherein a blown fuse was temporarily bypassed by placing a copper penny in the bottom of the fuse socket and then screwing the blown fuse back into the hole thus returning the lights to the ON state. It also placed the whole house at risk! It seems that fuses and toilet paper share a common attribute: few people remember to buy more when the last spare has been installed!

The simple appearance of a fuse can be misleading. The physics of designing and fabricating reliable fuses is not a trivial task. The fuse operates as an electrical equivalent of weak link in a chain. Its current sensor element is a conductor of carefully chosen alloy whose resistance and thermal characteristics provide predictable meltdown and interruption of the faulted circuit.

Fuses are sold primarily by their current rating, yet I can show you a 1 amp fuse the size of a match head and another the size of a small rolling pin. A second and very important requirement of fuses (and breakers) that is not so immediately obvious. They have fault current and maximum voltage ratings as well. A fuse may also need special thermal characteristics to make it either tolerant of or perhaps especially sensitive to short overload conditions. If a fault current rating were not important, then a 2-amp fuse used in the protection of an aircraft

branch circuit at 14 volts could also be used to protect a branch from a 440 volt AC power system in a building. The difference in these two situations is the worst case current that can flow when a short does occur downstream of the fuse.

For example, in your aircraft system, if you were to deliberately short the end of one of your circuit breaker branches to ground, the absolute maximum current that could be expected to flow in the microseconds before the fuse opens is on the order of 200 to 400 amps! Seems like a lot and the fuse thinks so too. That is why it opens up so quickly with the little flash of fire and the smoking up of the glass tube which contains it. Consider the same fuse in an application to protect a branch from a 440 volt bus in a building. Now the fault current potential rises to as much as 10,000 amps. Again this is only for microseconds but how much energy can be pumped into the little flash of fire that you observed in the 14-volt circuit? The answer is much, much, more. So much in fact that the fire would never go out. The fuse wires would simply melt away inside the glass tube and be replaced by a fire that would continue to destruction of the fuse holder and probably the downstream wiring or equipment that the fuse was supposed to protect. That is why you can find 2-amp fuses that range in size from size of paper match head up to an inch or in diameter and 6 inches long. Both will open at the same current but they are designed to work in very different environments.

The same considerations must be made in the design of circuit breakers. Now, how does this affect your decisions? Not much. The fault currents to be expected in a 14 or 28 volt DC vehicular system are well within the capabilities of just about any fuse or circuit breaker. The confusion factor to be aware of is the voltage rating that often appears on fuses and circuit breakers. A gentleman at Oshkosh '88 asked, "where he could find breakers rated for 14 volts? All that he could find in the Fly-Market were marked for 32 volts!" I was somewhat startled by the question because I had never considered the implications of such a marking. But it was a good question and it will

be answered again on these pages... Be advised that such markings on fuses and circuit breakers are maximum voltage ratings not operating voltage ratings. Furthermore, the voltage "rating" on a fuse or breaker is in reality a broad sort of fault current rating. Breakers and fuses may be considered for use as long as the voltage rating on the device is equal to or greater than the system voltage of your airplane.

ACRES OF BREAKERS . . .

A look at the power distribution panel of a modern twin turbo-prop will give the observer a look at what it's like to protect every wire in a complex airplane. When I was working on the Piaggio P-180 project a few years ago (it was the Gates-Piaggio GP-180 then), we had something on the order of 140 circuit breakers in the airplane; about 70 per side! And that was just in the cockpit, a few dozen more were stashed back in the tail. In that instance, virtually every wire which left the power distribution bus was protected with a circuit breaker. We sized the power distribution panels by the square foot!

I've been asked numerous times about how much is needed in the way of circuit protection; especially by the single place and tandem cockpit airplane builders where panel space is really at a premium. But even if your airplane is a two-place, side-by-side design, there is no point in carrying around any more weight nor using up any more panel space than is absolutely necessary. One is loath to assign panel space to components that are seldom called upon to protect the electrical system from an overload fault.

ONE FOR ALL OR ALL FOR ONE?

Question: "Does one really need a separate fuse or circuit breaker for each branch circuit from the power distribution bus?" Let us consider some additional space saving factors. There is no compromise of safety by powering more than one device from the same breaker as long as the breaker rating versus wire size are not exceeded. Example: Suppose you had three lighting circuits, none of which draws over one amp. The smallest wire to be used in any circuit is 22 AWG which is normally protected at 5 amps. Let us further suppose that the loss of all three lighting devices poses no real threat to your safety or mental well being. I would suggest then that these devices might share the same 5 amp fuse or breaker. Given that the fuses are so much less expensive per protected circuit than breakers, a builder is less inclined to cut corners by doubling up loads on a single fuse. Each powered circuit can enjoy its own circuit protection. Another plus for multi-slot fuseblocks is their compact size, it's no big deal for dollars, weight or space to plenty of SPARE slots for

future addition of powered equipment.

IN-FLIGHT RESETABILITY, REAL SECURITY OR SECURITY BLANKET?

What is the value of locating the a fuse or breaker within convenient reach of the pilot? One might expect, and it is obvious that most failures are passive in nature. That is to say that the failure of any one widget usually results only in the loss of that one device's ability to do its job. Fuses and breakers prevent failure from propagating to other systems by way of power losses or incineration. When the failure manifests itself by opening the breaker or fuse likelihood of recovering the system by replacing a fuse or pushing in a breaker is very, very small. So... Consider putting these critters in less handy places. How about a fuse panel that faces down, behind the panel, in the leg wells of the Eze-type airplanes. Or perhaps they could be on the forward face of the pilot's seat support, under the pilots legs.

The most likely cause of a breaker popping is from some failure within a device, be it a radio, light fixture, landing gear motor, etc., which has caused that device to draw an unusually high and ultimately dangerous amount of current. What's value is there in being able to see that a breaker has popped? Suppose you turned on your transponder and the breaker powering it pops. What do you know? The transponder is broke. What is the likelihood of recovering the use of that transponder by pushing a breaker back in? Whatever caused the breaker to pop in the first place is probably still lurking in there waiting to pop it again! Suppose you turn the transponder on and it doesn't work and the breaker does NOT popped. Now what do you know? The transponder is still broke. The second later failure mode is 100 times more likely than the first failure mode. Further, being able to see that a breaker feeding the transponder is or is not popped conveys no useful information to the pilot to help him with his task nor does the popped/not-popped information change the probable outcome of the flight.

The next most probable reason for fuses to open are wires whose integrity has been compromised. Perhaps an end somewhere or the insulation has rubbed through at some point where the wire was improperly installed. In a plastic airplane the probability of this event is small to zero! There is no metallic airframe to ground on. Every device in the plastic airplane must be supplied with a "ground" by means of a separate wire: usually the same kind of wire that carries the main power supply. Both of the wires are insulated. Here we have an equivalent of the double insulation found in some power tools. These devices usually have plastic housings and do not require three wire

power cords to be approved for safety considerations.

I have a lot of builders cite the FARs with respect to use of fuses in their airplanes. They mistakenly believe there is some requirement to have so many spares on hand for in-flight maintenance. Check out the FAR 23.1357 for yourself. It says a number of good things about how to utilize circuit protection in an airplane but let's look specifically at:

(d) If the ability to reset a circuit breaker or replace a fuse is essential to safety in flight, that circuit breaker or fuse must be so located and identified that it can be readily reset or replaced in flight.

(e) For fuses identified as replaceable in flight--

(1) There must be one spare of each rating or 50 percent spare fuses of each rating, whichever is greater; and

(2) The spare fuse(s) must be readily accessible to any required pilot.

Note that it speaks specifically of fuses powering equipment essential to safety in flight. Repeat after me, "I will have no item of electrically powered equipment upon which my comfortable termination of flight depends." See chapter 17 for more information on this. Further, while FAR23 may be consulted for good advice and accepted practices, it has no regulatory bearing on your project whatsoever.

FUSES OR BREAKERS

Question: "Is the weight, volume and cost of a breaker justified when a fuse will do the same basic job?" In most instances, a breaker and fuse can be considered to be electrically equivalent; either device will provide the prescribed safety margin with respect to electrical fires.

In the ten years I've been evolving this work, I've come to the conclusion that fuse blocks for the plastic, plug in fuses are equal to circuit breakers for safety and a whole lot less expensive than breakers. The best thing about these devices is ease of installation. In a matter of minutes, with the installation of a single component, you replace up to 20 breakers along with the work it takes to fabricate of bus bars and breaker panels. Fuse block are all 3.5" wide. We stock a 6-slot device that's 2.5" long, a 10-slot device with a length of 4", and a 20-slot block that's 7" long. All are about 1.3" thick. They utilize my favorite wire termination system, the 0.25" wide fast-on tabs for each

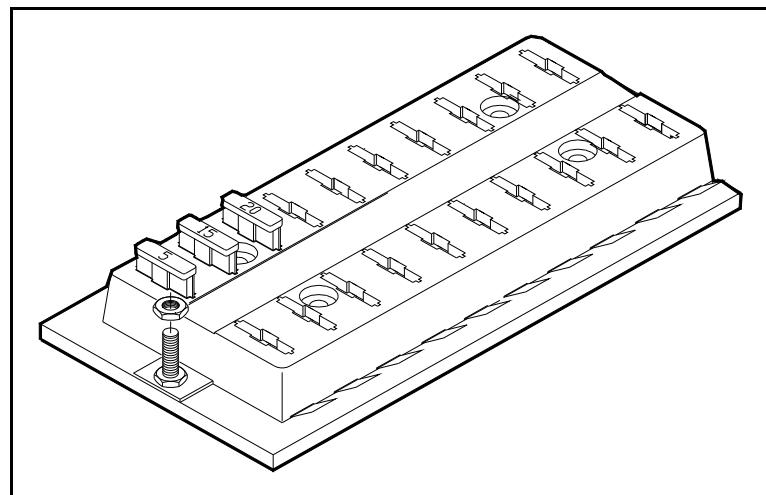


Figure 10-1. Multi-Slot Plastic Fuseblock.

fuse location. I encourage builders to mount these products with GROUND maintenance accessibility in mind. If that means you can't reach them in flight no problem.

The fuse block's grip on the tabs of a plastic fuse is much superior electrically than the u-shaped clip found on older cars with the 1/4 x 1-1/4" glass fuses. I'm comfortable with using the plastic fuseblocks with feeders up to an including 15 amps.

SWITCH-BREAKERS

There are breakers that have toggles on the front which are intended to be used as combination switch and circuit breaker. The major problem with most of the breakers of this type is that they force you to build a second bus bar distribution system on left side of the aircraft where pilot operated controls are grouped. The fuse block approach to distribution from the bus bar has a bus bar already fabricated and almost totally enclosed inside the fuse block.

Many builders view the switch-breaker as a time and space saving option. In the final analysis, there is no faster, less expensive nor more compact wiring combination than the switch/fuse-block combinations illustrated throughout this book.

FAT FUSES

An interesting fuse product not generally found on airplanes but non-the-less quite useful is the cartridge fuse with flat tabs suitable for bolting to a terminal on a wire. I've been using these fuses to protect the alternator output or B-lead feed so that the alternator can be conveniently tied into the starter contactor on the firewall. This

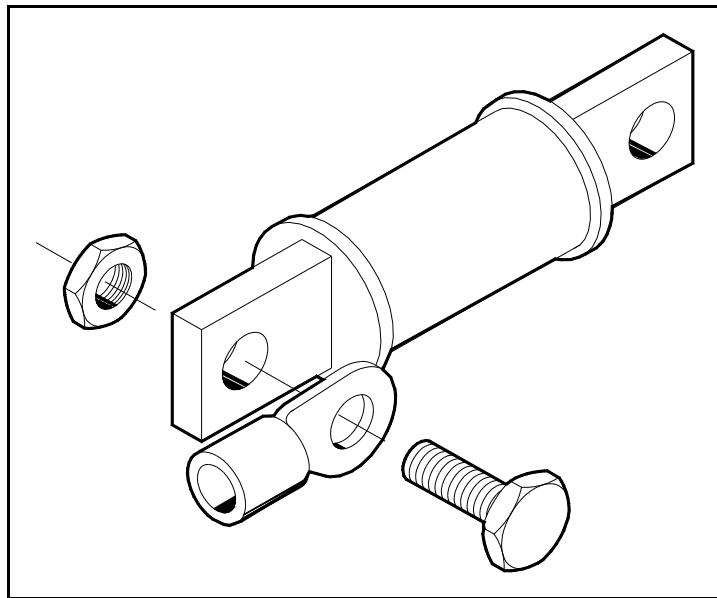


Figure 10-2. In-Line Fuse Adaptation of the JJN/JJS Series Cartridge Fuses.

technique is shown in all of the power distribution diagrams in this book.

Reliable fuses for over large loads, 50 amps or more can be had. In fact, good fuses up into the hundreds of amps in size are readily available. These are tab mounted devices which are held electrically and mechanically by retaining nuts on threaded studs. They are used extensively in the heavier twins and are usually referred to as "current limiters". Single engine airplanes generally don't have protection requirements that large. We offer 80-150 amp B-lead fuse kits from our website catalog with the vast majority of the installations taking an 80A fuse.

Our B-lead kit contains a fuse, terminals, assembly hardware and pieces of heatshrink for covering terminals. A larger hunk of heatshrink is provided to cover the entire assembly after it's all bolted together. This is a low cost, light weight technique for protecting the alternator B-lead and keeping all the noisy fat wires out of the cockpit. You can find similar fuses at distributors for electrical contractors. Ask for the Bussmann JJS or JJN series fuses or their equivalent.

In the power distribution diagrams further back, you'll find only a few circuit breakers called out. I recommend crowbar overvoltage protection which needs a circuit breaker. I'll generally install the ALT FIELD breaker in the same row and adjacent to the DC PWR MASTER switch.

THE "OTHER" FUSE - FUSIBLE LINKS

A third fusible protection device is called a "fusible link". Used in automobiles for decades, I've found several places where they make sense on airplanes as well. The fusible link is simply a piece of wire, 4AWG wire steps smaller than the wire it is supposed to protect. 4AWG wires steps is a 60% reduction in cross section. Obviously, this becomes the requisite "weak link" in a power pathway. For a fuse to do it's job, it should fail in a predictable manner that does not create a hazard to the airplane or its wiring. To insure this orderly destruction of the fusible link wire, we'll cover it with a Fiberglas sleeving impregnated with silicone rubber.

One fabricates the fusible link by butt-splicing a 4" piece of 4AWG smaller wire to the hot end of a protected feeder and terminating it with the proper terminal to mate up with the feedpoint hardware. Our website has a photo pictorial on how this is done. A fusible link takes place of an inline fuse holder. Since it's made from ordinary wire, terminals and butt-splices, the long term integrity of the device is quite good. You'll see fusible links called out in numerous places in the power distribution diagrams at the back of the book.

As a general rule, I wouldn't recommend a fusible link for anything except relatively low current feeders such as alternate feed to the essential bus, always hot feed to an electronic ignition, Hobbs meter, electric clock, etc. A 24AWG fuse link should be used to protect a 20AWG wire but the circuit load should be limited to 3A maximum (24AWG wire rating). A 22AWG wire protects an 18AWG wire in a 5A maximum (22AWG wire rating) circuit. There are a few places where some larger links are shown in the power distribution diagrams for protecting the feed lines of PM alternators. Our website catalog offers a Fusible Link Kit with sufficient 24AWG wire, silicone impregnated Fiberglas sleeving and butt-splices to fabricate 4 fusible links.

SO, YOU'RE GONNA DO THE BREAKER THING ANYHOW . . .

If you really, REALLY gotta have breakers, then consider the flowing: Bus bars are best made from sheet brass or copper . . . it doesn't need to be real thick. .032" is fine but it can be thicker. Hobby shops and many hardware stores have a display of metal shapes by K&S Engineering. Their display has various compartments of aluminum and brass shapes including a 4 x 10" sheet of 0.032" brass. Their catalog # is K&S253 and costs about \$4.

Go to a sheet metal shop and cut some 1/2" wide strips off

the long side. Two or three are enough to do the whole breaker panel in most airplanes. The best breakers for this task have screw terminals as opposed to fast-on tabs or solder terminals. Measure the thickness of the breaker you plan to use and decide how far apart you'll space your breakers on the panel I use 0.70" spacing for the miniature Klixon breakers. Drill a row of #26 holes in your strips of brass, 0.70" apart. Mount the breakers on 0.7" centers and use the strips of drilled brass to bus all of the breakers together. Obviously, you'll need separate bus bars for the main and essential busses.

If you must arrange the breakers in multiple, shorter rows, then you'll need inter-bus jumpers to tie common rows together. This is easily done with 10AWG wire bolted to the bus bars in the spaces between breakers. Don't use breaker screws for this. Inter-bus jumpers should have their own 8-32 screws, nuts and lockwashers. If you need a multiple row installation, put all the high current breakers (like landing lights, taxi lights, pitot heat,

hydraulic pumps, etc) on one row. Then attach the main bus feedline to this bus bar with its own 8-32 screw, nut and lockwasher. All remaining breakers won't exceed 30 amps continuous loading so the 10AWG inter-bus jumper is not going to be stressed too hard.

If you really, REALLY want to use switch-breakers then plan on two breaker panels. One on the left side to handle the switched circuits and one on the right for the remaining, non-switching breakers. They'll both need the brass strips to tie the one side of each row together. Generally, all high current loads (except perhaps a hydraulic pump) are pilot switched, so bring the main bus feed into the pilot side breaker panel. Then fabricate a 6AWG jumper to take power to the right side. Take some pains to secure this wire from potential chafing and other sources of mechanical compromise. Again, don't use breaker screws to attach main power feedlines or inter-bus jumpers . . . these things should get their own 8-32 fasteners.

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Switches, Relays and Contactors

Switches, relays and contactors are a family of basic devices used to control flow of current in an electrical system. The generic switch has been around from the very beginning of electrification. Houses were converted from gas or oil to electrical illumination by literally fastening lamp fixtures to ceilings, switches to walls and connecting the whole mess together with wires that were stapled to the surface. Even in these rudimentary beginnings, switches were constructed to accomplish connection or disconnection of electrical circuits with a *snap*. As one rotated the handle of an early light switch, a feeling of winding up a spring was unmistakable. At some point, tension was sufficient to push internal parts past a detent and the switch would complete its operation with a "click"; a sudden release of tension could be felt in the fingers.

The need for snap action was well understood, especially in the early days of domestic power distribution. Most houses were first supplied with direct current (d.c.) in contrast with present day systems which supply alternating current (a.c.). In the section on over voltage protection I described special design efforts required to control the fire between spreading relay contacts which are attempting to bring a failed alternator/regulator system under control. When d.c. was routed to our ancestors homes, the problem of controlling high voltage had to be addressed. In this instance, the high d.c. voltage was not developed by a collapsing magnetic field. The voltage was already high; 100 volts or so as delivered to the back of the house!

A simpler device known as a knife switch was universal in industrial applications. It operates in a manner which is suggested by its name: a blade of conductive material was moved by an insulated handle so that it was forced between two spring loaded leaves of conductive material thus making a connection. Breaking connection was accomplished by simply pulling the blade from between the leaves.

My earliest recollection of knife switches is from old black and white movies. The good Doctor Frankenstein, standing over his patient, is yelling instructions to Igor who manipulates many switches and knobs on the laboratory apparatus. Operation of these switches is always accompanied with flashes of fire and puffs of

smoke. The effects were undoubtedly enhanced for the benefit of the movie viewers, but then fire and smoke was not totally out of character for this type of switch. Indeed, hesitant or sloppy operation of a knife switch in a high voltage circuit would produce long, hot blue sparks accompanied by subsequent damage to the switch.

Purveyors of early electrification products and services knew that consumers would not be favorably impressed with little fires and puffs of smoke at their fingertips. Snap action switches were developed in a successful attempt to keep "lights" off of walls and up on ceilings where they belonged! Control of high voltage d.c. using snap action switches required no instruction or special action on the part of the switch operator. A child could easily accomplish a making or breaking of connection. Thus children began to "make" more connections than they "broke" and the seeds of eternally illuminated children's bedrooms were planted. They thrive to this day!

If you have ordered catalogs from firms listed in Appendix A, then you have access to a pretty good cross section of many ways in which switches are made. Start with parts that hang out through the panel: the actuator handle. For actuator choices one finds toggles, rockers, paddles, buttons and knobs, just to name the most ordinary. Then there are single-pole, double-pole and many-pole types capable of switching several circuits simultaneously. The part of a switch that hides behind the panel has about as many different configurations as the part that sticks out the front!

To assist in communicating switch functions, a simple language has been devised. It goes like this: to describe a switch that simply controls a landing light, one would ask for a "single-pole, single-throw" switch. This is abbreviated by writing SPST. To describe a switch like that used to control the avionics/essential bus on wiring diagrams in Appendix Z, one requests a "two-pole, double-throw" with terminal interconnections made in all three switch positions. Its function is abbreviated by writing DPDT, ON-ON-ON. On the same diagrams a combination fuel pump and electric primer switch are shown. This switch is identical to the avionics bus switch except an extreme position is spring-loaded to center.

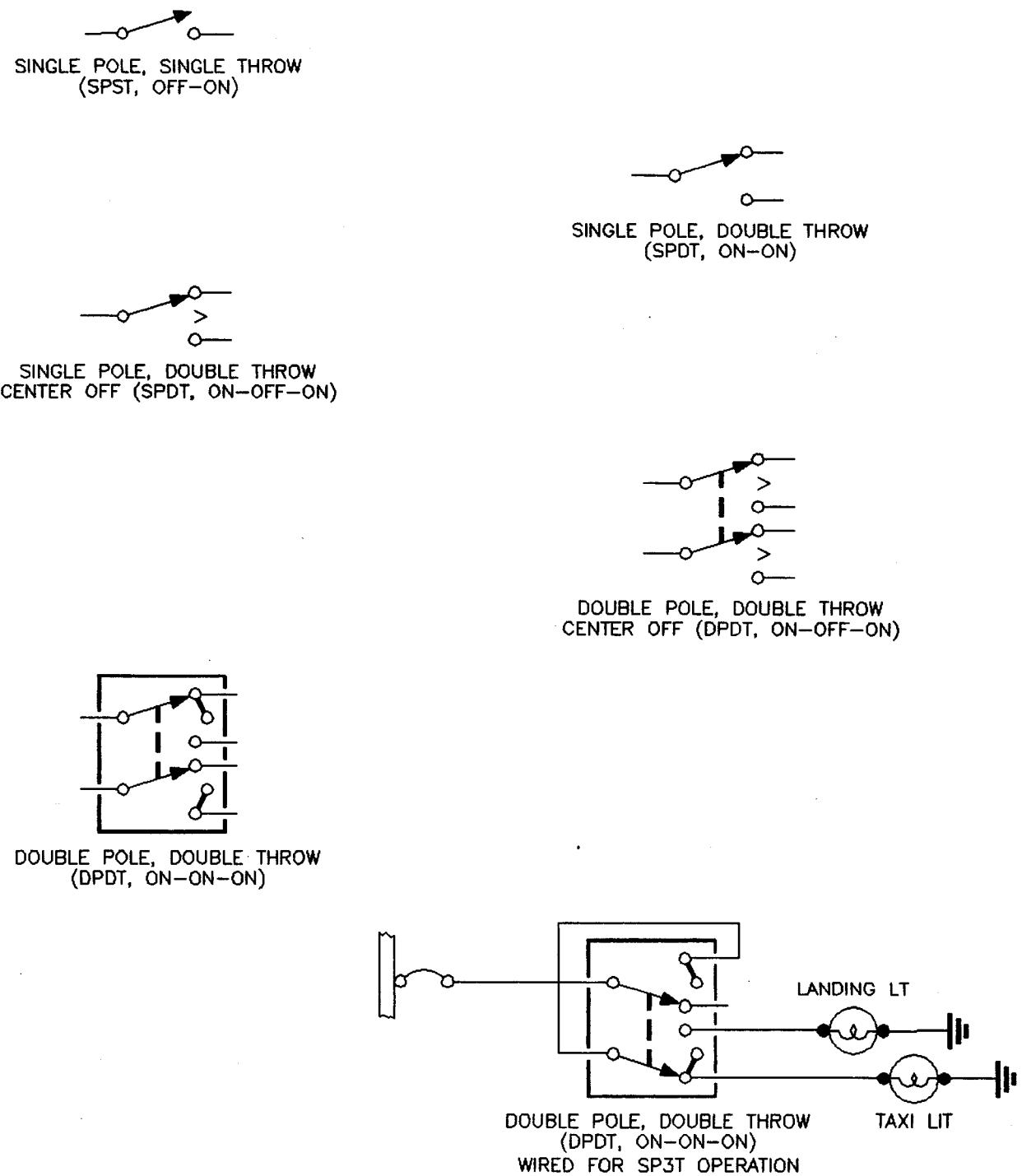


Figure 11-1. Toggle Switch Configurations

Its abbreviation is DPDT, ON-ON-(ON). The parenthesis about one of the positions indicates spring loading. Suppose you needed a switch to operate an electric trim actuator with a permanent magnet motor. An appropriate switch would be a DPDT, (ON)-OFF-(ON). It would provide a trim up and trim down positions with spring loading to the center off position.

Specialized switches permit single switches to perform multiple functions thereby reducing panel space needed to do a job. Wiring diagrams in Appendix Z have several examples of "panel space conservation". For example, the magneto switches also control starter functions. The fuel pump switch also controls an electric primer valve. The avionics master switch controls essential bus connection to main bus, selects an emergency mode essential bus feed directly from battery and also disables the starter circuits if the switch is not positioned to shut off the avionics! How's that for squeezing triple duty from a single switch? If you plan to install both landing and taxi lights, consider a single switch of the DPDT, ON-ON-ON type. Wire it for the SP3T function like the avionics master but leave the lower position connection unused for "OFF", wire the mid position to illuminate the taxi light and the upper position to illuminate the landing light. These examples are illustrated in Figure 11-1.

Switch selection tasks usually begin with a choice of actuator. . . . the part you grab with your fingers. The traditional actuator is the "bat handle" which accurately describes its appearance. Other shapes include flat paddles, tapered paddles, rockers, lighted rockers, etc. This part of the selection is a matter of style and is pretty much up to the builder and his pocket book!

The next consideration is the electrical rating of the switch. Most of the catalogs from the vendors listed in Appendix A will have abbreviated if not complete specifications for the switches they offer. Unfortunately, the real implication of the manufacturer's ratings is not cut and dried. Here is a sketch of what the ratings are about:

A switch will have both a voltage and a current rating equated with a switching task. For example, suppose you read that a switch is rated at 10 amps *resistive* at 125 volts AC, 7 amps *resistive* at 250 volts AC and 5 amps *inductive*. Sometimes you even see a "*tungsten*" rating on a switch which refers to its ability to handle light bulb loads. A sampling of the three types of loads is shown in Figure 11-2. Is the thing suited to an application in your airplane? Let us consider the character

of these loads first.

A *resistive* load refers to a device which is neither *inductive* or *tungsten*-like in nature. Very few devices in an airplane fall into the category of *resistive*. Avionics components will make up the bulk of *resistive* loads. The nature of a *resistive* load is that the inrush, running and breaking currents and voltages are all the same. For example, suppose you were selecting a switch to control a 450 watt electric heater in a 28-volt Long-Eze. Referring to the techniques introduced in Section 1, you may deduce that a 450 watt heater will draw $450/26 = 17.3$ Amps. Why 26 volts? Recall in earlier discussions many devices with large current draws will be rated for operation at some level below normal bus voltage. Sharp component designers recognize the fact that zero resistance wire is not available and some drop in interconnect wiring is to be expected. An electric heating element is almost purely *resistive* meaning that the instant the switch is closed, an inrush of 17.3 amps can be expected. While the switch is closed, a running current of 17.3 amps can be expected. And lastly, when the switch is opened, no *inductive* voltage spike is expected. With no *inductive* spike the contact spreading velocity of the switch may be characterized for breaking a 28-volt circuit, not a several hundred volt circuit!

An *inductive* load is a device which is internally constructed with coils of wire around magnetic materials of some type. These devices include motors, relays, contactors, solenoids, some strobe light power supplies, electric primer valves, etc. The *inductive* spike phenomenon was explained in detail in the section on overvoltage protection so I won't dig into it here. Suffice it to say that the act of turning an *inductive* load OFF is the difficult part. When a switch is poorly adapted to its task, energy stored in the magnetic circuit of the *inductive* component is dissipated at the opening contact points of the switch. Motors present a worst case sort of switching task. Obviously wound with many turns of wire, they are quite inductive. However, it also takes much more current to start a motor than that which is required to run it. Motors will be described in detail in a later section but we are all familiar with the dimming of the house lights when an air conditioner or washing machine kicks on. Furthermore, it is a rare airplane that doesn't show a momentary but distinct dimming of panel lights when electric flaps or landing gear are extended. Motor inrush currents may be 4 to 10 times the running current.

Heavy duty contactors can also wreak *inductively* induced havoc. An *inductive* spike from the coil of a

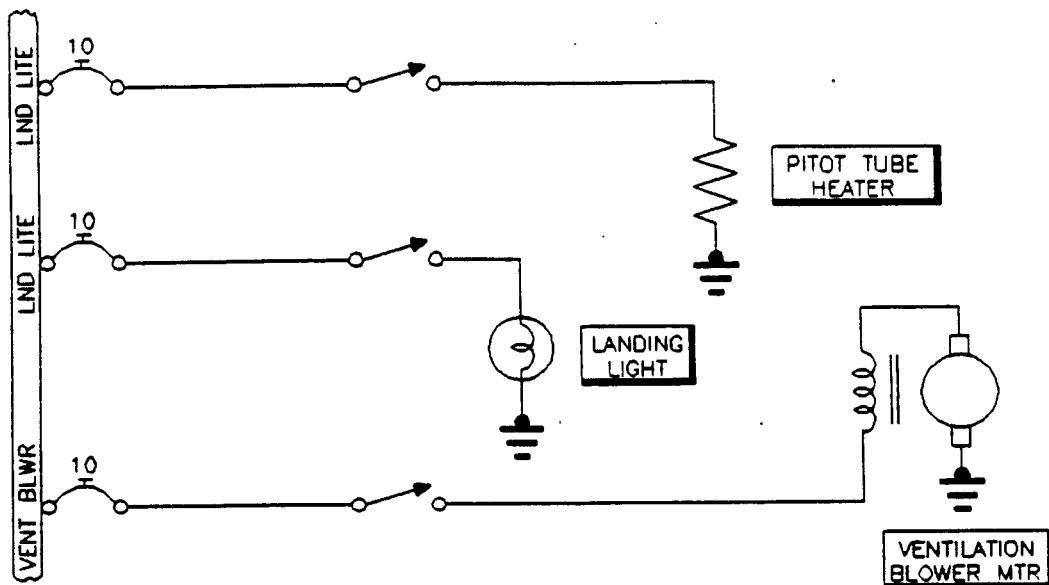


Figure 11-2. Resistive, Tungsten and Inductive Loads.

contactor can be hard on the switch that controls it. It can also damage sensitive, improperly protected electronic components. For now I will concentrate on the task of controlling inductive devices; the taming of the inductive shrew will be discussed in detail in the section on electrical noise.

The so called *tungsten* characteristic refers to light bulbs. In the section on lighting I will discuss the operation of lamps in detail but for now, know that the theoretical inrush current on a landing light can be 16 times its running current! Lets see... 150 watts divided by 13 volts is 11.5 amps. Sixteen times 11.5 amps is 184 amps!!!!

What's a mother to do? Where are we going to find a panel mounted switch for a landing light that is good for 184 amps? Take heart. Note that I used the term "theoretical" in front of the word "inrush". All inrush values assume that full rated voltage is available to power the lamp from the first instant of switch closure. Let us accomplish a quickie analysis of a landing light turn-on scenario:

The device which is capable of delivering the landing light inrush current is the battery. The alternator's output will mitigate any load on the battery. However, for the purposes of this analysis we will assume that it's assistance is negligible. Starting with the battery, let us assume that the internal resistance of the battery is 12 milliohms which says that the dead short current limit on the battery is on the order of 1000 amps. Let us further assume that our Long Eze uses 6AWG battery supply and ground wires totaling seven feet for an additional 3 milliohms. Let's call out the landing light supply and ground wires as 16AWG and 8 feet long for another 32 milliohms. Looking at the light bulb itself, to draw 184 amps at 13 volts requires a cold filament resistance of $13/184 = .065$ ohms or 65 milliohms.

Adding up all of the resistances we get $65 + 32 + 3 + 12$ for a total of 112 milliohms. In the section on batteries, I described a battery as a 12 volt device internally so the real inrush current at the instant of switch closure is more on the order of 12 volts divided by 0.112 ohms or 107 amps! This number is still big but certainly much less than 184. There are *inductive* effects of the wiring to consider and lastly, this inrush lasts for less than a

millisecond since the lamp bulb's current draw drops rapidly as the filament warms up.

In actual practice, the landing light may be expected to have a peak inrush on the order of 80 amps or about 7 times the rated load current of the lamp. The same sort of conditions apply to motor starting loads but they last much longer. As a general rule, motor inrush currents will be ten times longer in duration because load current is a function of motor speed and it takes longer to spin up a motor armature than it takes to heat a lamp filament.

A *resistive* load is the most benign. Therefore, a *resistive* load rating is the larger of the three for all switches. Depending upon a switch's design, either *tungsten* or *inductive* loads could be considered to be a worst case. A switch might have very heavy contacts and be quite suited to high inrush switching but heavy contacts are harder to accelerate apart and the switch might get lower marks for *inductive* loads. On the other hand, a very fast over-center mechanism might be driving light weight contacts. This device might be capable of breaking the nastiest of *inductive* spike arcs but the light contacts won't do so well in the high inrush application.

Looking at the manufacturers' ratings again, suppose we put a switch rated at 15 amps *resistive* into a slot that controlled our 17.3 amp heater? Does this mean the switch is going to smoke after a few minutes? Suppose we used a miniature toggle switch mounted on a control stick for electric trim. The switch was rated for 2 amps *inductive*. We were running a 1 amp trim motor with it but the switch failed. Teardown disclosed a functioning mechanism but badly burned contacts. What went wrong? In the section on overvoltage relays I said, "if you let me pick the 2 amp *inductive* circuit, I would show you how to melt down a 10 amp *inductive* rated relay or switch." Well, here is the rest of the story about switch ratings.

There are hundreds of test specifications for rating switches. The military has written at least 50 different specs that I have referred to over the years. Underwriter's Laboratories has a fist-full of test specs too. However, UL testing is user safety oriented, not product performance oriented. I've had experiences with UL approved devices that didn't work worth a toot but they didn't set my house on fire either! Added to this are many commercial and industrial specifications for rating switches. A great deal of commonality is shared by these specifications. However, each spec was created to address a "special" need. The need might be

as exotic as an application on a spacecraft. Or perhaps the manufacturer simply tailored the specs to match his ability (or inability) to build switches.

The rating of a switching device can be deceptive. I remember two instances wherein I was mandated to use a "heavier" switching device than I had originally specified just as a safety factor. Both situations involved secondary trim systems, one a twin jet and the other a high performance twin turboprop. In the instance of the jet, I had designed a seventeen dollar, 2-amp *resistive*, 1-amp *inductive* rated relay into the direction control system of a motor that was drawing 1.8 amps worst case though the relay. I had spent many hours selecting arc suppression networks to match the system characteristics and had proved the relay to be good for over 100,000 cycles as designed. The customer arbitrarily selected a 5-amp *resistive*, 3-amp *inductive* device to go in the same slot. This newer, "stronger" relay sold for over \$100 a copy! It was simply "insurance" they said.

My inspection of the relay showed that it did indeed have heavier contacts and was well suited to carrying 5 amps but the spreading velocity was much slower and the final resting air gap between the open contacts was less one half the gap in the 2-amp relay! My protests yielded naught and the big husky relay went into production. Over the next few years that I was associated with that product, the direction change relay was in the top five trouble items for the product. The heavy duty relays often failed in less than 100 hours of flight service. Somehow nobody could seem to recall who spec'd the bigger, more expensive relay into the product and we fielded a lot of flack over the failures. But, the product was certified and the cost of recertification was too much to justify any changes.

The other was a case where I had specified a subminiature switch to be used in a pilot's secondary trim switch mechanism. The switch I had selected was by a well known manufacturer and again, I was using it at or near its design limits. My superior wanted some "insurance" and insisted that I find a "better" switch. I did find a switch by an obscure manufacturer that had a slightly better rating. I found that it was better only because of the spec that it was tested to but that was of no concern to my boss. If the catalog gave it a better rating, it had to be better in our application so that's what we bought. Fortunately, that switch has proved to be satisfactory so far; I am aware of no particular difficulties with it.

The problem presented to you as purchasing agent for Podunk Hollow Homebuilts is to understand how all this does or does not affect your decisions on selecting and buying a switch. I am sure you have neither the time nor an inclination to approach the task with the energy, determination and budget of a NASA engineer.

First, let us address the issue of style. My personal favorite is the standard bat handle for a switch operator. Reason: many manufacturers supply similar if not identical looking switches in a variety of special functions. These switches usually mount in a single 15/32" round hole; they utilize a keyed and tabbed anti-rotation washer for additional security in installation and they install with a single nut. Switches with other styles of handles are more limited in the availability of special functions except by special order. Rocker switches are the worst of the lot for mounting since they require square cornered rectangular holes and two mounting screws. The lowly bat handle can be spruced up with colorful plastic booties. However, the choice is yours . . . I have seen some very snazzy looking panels with rocker switches or multi color paddle switches on them.

The next consideration should be directed not so much at ratings as at the mechanical quality of a switch. The best way to acquire some confidence in the mechanics of a switch is to pick from well known manufacturers. Microswitch, Cutler-Hammer, Potter and Brumfield are a few good sources of many sizes of switches. C & K, Cutler-Hammer and ALCO are additional choices for miniature switches. A military specification number builds some confidence in a switch's pedigree. The reason for concentrating first on mechanical attributes over electrical attributes is the fact that a hand operated switch in the panel of an aircraft is more likely to fail *mechanically* than it is to fail *electrically*.

Explanation: All credible manufacturers of panel switches have electrical and mechanical ratings of in the tens of thousands of operations or more. One hundred thousand is not uncommon. How long will it take you to put even 10,000 operations on any switch in your airplane? Yet, most switches fail in service with a small fraction of this number of cycles on them. Teardown usually shows a mechanical failure; the electrical contacts are still in good shape. In the laboratory testing environment, the 50,000 or 100,000 cycles is applied to a product in a short period of time. One operation per second is 3600 per hour. Less than 28 hours are needed to "test" a switch to 100,000 cycles. The telling stresses on a switch in service are temperature cycles, humidity

cycles, vibration, etc. Over time, these stresses can be harder on mechanisms than upon the contacts of a switch.

Let's look again at electrical ratings. In the area of mild overload, of say 50%, the effect is not going to be inducement of immediate failure but one of shortening of the electrical life. In the laboratory, the electrical and mechanical lives of switches are similar. So, does it bother you a great deal that the way you are using a particular switch might reduce its life to a paltry 10,000 cycles? The major switch contact killer is the inductively induced fire created in the spreading contact air-space.

The next most common failure is induced by steady state overload which produces a precipitous acceleration toward self destruction. The phenomenon was described in the section on circuit protection wherein two pieces of metal which are normally in tight electrical contact with each other get just a little corroded. The contact resistance goes up which increases the heat generated at the contact. Corrosion accelerates due to heating and the resistance goes up some more, the heat increases again as a result and so on. Eventually the thing catches fire and/or just melts down.

Except for the big electric heaters used in the Eze's, and pitot tube heaters, no large loads are of the continuous duty type. Landing gear motors, flap motors, landing lights, etc. are intermittent, short time loads. Switches used for these kinds of service are not very prone to precipitous corrosion failure. There is a third type of switching device failure, which usually happens only to contactors, but we'll discuss it here.

The third switch failure mode is a bit more complex: when working with large current flows in d.c. power systems there is no practical way to reduce the arcing at the contacts to zero. Some arcing will occur at time of contact closure and again at contact opening. Arcing at switch closure happens because of contact bounce (? ? Yes, bounce!). Imagine yourself to be 0.1 inches tall. In front of you are a pair of contacts in a switch designed for, let us say, 30 amps. These contacts might be 0.1 inches in diameter, 0.05 inches thick and be normally separated by 0.1 inches of airspace when open. These dimensions scaled up to your normal size might translate into 6 feet in diameter, 3 feet thick and 6 feet apart. Now, let's smack these chunks of metal together so as to cause them to close a circuit and carry current. Be assured that they will not stay in contact with each other after the first closure. Nor perhaps the

second or even the third. This 'bounce' is present to some degree no matter what the scale of the switch is. I have personally documented as many as eleven separate contact closures on some types of relays. All this happens in tens of milliseconds and the air gap between bounces is quite small; not much is happening here in most cases but suppose we're trying to warm of the filament of that landing light with each bounce putting a 107 amp pulse of current to the lamp! (There are some bounce-free designs for switches and we'll talk about them later.)

The next opportunity for arcing occurs at switch opening time as we've discussed before. With *tungsten* and *resistive* loads it is no big deal. However, if the load is *inductive* all the excess energy stored in the magnetic circuit of the *inductive* device tries to warm up the contacts of our switching device with fires fueled by a voltage which happily grows larger as the contacts get farther apart. Again, if the contacts move rapidly and their thermal mass is sufficient, the device can be expected to work under its rated conditions for many thousands of cycles. It is a matter of degree; the ability to prevent arcing in the circuit versus the ability to withstand arcing in the switch: a design trade-off between expense and function.

So, if arcing is never zero, what are the consequences? First, let us consider the characteristics of an electric arc. If you ever get to look directly at contacts in operation on some open switch or relay, the color of the arc is yellow-white to blue. These colors imply temperatures on the order of thousands of degrees! No matter how small an arc may be, some amount of contact metal will be vaporized. When the metal molecules are ripped off the surface of the contact by an electric arc, they tend to loose a few electrons from their outer shells and they become ions with positive charge, free to roam about in the hot gasses of the arc. It is only natural that they migrate toward the more negative terminal of the two contacts and when they strike the colder metal they stick and pick up their missing electrons from the current flow.

If you recall a badly worn set of points removed from an automotive ignition system, the contacts were never worn evenly. They mated together when closed but one contact would be fatter, perhaps convex in shape. It would exactly fit into the concave surface of the other contact. This is the most routine example I can think of where the transfer of metal from one contact to the other can be observed. In the case of manually operated switches, this metal transfer phenomenon is seldom

observed. This is because switches as a class of device in an airplane are seldom required to handle over 10 amps of *inductive* or *tungsten* load for very many cycles. If you ran a set of ignition points for 10,000 miles at 3000 revolutions per mile in an 8 cylinder engine, they would have to make and break a 2-amp *inductive* load 120 million times! Not much arcing takes place at each switching action but 120 million itty-bitty arcs can transfer a substantial amount of metal.

Metal transfer is the culprit in another switch failure mode. It works like this: suppose after many normal operations of a particular switch some significant metal transfer has taken place. A general form of the transfer is for metal deposited on the positive contact to form a little sharp topped micro-mountain only a few thousandths of an inch high. Now let us suppose that on some particular closure, this little mountain of metal does not fall exactly into the valley on the other contact and instead it hits on the rim. If the switch is carrying a high inrush load like a motor or a large lamp, the tip of the mountain, as a poor conductor of large currents, becomes the welding material for sticking the two contacts together! Contact closure welding is a phenomenon most often found in large relays or "contactors". Contactors are special switches; a topic of the following few paragraphs. The starter contactor is most likely to suffer contact welding although I have seen battery, landing gear and flap motor contactors stick too.

ROTARY SWITCHES

For a device which simply connects or disconnects wires from each other, switches can be very complex too! Take a look at the cam operated switches in a washing machine or an automatic dishwasher some time. Aircraft circuit designs seldom require such complexity but there are a few cases where a simple toggle switch won't do the job. The transmitter selector switch for an aircraft microphone circuit is often actuated by twisting a knob through three or more positions. This single, rotary switch might control the interconnections of up to 20 wires!

Illustrations of rotary switches are shown in Figure 11-3. This figure shows an example of a rotary switch section (sometimes called a wafer) and examples of schematics representing a rotary switch. Switch sections are assembled on a shaft to any practical number. At Hughes Aircraft about 25 years ago, I recall repairing a test fixture wherein the fifth section in a

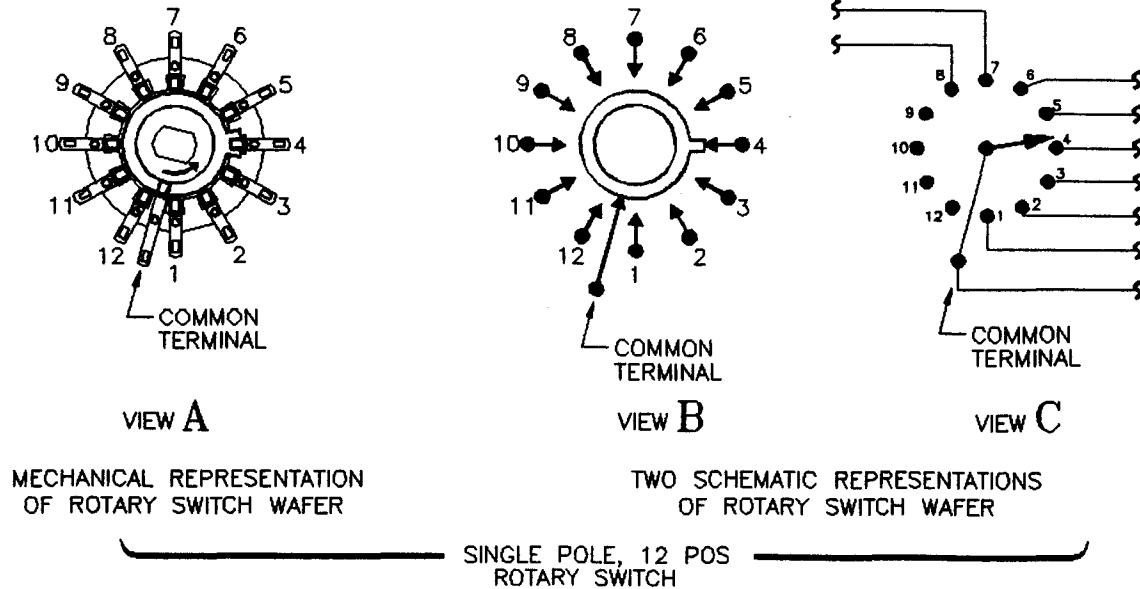


Figure 11-3. Rotary Switches.

ack of about 12 was burned. I was able to disassemble the switch, remove and replace the burned section, and reassemble the switch. Only ten connections out of the 100 or so total were soldered to the damaged section. You are unlikely to need many sections for an application in your airplane. In a later section on instrumentation, we'll discuss the use of a rotary switch to select from a variety of thermocouples for the measurement of temperatures.

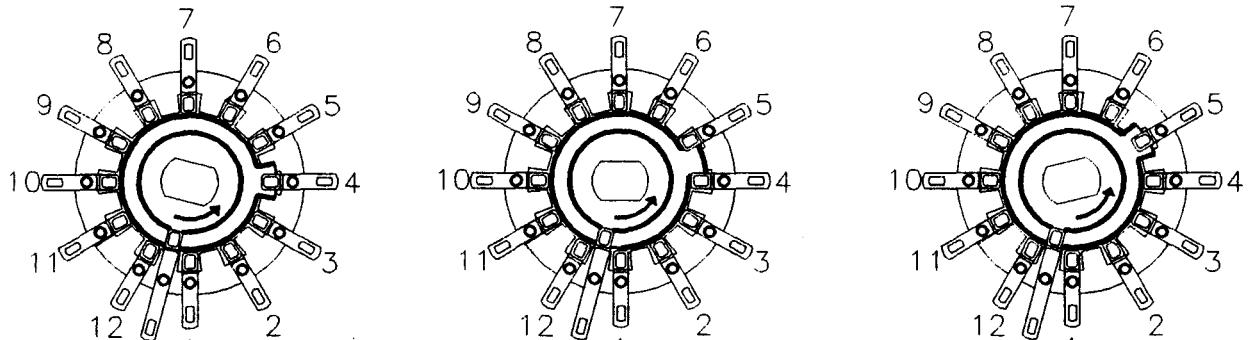
A subscriber told me of a trip to a local parts store to purchase a rotary switch. The clerk asked if he wanted a "shorting" or "non-shorting" type. He replied, "non shorting, of course. Who would want to buy a shorted switch?" The clerk didn't answer his question; the reader asked me about it in a later telephone conversation. I explained as follows:

In some circuit designs, it is undesirable to have the common terminal become disconnected or "floating" during the transition from one position to the next. In Figure 11-4 I have shown a series of views for the two types of switches. Observe that the rotor in both series of views is transitioning from position 4 to position 5. The center views show mid positions. In view B, the rotor tab is wide enough so that it makes contact with

the next position (5) before it breaks with the last position (4). In view E, the narrow tab has already broken connection with position 4 and has not yet made connection with position 5. Most of the time, a non-shorting or break-before-make switch is appropriate. In some instrumentation or audio selector applications, the shorting or make-before-break is used. Do not rely on a schematic symbol to make definitive statements as to the type of switch needed for the task. A bill of materials part number or description in accompanying text should be consulted to determine which type of switch is recommended.

"MICRO" SWITCHES

There is a class of switches ordinarily referred to as micro switches. These are plunger operated, single pole, double throw switches like those illustrated in Figure 11-5. To call every example of these switches "micro switches" is like calling all copy machines "xerox's." Microswitch is the name of a company that pioneered little plunger operated basic switches and the name sort of stuck. In the examples shown, a variety of sizes and actuating systems are given. The devices in



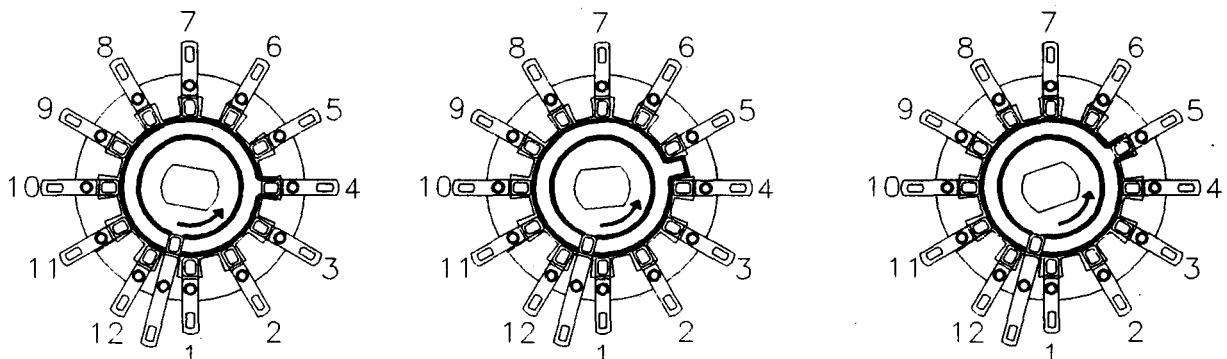
VIEW A

VIEW B

VIEW C

A "SHORTING" TYPE ROTARY SWITCH

A SHORTING TYPE SWITCH WILL MAKE THE NEXT CONNECTION BEFORE BREAKING THE LAST CONNECTION. NOTE IN THE EXAMPLE ABOVE THAT THE SELECTION TAB ON THE ROTOR IS WIDER SO THAT IT CONTACTS TERMINAL 5 BEFORE BREAKING CONTACT WITH TERMINAL 4, AS IT TRANSITIONS FROM 4 TO 5.



VIEW D

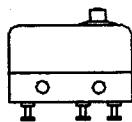
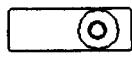
VIEW E

VIEW F

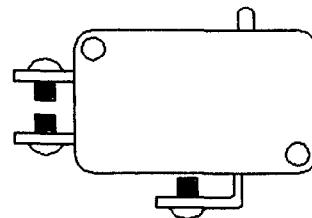
A NON-SHORTING ROTARY SWITCH

A "NON-SHORTING" SWITCH WILL BREAK THE LAST CONNECTION BEFORE MAKING THE NEXT CONNECTION. NOTE IN THE EXAMPLE ABOVE THAT THE SELECTION TAB ON THE ROTOR IS TOO NARROW TO CONTACT TWO TERMINALS AT ONCE AS IT TRANSITIONS FROM POSITION 4 TO POSITION 5.

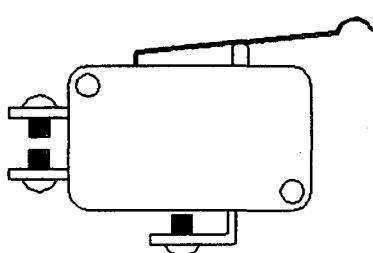
Figure 11-4. Shorting versus Non-Shorting Rotary Switches.



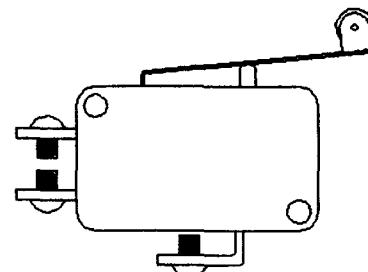
VIEW A



VIEW B

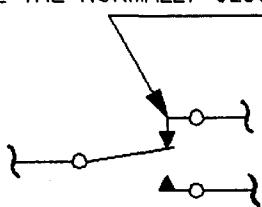


VIEW C

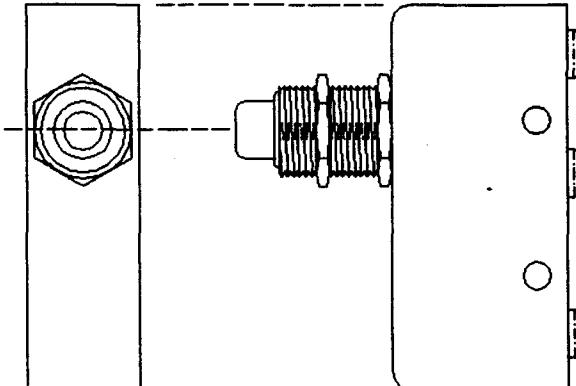


VIEW D

MANY CIRCUIT DESIGNERS USE THE RIGHT ANGLE 'HOOK' ON ONE CONTACT TO DENOTE THE NORMALLY CLOSED CONTACT.



VIEW E



VIEW F

Figure 11-5. Plunger Operated Basic Switches.

the illustration are approximately actual size. There are some smaller as well as larger but these will take care of about every application in a homebuilt.

A familiar application of basic switches is for limit sensing in mechanisms. Applications include up and down limit sensing in flap and landing gear systems. Other tasks include sensors for unlocked canopy latches, open baggage doors and sensing whether or not pitch trim is in take-off position. Basic switches are often combined with a pressure sensing diaphragm to fabricate an under-pressure or perhaps an over-pressure warning circuit. Small plunger or lever operated switches are used to sense down locks on landing gear mechanisms. "Three-in-the-green" on short final means that three separate switches have been actuated and now show that all gear mechanisms are down and locked.

Catalogs are available from Microswitch and others which detail an uncountable combination of ways these switches may be configured. It is unlikely that you will need to order anything very exotic from a catalog listing. However, the catalogs are invaluable for *identifying* a switch's characteristics. You can probably find switches suited to your needs in surplus catalogs, fly/flea markets, etc. Most switches will be marked with the name of the manufacturer and a part number. Manufacturer's catalogs will then help you determine the electrical ratings, mechanical characteristics and special features which may have been built into the switch. They are not expensive switches when new. They are built by the millions and regularly surplused by industry in large quantities. Surplus outlets should be considered good sources for basic switches.

Figures 11-6 and 11-7 give some examples of basic switch application. In Figure 11-6, the switches are wired to provide automatic shutoff of an electric trim motor, just before the mechanism reaches hard mechanical stops. In this example, the motor current is low enough to allow the basic switch to carry motor current. In Figure 11-7, an electrically extended flap system is illustrated. Here the motor current is too large to run through small switches so control relays are added to the system. The pilot's panel operated switch and the basic switches used as limit sensors may now be rated to carry relay coil current (milliamps) instead of motor current (tens of amps).

RELAYS AND CONTACTORS

This brings us to the next topic of discussion in this

section: relays and contactors are types of remote controlled switches. A need for a remotely controlled switch can arise from: (1) the current to be controlled is too great to be carried by a basic, hand operated device or (2) a large number of circuits must be switched simultaneously but the system design makes it impractical or impossible to bring all of the wires to a hand operated switch location.

An example of multiple circuit switching can be found in many VHF COMM transceivers (See Figure 11-8). Pressing the microphone button closes a single wire circuit which energizes the electromagnet of a relay. A two pole, double throw DPDT relay inside the transceiver disconnects the comm antenna from the receiver and connects it to the transmitter. At the same time, a second pole disconnects power from the receiver and applies it to the transmitter. The act of changing from a receive to transmit mode may require the changing of many more circuits than antenna and power. I remember the very unpopular chore of changing out the transmit/receive relay on a particular FM Two-way transceiver back in the '60's. The thing occupied only about 2 cubic inches of volume and was buried deep in the guts of the power supply. It had 12 wires attached to it that were never long enough to allow clipping the old relay out and soldering in a new one. The job took over an hour! In that instance, 7 different circuits, some with hundreds of volts on them, were switched when the operator pressed one little button on the microphone.

The most familiar form of contactor is that which is used to control the airplane's battery and starter motor. A contactor is really just a big relay but it has features which make it unique and worthy of the name "contactor". Some people call these devices "solenoids"; close but no cigar. A solenoid is an electric motor; it imparts motion to a mechanism when electrical power is applied. Contactors are solenoid operated switches and indeed, many starter engagement solenoids on automobiles also control the electrical side of the starter motor.

There are features which set a contactor apart from the relay: first, the magnetic motor that actuates it is more powerful than the one found in a transceiver's transmit/receive relay. For relays, a few ounces of force is sufficient to hold the contacts closed. A contactor may require several pounds of force for reliable operation. The form of the contacts is unique too. The schematic symbol for the contactor suggests an electrical conductor is bridged between *two* contacts as the device closes. There are a couple of good reasons for

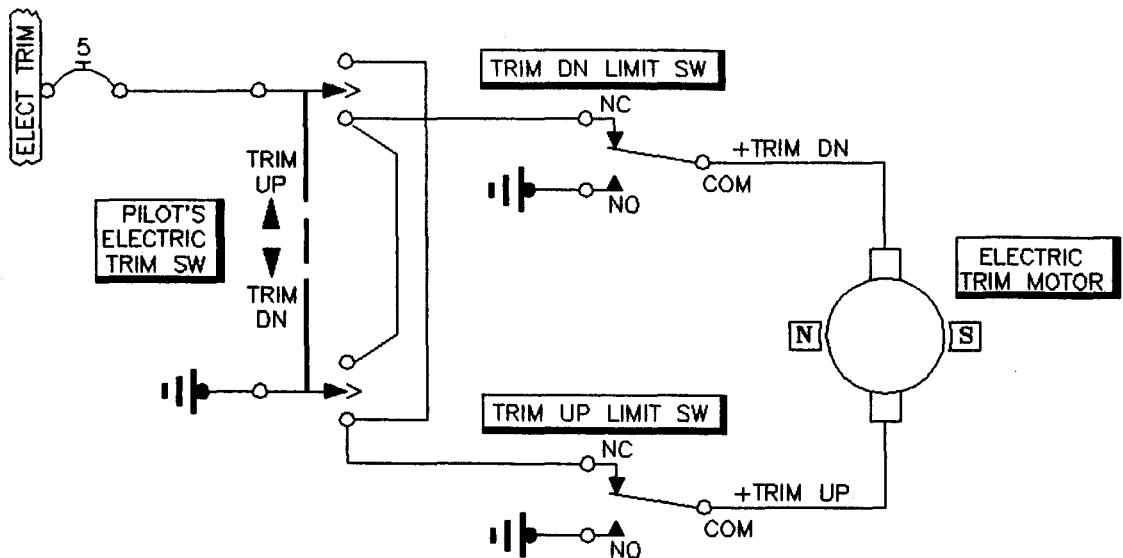


Figure 11-6. Basic Switches as Motion Limiters in a Low Current Motor Circuit.

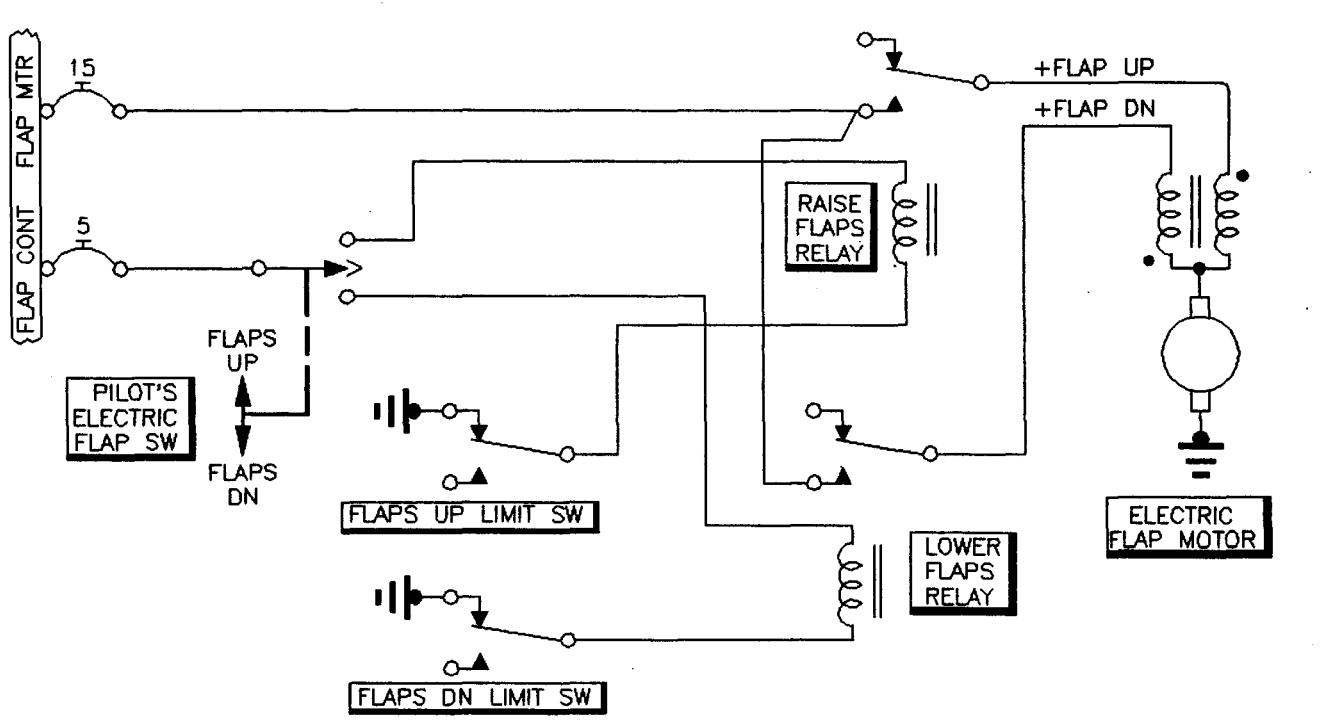


Figure 11-7. Basic Switches in Combination with Relays.

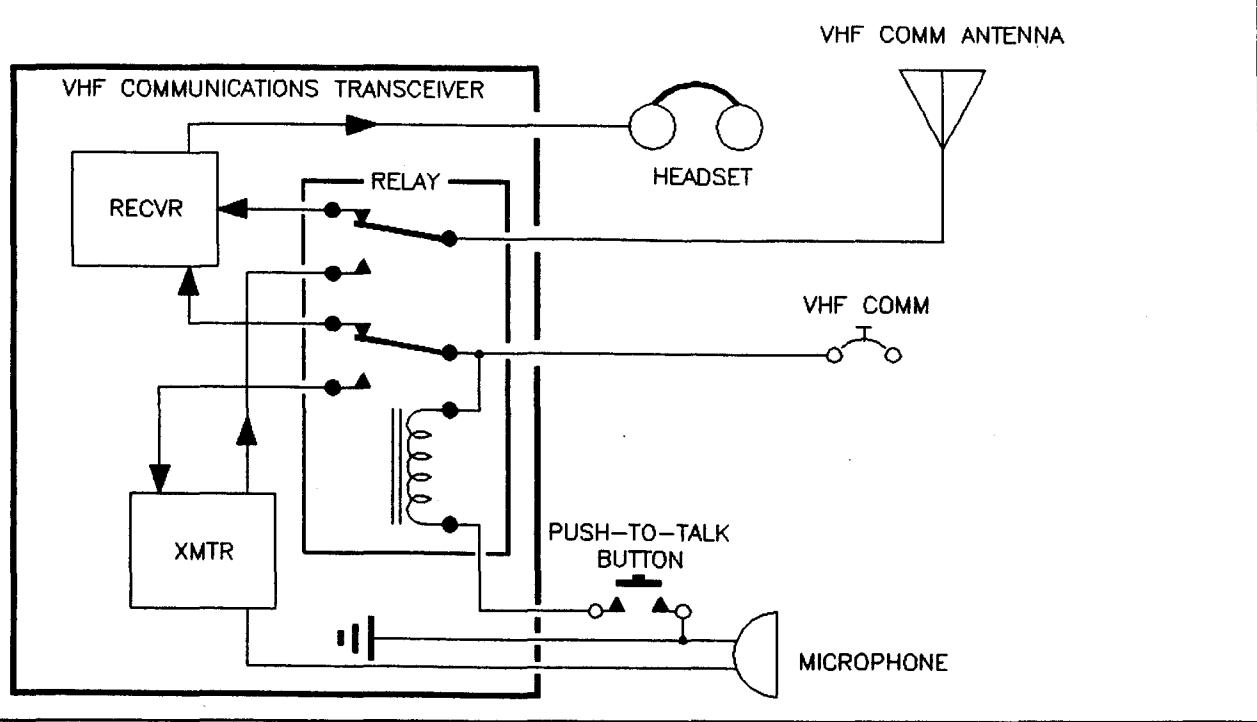


Figure 11-8. Multiple Circuit Switching in a Transceiver with a Relay.

this approach to the design. One is simplicity. In relays, a flexible conductor is often incorporated to make electrical connection to a contact which moves. A flexible conductor rated for hundreds of amps isn't very flexible! So, by using a movable contact to bridge between two stationary contacts, the need for a flexible conductor is eliminated.

The second reason has to do with contact life. Recall that switches with a very snappy action have fast contact spreading velocities and are able to break an arc before it builds to intolerable heat levels. The massive moving components of a contactor simply cannot be made to "break" quickly. The problem is compounded when the contactor is used to operate the engine starter motor which is quite *inductive* and capable of storing considerable energy in its magnetic circuits! The contactor really has two sets of contacts in series. So . . . when one of the contacts has opened to a gap of 0.050", so has the other. The result is the same as though the contactor had a single air gap of 0.100". The series connection has the net effect of doubling the air gap *and* the contact spreading velocity on what is otherwise a slow moving clunker of a contactor.

Contactors which you are likely to encounter come in two basic forms illustrated in Figures 11-9 and 11-10. For the sake of discussion we'll call these Type I and Type II. Type I is a "trickle up" technology from automotive and industrial applications. This contactor has been used by the tens of thousands on Cessnas, Pipers and some Beech single engine airplanes. The contactor sells for under \$20 from Newark and others. This contactor has taken a lot of flack for its propensity for failure and high cost of replacement at Smiley Jack's Airdrome Services.

I've disassembled a lot of dead Type I devices over the years. I can tell you that a goodly number of the contactors I've opened failed prematurely from environmental abuse of one kind or another. I've seen them rusted out and/or water damaged inside. Some years ago, Cessna went to a floating cowl for cabin noise reduction. The gap formed by shock mounting the cowl allows rainwater to run down the firewall. Cessna mounts a lot of electrical hardware on the firewall. Their "fix" was to seal things up with epoxy, silicon rubber, and other sorts of ickum-yucky. Sealants are minimally successful in these situations, a topic I will discuss in an upcoming section on reliability.

STATIONARY CONTACT FORMED
ON END OF TERMINAL POST.

MOVEABLE CONTACT DISK MOUNTED
ON END OF SOLENOID ARMATURE.

TAKE CARE DURING
INSTALLATION TO
PREVENT TERMINAL
POST ROTATION WHILE
TIGHTENING TERMINAL
NUTS.

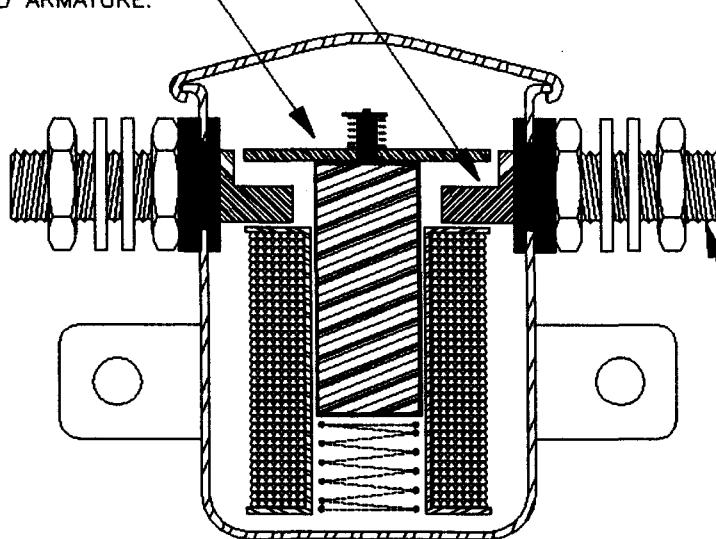
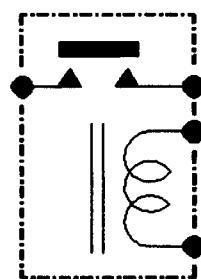
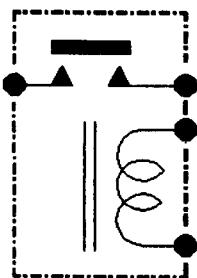


Figure 11-9. Type I Contactor Cutaway View.

MOVEABLE CONTACTS ARE MADE FROM
SILVER-CADMIUM ALLOY AND BRAZED
TO BUS BAR.



STATIONARY CONTACTS ARE
BRAZED TO SOLIDLY MOUNTED
BUS BAR. RISK OF MISALIGNMENT
DUE TO INSTALLATION ERROR IS
ELIMINATED.

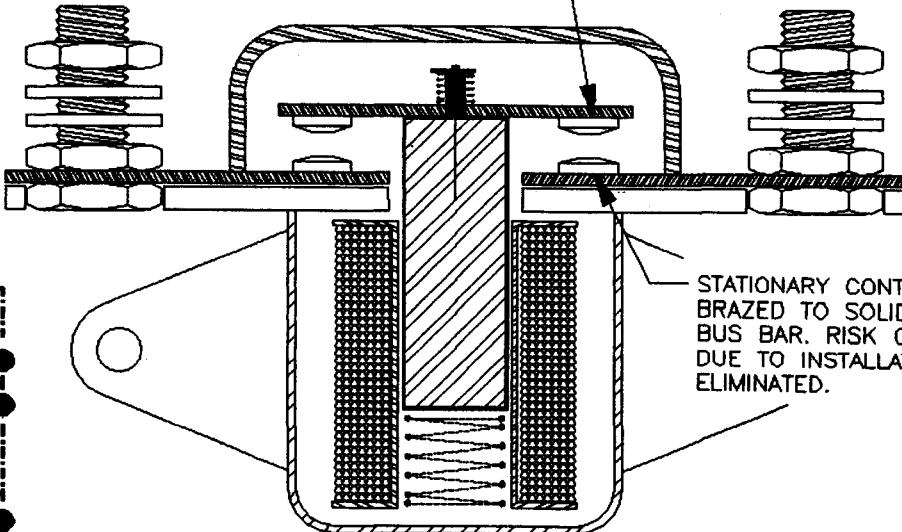


Figure 11-10. Type II Contactor Cutaway View.

Suffice it to say here that internal damage from water entry is not an uncommon cause of contactor failure in Cessnas.

Another form of failure in Type I devices is precipitated by the mechanic who installs a new contactor. Note that the stationary contacts are fabricated on the end of the threaded connector stud which penetrates the housing wall. If the installer is not careful, the stud is rotated a tiny amount due to overzealous tightening of the stud nuts. The resulting tilt placed on the face of the stationary contact prevents good mating with the movable contact. The reduced area of contact precipitates early failure.

Earlier in this section I discussed switch failure modes precipitated by contact heating which raises contact resistance which increases heating which increases resistance This precipitous slide to failure is "lubricated" by moisture and accelerated by external heat sources such as exhaust stacks.

The Type I devices that failed by just being tired had many hours of service on them. My personal judgment of these devices is that they will perform well if you (1) keep them from getting wet, (2) don't twist their arms too hard during installation and (3) mount them free of radiant and/or conducted sources of heat. An advantage of the Type I contactors is their low cost. I would happily use them in any airplane I built, and carry spares!

Type I devices have a catalog rating of only 70 amps. Properly applied, they have performed well in systems where they are routinely loaded to 200 amps during cranking.

Type II contactors are "trickle-down" technology from military specified devices. The contacts are indeed an on purpose, cadmium silver button designed for heavy duty relay service. This is in contrast with Type I contactors where a raw copper disk is mashed down on raw copper flats machined into the terminal studs. Note too that Type II studs are independent of the contacts and interconnected with them by a bus bar.

Type II contactors are available in ratings up through 400 amps--larger than you will ever need in a single engine airplane! In fact, you could use 100-amp devices in either battery contactor or starter contactor applications. The contactors would be overloaded to some degree during cranking but only momentarily and infrequently. If you are interested in using Type II devices, check in the catalogs for Cutler-Hammer 6041 series parts.

Relays and contactors have contact ratings much the same as those of a switch. A fully specified relay or contactor may

have separate ratings for *resistive, inductive or tungsten* loads. These devices must have a second rating as well for their electromagnetic operating motor, sometimes called the "coil" rating. The coil rating may or may not have anything to do with the rating of the contacts. For example, the relay used to turn on the fan motor in your furnace or air-conditioner may be operating on 24 volts AC for the coil but the contacts will be handling 120 or perhaps 240 volts! The relay or contactor is simply a remote controlled switch and the controller may be rated to operate in an entirely different electrical environment than the contacts.

When selecting a relay or contactor for a specific task in an airplane, consider both the coil and contact ratings. The coil will need to be rated at 12-14 or 24-28 volts D.C. Important! . . . AC and DC coils are designed differently. You cannot use a 12-volt AC rated relay coil in a 14-volt DC airplane. There may also be a duty cycle rating on a contactor coil. Relays are almost always designed to be a continuous duty device. That is to say that there is no time limit on how long the relay coil can stay energized. Some contactors have over-stressed coil conductors to provide extra pulling power without increasing the physical size of the electromagnet. This is commonly done when the contactor is expected to see very short ON times (such as for engine cranking). The battery contactor, however, must have a continuous duty rating since it must operate continuously for hours at a time.

Contactors are frequent finds at surplus stores and fly/flea markets. If you are considering a Type I *which is not in its original packing container and/or bears signs of having been installed*, I wouldn't give more than \$5 for it. (Check for circular scratches on the mounting ears and dings on the nuts to answer the installation question.) If very clean and/or in original factory packing then look for an identifiable part number; a search in the catalogs will give you the critter's pedigree. Now, suppose you have a pretty clean, not rusted Type I contactor. Let us further suppose it shows signs of installation (scratches, nuts missing, etc.). \$5 to \$10 isn't much of a risk. If no catalogs are handy, an ohmmeter check of the coil terminals will give a clue as to its duty rating. On 14-volt devices, a coil resistance of 15 ohms or less suggests an intermittent duty contactor, suited only for starter motor control. Coil resistances above 15 ohms suggest continuous duty rating on the coil. Double these values for a 28-volt device. Many Type I devices have only one coil terminal brought to the outside. This means the other end of the coil is connected to a main terminal stud or to the metallic case; your ohmmeter check will confirm which.

Surplus Type II devices may be disassembled for inspection. A cover over the relay contacts may be removed with simple

tools. If you can find clean surplus parts in the Type II devices, they should be priced on the order of \$30 or less; new ones are \$160 and up. 14-volt Type II devices from surplus sources will be rare since most were originally purchased for 28-volt military vehicles.

THINGS YOU CAN DO WITH SWITCHES

Say what? Everybody knows that switches turn things on and off. What's the big deal? I'd agree that most of the switches we operate every day are simply a handy means of opening and closing a gap in a wire. I'll add that switches come in a variety of flavors. Aside from the simple on/off control of, say a light bulb, variations on a theme give us handy tools to simplify a variety of switching tasks.

Table 11-1. AeroElectric Connection
S700-Series Toggle Switches

Dash No.	# of Poles	# of Positions	Action Keyway - Center- Opposite
1-1	1	3	ON-OFF-ON
1-2	1	2	OFF-none-ON
1-3	1	2	ON-none-ON
1-5	1	3	(ON)-OFF-ON
1-7	1	3	(ON)-OFF-(ON)
1-8	1	2	(ON)-none-ON
2-1	2	3	ON-OFF-ON
2-2	2	2	OFF-none-ON
2-3	2	2	ON-none-ON
2-5	2	3	(ON)-OFF-ON
2-7	2	3	(ON)-OFF-(ON)
2-8	2	2	(ON)-none-ON
2-10	2	3	ON-ON-ON
2-50	2	3	(ON)-ON-ON
2-70	2	3	(ON)-ON-(ON)

First, I'd like to introduce you to our numbering convention. As we update schematics and power distribution diagrams, we'll try to add more detail to a switch's description. Adjacent to the reference designator number (S1, S2, S3,

etc.) we'll include in parentheses the dash number out of Table 11-1 which describes the switch's number of poles, number of positions and its action.

The left column of Table 11-1 is the suffix to add to the basic switch specification number. To fully describe a switch you would precede it with the standards number followed by the dash number appropriate to the action you want. For example, an S700-2-7 switch is a two pole, three position toggle switch spring loaded to center from both extremes and having an (ON)-OFF-(ON) action. The parentheses () around an action label means the switch is spring loaded to leave that position when released. Other styles of switches (like rockers) will replace the "S700" with another number but the dash number to describe the number of poles: number of positions and action will remain the same.

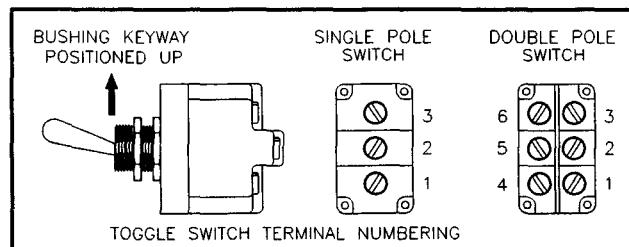


Figure 11-11. Toggle Switch Terminal Numbering.

We'll standardize all our drawings to conform to the above terminal numbering convention for switches. The mounting for a toggle switch is a 15/32" threaded bushing with a keyway cut on one side. Switch actions described in the last column have keyway side positioning of the toggle first, followed by center positioning (3-position switches only) and opposite side positioning on the right. For most applications, switches are mounted with bushing keyway oriented UP in the panel.

It is appropriate to mention here that toggle switches can be difficult to keep tightly mounted in the panel. This is because it's

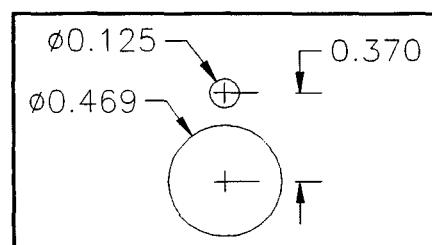


Figure 11-12. Hole Layout for S700 Series Toggle Switches.

attached with threaded fasteners and you're always yanking on its handle. You could use thread-locker to make the nuts difficult to move after the switch is installed but this makes

the switch difficult to replace later.

The best solution is to take advantage of the anti-rotation keyway washer and internal tooth lockwasher that is supplied with all switches from our catalog. The keyway washer has two tabs, one to engage the keyway in the switch bushing, the other to engage a 0.125" hole that you need to drill in the panel, 0.37" above the 15/32" mounting hole. The anti-rotation keyway washer installs from the back and will not protrude through a panel of .062" thickness or more. Most panels have a placard to label the switches that will cover a 0.125" hole. Inclusion of this hardware in your installation will keep the switches right where you installed them. Leaving thread-lockers out of the installation will make them easy to replace should it become necessary.

By the way, you'll find a 9/16" "Spin-Tite" or nut driver very useful when installing or replacing toggle switches. I have several that have been polished with crocus cloth to a very shiny surface where it touches the panel. This little modification to the stock tool assures you that it cannot scratch your panel placard . . . even if it's plastic.

SINGLE POLE SWITCHES

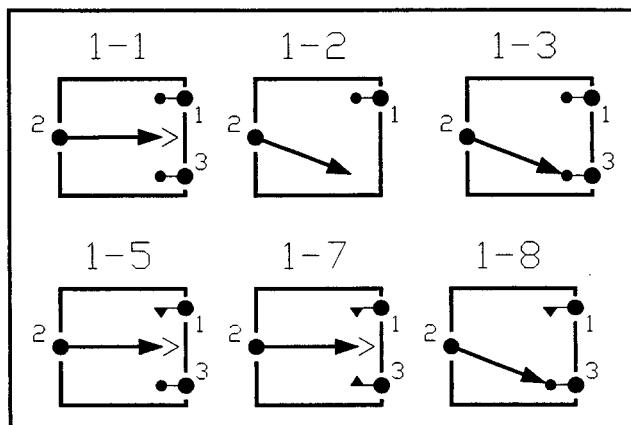


Figure 11-13. Family of Single Pole Switches.

Here's how the single-pole switches look in our schematics. The symbols have a great deal in common but there are differences that give you clues as to what kind of switch is being called out . . . and how it works.

First, I'd like to point out the ">" symbol between terminals 1 and 3 of three switches illustrated in Figure 11-13. This tells you that there is a center position that makes it a 3-position device. Switches without this symbol are 2-position devices. Note also that the moveable "arm" of the switch can be swung to make contact with either a solid dot (●) or a solid triangle (▼). The dot represents a sustained position

for the switch while the triangle represents a momentary or spring loaded position.

Okay, 6 kinds of toggle switches . . . why would we want so many and what would we do with them?

1 dash 1, ON-OFF-ON switches are useful for selecting either of two devices with a both off position. How about having a landing and taxi light fixture share a single fuse or breaker? Terminal 2 connects to the bus, terminal 1 might power the landing light fixture while terminal 3 connects to the taxi light.

1 dash 2, OFF-none-ON switches are useful for any simple task of controlling nav lights, landing light, fuel pump, pitot heat, etc. We don't stock this kind of switch because a 1-3 switch has the same functionality. If you want a 1 dash 2, we can supply it to you. Note that the only "ON" condition is with the toggle placed opposite the keyway. To use this style switch for a landing light, you would have to mount it keyway down in order to have the switch close when the toggle is moved up. On the other hand, a 1 dash 2 switch would serve nicely as a magneto switch. Unlike landing lights, magnetos are "ON" when the switch is open. I've included them in the family tree of switches because they do exist.

1 dash 3, On-none-ON switches select either of two circuits but doesn't permit both to be off. Obviously, terminal 3 of the 1 dash 3 switch can be ignored when the switch takes on simple tasks of the 1 dash 3 style switch described above. Since connection is made at both extremes, you could use a 1 dash 3 switch to use a single fuel gage to monitor either right or left-hand fuel tanks. Or how about switching a single dimmer between two lighting loads, say a map light and an overhead flood?

1 dash 5, (ON)-OFF-ON switch has one position spring loaded to center, the other is a sustained position. One application that comes to mind would be an ignition-start combination switch for an engine like a Rotax. Terminal 2 would be connected to ground. Terminal 3 would ground the ignition in the down position (kill the engine), leave the ignition free to function in the mid position, and operate a ground-to-energize starter contactor in the up position. Here's a first example of getting a single switch to do two separate but related functions. I've had some builders use the 1 dash 5 switch for electric flaps where a single action selects fully "extended" flaps but the spring loaded "retract" operation is conducive to milking the flaps up during a go-around.

1 dash 7, (ON)-OFF-(ON) switches have momentary throws both sides of center. This action might be used for

electric trim operations where momentary blips to either direction of trim are desired. On of my Defiant builders plans to use a 1 dash 7 switch to control front and rear starter contactors from a single switch.

1 dash 8, (ON)-none-OFF switches have a sustained and momentary contact at either extreme of two positions. The **1 dash 8** action could be used to replace a push-button where terminals 2 and 1 are used to momentarily operate some device (like the starter contactor).

TWO POLE SWITCHES

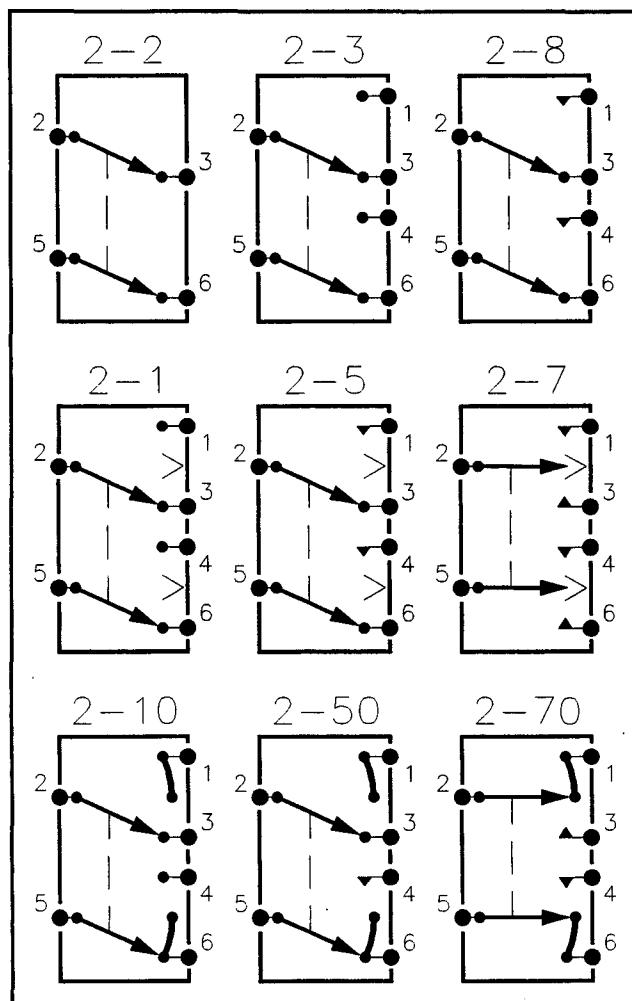


Figure 11-14. Family of 2-Pole Switches.

Wow! wouldja look at all those two-pole devices! You'll recognize the first 6 as close cousins to the single pole devices shown earlier. We've simply doubled up the mechanism so that two switches side by side share the same

behavior. When a 3-position switch has more than one pole, small changes in the transfer mechanisms can yield some unique functions.

I don't have applications for all of the switching actions depicted but here are a few that I've used in the past. Some of these are also shown on our power distribution diagrams and wire-book examples.

2 dash 3, On-none-ON is a common part number we stock. This device is recommended for combination battery-master/alternator-field switching. MUCH less expensive than the popular but unnecessary "split rocker" found on many certified ships, the **2 dash 3** works quite nicely in this position. The **2 dash 3** also serves nicely as a magneto switch. You can use terminals 2 and 3 to kill the magneto in the down or OFF position. The other pole is used in series with the second magneto switch. Properly wired, you can disable the starter except when the impulse coupled magneto is ON and the non-impulse coupled magneto is OFF. Use of toggle switches with a starter lockout feature eliminates the kickback hazard inherent with the key-type OFF-L-R-BOTH-START switches found on most certified single engine ships. Furthermore, toggles are easier to mount and much less expensive than the key-switch. The big bonus of using toggles comes when and if you replace either or both magnetos with electronic ignition. The existing toggle is "electronic ignition ready."

2 dash 7, (ON)-OFF-(ON) is commonly found in trim or flap systems that use permanent magnet motors. When wired as shown below, the **2 dash 7** reverses polarity of power applied to the motor to reverse its direction.

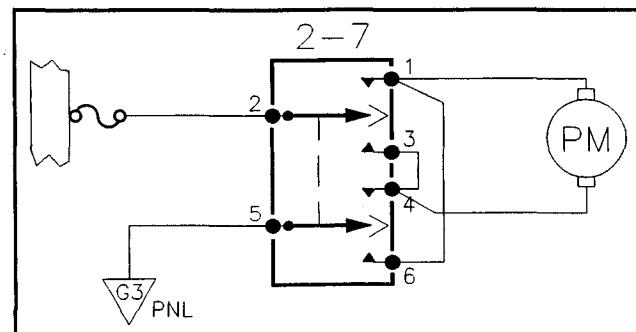


Figure 11-15. example of a 2 dash 7 Switch Application.

The spring loading to center from both extremes makes it easy to "bump" the switch for small trim changes.

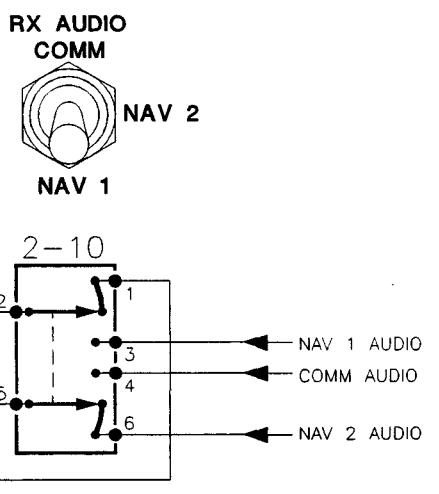


Figure 11-16. Example of a 2 dash 10 Switch Application.

2 dash 10, ON-ON-ON. Here's an interesting example of how you can wire a 2 dash 10 switch to implement a single-pole, three-position action. In the drawing above, I show how a headset can be switched individually to any of three audio sources. Incidentally, four pole switches are available in the dash 10 configuration so that you can implement a 2-pole, three-position configuration.

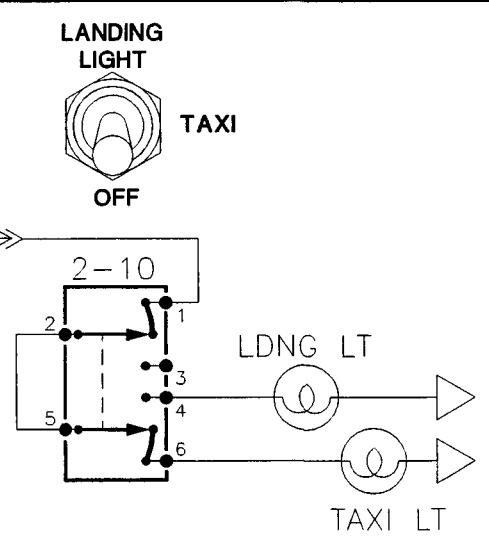


Figure 11-17. Example of a 2 dash 10 Switch Application.

control landing and taxi lights from a single switch powered from single source.

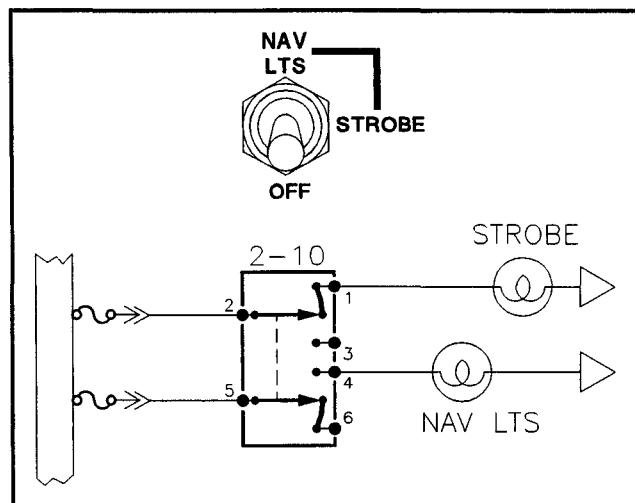


Figure 11-18. Example of a 2 dash 10 Switch Application.

Another space saver for switch panels uses a 2 dash 10 switch to control both strobe and nav lights. The first position brings up the strobe lights while the second adds nav lights. Each lighting circuit has its own power supply and circuit protection.

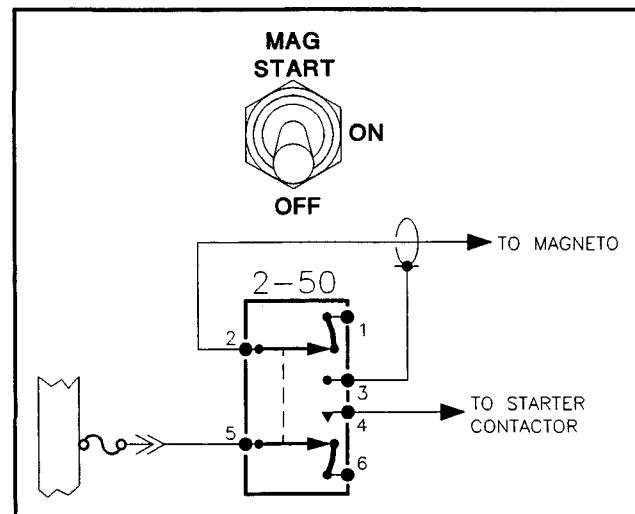


Figure 11-19. Example of a 2 dash 50 Switch Application.

Shuffle the wires a little bit on a 2 dash 10 and you can

Here's a way to combine magneto switching with starter

control. Using the **2 dash 50** in this configuration makes it easy to change out magnetos for electronic ignition at a later date. Just use terminals 1 and 2 to control DC power to the ignition system.

4-pole versions of these switches follow the same numbering conventions. The need for a 4-pole device is pretty rare but a 4 dash 10 switch could be wired as a 2-pole, 3-position transmitter select switch or perhaps to use a single instrument for monitoring volts, main alternator load and aux alternator load.

Virtually all applications I've had for 4-pole switches were some small signal application where a miniature toggle was called for. We may not stock these soon but if you need one and have trouble procuring it, we'll be pleased to assist.

FUN PROJECTS WITH CONTACTORS

Battery Master Contactors - everyone needs at least one. The ship's battery is capable of serious output of hundreds of amps - way too much to manage with manual switches. Primary control of batteries is delegated to the battery master contactor. Figure 11-20 illustrates typical battery master contactor wiring. Note that I've shown a 3-terminal contactor, but it could just as easily have 4 terminals. In this case, coil terminal has been internally wired to one of the large terminals. Many times the large terminal will be stamped "BAT" by the contactor manufacturer. If you use a 4-terminal device, you'll have to provide your own jumper between the upper coil terminal and the always-hot battery terminal.

A battery contactor needs to be a continuous-duty rated device. I.e., being energized for hours at a time doesn't generate so much internal heat from the coil that it raises its temperature to destructive levels. Note that I show the battery master contactor being controlled simultaneously with the alternator field circuit using a 2 dash 3 style switch. The "traditional" split rocker switch used on most certified single-engine airplanes for controlling DC power offers no particular utility or advantage.

Note also the use of a diode across the contactor's coil terminals. Contactor coils are inductive devices. When the energizing circuit is broken, the magnetic field collapses very rapidly (see Kettering ignition discussion in Chapter 6). If allowed to progress unrestrained, the voltage spike

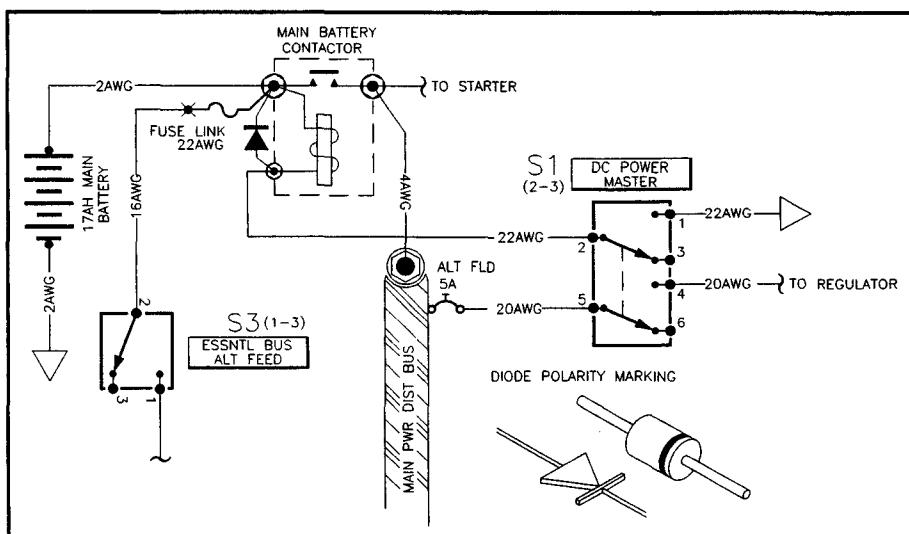


Figure 11-20. Battery Master Contactor Wiring.

generated by this magnetic field collapse can be hundreds of volts in amplitude. The use of a diode catches this spike and keeps it from eroding the contacts of the master switch. It is a popular belief that diodes wired in this manner are protecting avionics and other fragile devices from the ravages of contactor coil spikes. Actually, these spikes are very low energy and easily filtered off by power input conditioning built into all modern avionics products. The device at risk from potentially high voltage discharges is the battery master switch. Repeated breaking of the unrestrained inductive load will erode the switch's contacts.

Until Revision 8 to this book, I've recommended metal oxide varistors (MOV) as "spike catchers." I liked them because they are AC devices and work well connected in either direction - you can't hook them up backwards. However, they're not a commonly stocked item with electronics suppliers in the voltage ratings needed for 14V systems.

Diodes are very easy to obtain and the only caveat in their use is to observe the polarity of the device as compared to its schematic symbol. These are illustrated in Figure 11-20. One further item to point out: note that there is no circuit breaker associated with the control circuit of a battery master contactor. This is because there are no failure modes that would burn the wire. Opening the wire simply causes the contactor to fail to function. A grounding of the wire causes the contactor to be continuously energized . . . it will certainly run the battery down but it doesn't put the wire in jeopardy. This is in contrast to the other circuit which shares a DC Power Master Switch - the alternator field circuit is supplied from the bus. Faults on this wire are quite capable of smoking the wire . . . besides, this is the lead that gets deliberately faulted by a crowbar OV module . . . we always put a breaker in this line.

Starter Contactor wiring shown in Figure 11-21 is typical. Note that this circuit does get circuit protection by way of a breaker or fuse. This particular contactor is also a 3-terminal device with one side of its solenoid coil grounded to the mounting base. Unlike the battery contactor that needs a GROUND to operate, the starter contactor needs a SOURCE of power. When mounted on a metal firewall, this contactor gets an operating ground from the firewall. If you mount this contactor on a nonmetallic and/or ungrounded surface, you'll need a separate wire from a mounting bolt to the most convenient power ground in the airplane.

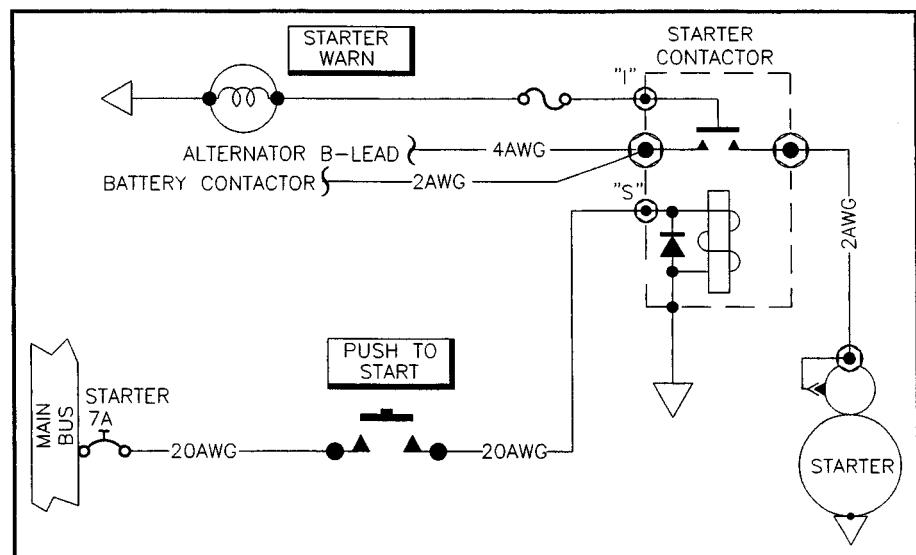


Figure 11-21. Typical Starter Contactor Wiring.

Note also that this contactor has the diode INSIDE the symbol . . . the new line of starter contactors we're stocking has spike suppression diodes built right in. I think this is a trend for future products from most companies. However, if you're in doubt as to the existence of a built in diode, go

ahead and put one outside . . . there's no problem with having two diodes . . . lots of problems with having no diodes!

Our starter contactors have a fourth, smaller (8-32 threaded terminal). Many starter contactors do. It's generally marked

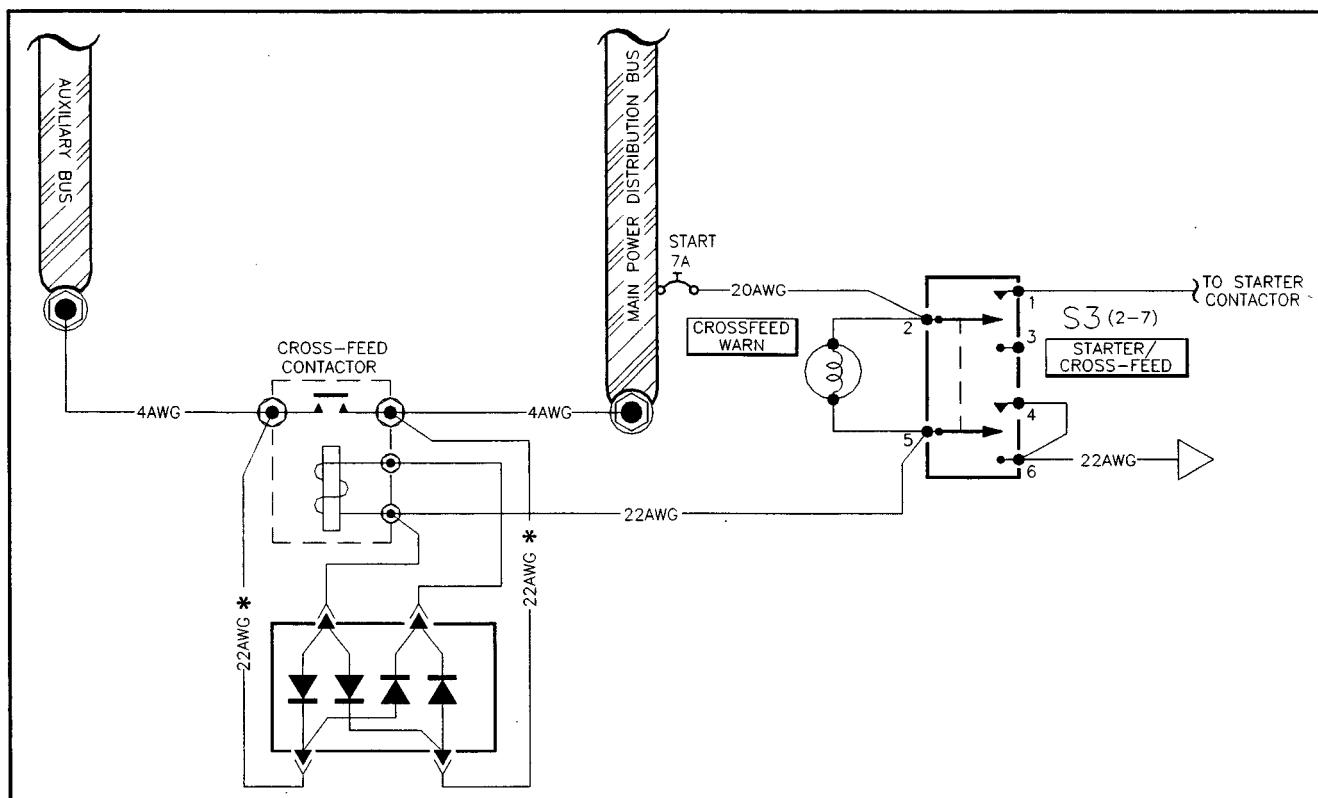


Figure 11-22. Crossfeed Contactor Wiring.

"I." This terminal becomes "hot" when the contactor is energized. If you'd like to have a "Starter Energized" warning light on your panel, you may bring a 5A inline fuse off the "I" terminal and route it to an indicator lamp on the panel. Should the starter contactor or its operating button become stuck, the lamp will remain illuminated after you take your finger off the button.

Crossfeed Contactors are useful when you have independent DC power systems that need to share resources from time to time. There's a dual battery, dual alternator diagram in Appendix Z that features a system crossfeed contactor. An excerpt from that diagram is shown in Figure 11-22. Here's another application for the diode bridge rectifier you see in many of my wiring diagrams. Here we're able to make use of all four diodes in the assembly. Note that a diode from the main and aux bus sides of the crossfeed contactor supplies power to the upper coil terminal. This means that EITHER bus may be used as a power source to get the contactor closed.

In this design, I show a 2 dash 7 switch wired so that when you press the switch to the upper, spring loaded position, you energize the starter contactor with power from the main bus. At the same time, we close a ground to the lower coil terminal of the crossfeed contactor causing it to close. This places both batteries in parallel for better cranking capacity. When the engine starts and you release the switch, both the starter and crossfeed contactors lose power and de-energize. If you trace out the circuitry carefully, you'll find that the remaining two diodes are in a position to serve as "spike catchers" for the crossfeed contactor's coil. Crossfeed contactors should be rated for continuous duty.

In case of alternator failure on either the main or auxiliary bus systems, the Starter/Crossfeed switch can be placed in the lower, maintained position energizing ONLY the crossfeed contactor. This allows power from the full-up bus to flow to the bus with the ailing alternator. Similarly, should the battery contactor fail on one bus, closing the crossfeed contactor places a good battery on both busses. Even when the paralleled alternators don't evenly share the ship's loads, they're both available up to and including their full capacity stabilized by the remaining good battery.

Ground Power Contactors are left off many ground power receptacle installations. Here's why I think they're a good idea. Referring to Figure 11-23 note that I show a contactor in series with the main power between the receptacle and the battery. This gives the contactor command and control over any power source connected to your airplane's electrical system. Note that with the GROUND POWER switch-breaker closed, the ground power contactor will energize any time power is present on the receptacle... provided it's the right polarity. The contactor is prevented from closing in case of accidental reversal of ground power polarity by a diode in the lead between the receptacle's small sense pin and the contactor coil terminal. Polarity reversal accidents are most common with battery carts that routinely receive maintenance that requires unwiring and rewiring a stack of batteries.

Another feature of this circuit is inclusion of a crowbar overvoltage protection module across the coil. This feature is useful when the line boy puts 28 volts to your 14 volt airplane. It's an easy mistake to make: it has happened to me. An OV condition trips out the switch breaker on the panel. The switch breaker is useful because it puts control of ground power in the hands of the pilot. If for any reason you want power removed, you have only to flip the switch. Further, it cannot be put on the airplane until you're ready to allow it.

I like to tie ground power directly into the battery as shown. This feature allows you to charge a dead battery without removing it from the airplane and without powering up any

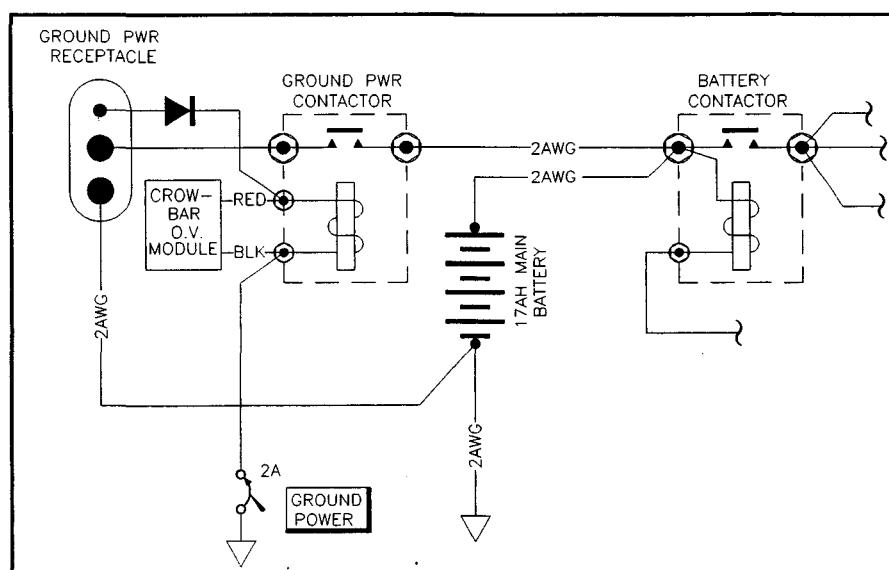


Figure 11-23. Ground Power Contactor.

of the airplane's electrical system. I show a 4-terminal contactor in this application. Further, a continuous duty contactor is appropriate for this service.

CONTACTOR INSTALLATION CONSIDERATIONS

Aside from the obvious caveats mentioned earlier, contactors can be mounted about anywhere. Battery and ground power contactors should be close to a battery. Starter contactors should be close to the starter.

There's an ol' mechanic's tale out there about installing your contactors so that in-flight g-loads don't cause unintentional contact closure. Seems an airshow hot-dog landed to discover a smoked starter and a chewed up ring gear. The theory advanced at the time was that maneuvers during his performance caused the starter contactor to experience tentative closures causing the contacts to weld shut.

I'll suggest that the starter contactor welded when he started his engine. Without a "starter engaged" warning light, he

flew the entire performance with a starter shucking out little bits of metal. How does this story influence what we should do as designers and builders of the world's finest single-engine airplanes? Not much. First, battery contactors are always closed in flight; g-loading--if it ever was a factor--is not a factor here. Ground power and crossfeed contactors are not subject to welding if subjected to momentary, unintended closures. The starter contactors we stock and recommend have an operating axis that usually mounts on the firewall with its operating axis at right angles to aerodynamically induced g-loads and are immune to this influence. Last but not least, if you plan to do advanced aerobatic maneuvers in your airplane, there are lots of system issues to be considered... get the advice of someone who does it for a living!

If you are looking for something worth worrying about in the design and maintenance of your electrical system, I'll suggest that knowing your battery's capacity throughout its service life is much more deserving of your undivided attention.

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AIRCRAFT LIGHTING AND LIGHTING CONTROLS

In this section I'll discuss operation, design and installation of aircraft lighting systems. If an airplane is to be used for night flight, then lights are probably the most prolific class of devices on the airplane. Designing an aircraft lighting system can be a frustrating experience; panel lighting is a **real challenge**. On production aircraft, the goal is to make every instrument, display and control appear uniformly illuminated for every environmental situation. In 1950 there were only a few instruments, a handful of controls and no radios. A couple of red flood lamps on the cabin overhead did the job. If you had a first class lighting system, an ultra-violet flood would make radium painted dials on instruments glow like they were on fire! Somewhere in my junk boxes I have some old toggle switches from that era. Their handle tips have plastic inserts with small spots of fluorescent material. Under a black light illumination, the tip of a switch glows bright green.

Modern general aviation airplanes have dozens of knobs, switches and circuit breakers. Just for fun let's toss in instruments having no lighting and instruments with internal lighting. Finish with a sprinkle of radios with incandescent, gas discharge or liquid crystal displays. I have observed and sometimes participated in struggles to make all these things uniformly visible under all lighting conditions. The problems are not confined to the cockpit. Placement of position lights, landing lights and anti-collision lighting for maximum effectiveness without increasing drag or adding fixtures is challenging too. So, if you have been thrashing around with a lighting system design problem in your airplane for some time, don't get discouraged or feel singularly abused. Professionals struggle with this task too!

WHAT IS LIGHT?

Light is electromagnetic energy just like signals that radiate from a comm antenna when you transmit. Turning a dial on a radio or television receiver adjusts the receiver's ability to accept, amplify and detect energy in a particular band of the electromagnetic spectrum, which is very large. In order to talk about specific locations within the spectrum, a specialized

terminology has been developed. The most common landmarks (or "spectrum-marks") we use are spoken of in terms of frequency. For example, KFH AM radio in Wichita operates on a frequency of 1330 Kilohertz or KHz. The PICHE outer marker beacon at MidContinent Airport is on 332 KHz and the Unicom frequency for Benton Airport is 123.0 Megahertz or MHz.

These same landmarks can also be defined in terms of their *WAVELENGTH*. One descriptive explanation for the concept of wavelength is shown in Figure 12-1. I stole this image from a very old text I have on electronics which was given to me when I was about ten years old. The picture shows a pool of water into which a rock has been thrown. This disturbance of the surface radiates outward in waves which have a series of crests and valleys. If you could freeze the water instantly and then saw through the chunk of ice in a vertical plane, a shape not unlike that in the lower half of figure 12-1 would be seen. The distance from one crest to another in these 'waves' would be wavelength. It may be expressed in terms you use to measure any distance: feet, inches, barleycorns, furlongs or perhaps meters. Meters are the most useful because the metric system is mathematically elegant.

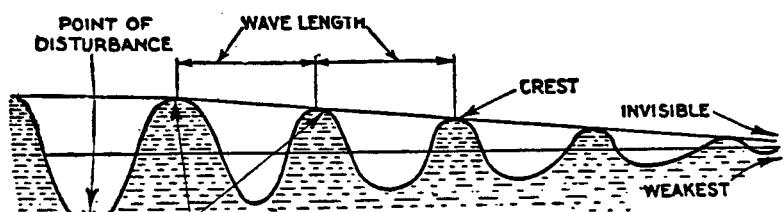
Back at the pool I observe that waves move outward from a center of disturbance at some velocity. Therefore, if I select a fixed point some distance from the center of disturbance and counted numbers of wave crests passing the point per given time I may compute waveform velocity in meters per second.

The velocity of electromagnetic energy (radio and light) in air and vacuum is constant and very close to 300,000,000 meters per second. Variable attributes for electromagnetic waves are wavelength and frequency. A concept of frequency and wavelength will be very useful to us later in chapters on antennas and feedlines. The reason for discussing it here is to lay foundation for defining color.

A graphical presentation of the electromagnetic spectrum is shown in Figure 12-2. The graphics are logarithmic; the bandwidth (spectrum space) of each



—Effect of throwing a stone into still water: it produces waves which travel outwardly in expanding, concentric circles from the point where the stone enters the water or *point of disturbance*.



—Sectional view of waves produced by throwing stone in still water, illustrating crest of wave, wave length and gradual weakening of the waves as they travel from the point of disturbance.

Figure 12-1. Electromagnetic Waves Travel Outward from the Center of Disturbance.

THE ELECTROMAGNETIC SPECTRUM

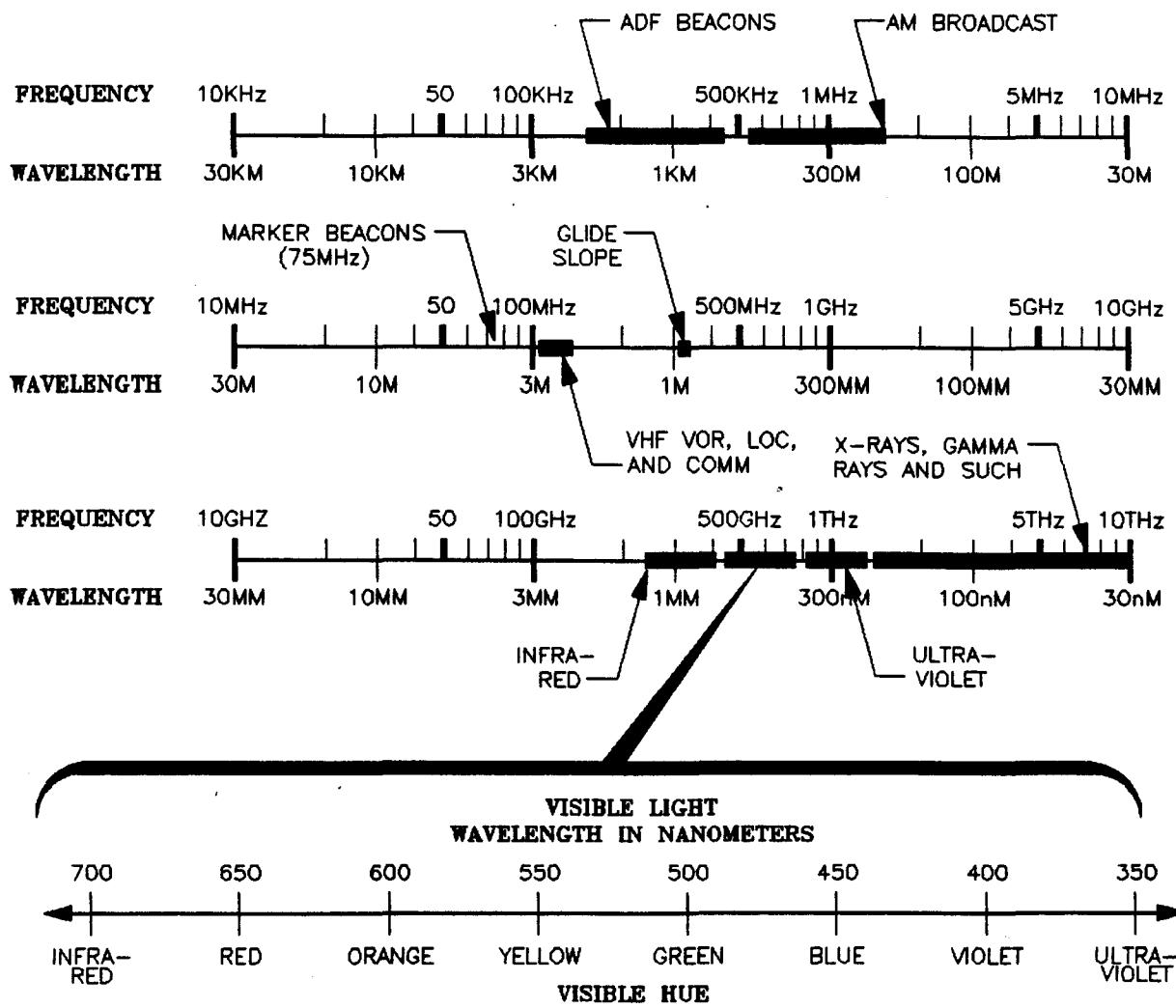


Figure 12-2. The Electromagnetic Spectrum.

decade is nine times wider than the sum total of all the spectrum below it.

When describing any form of light, to speak about wavelength we also speak of color. Colors of the rainbow are distributed in their order of wavelength. Red is the first color visible on the outer edge followed by orange, yellow, green, cyan, blue, and finally violet. Are the colors we see in a rainbow all there is? No. A very broad spectrum of energy is represented by sunlight. A rainbow is created by prismatic, spectrum spreading effects of water droplets in air. If eyes were sensitive to a broader spectrum of light, we would perceive more "colors" beyond red and violet which presently define the edges we see.

INCANDESCENT LAMPS

Before I go to specific applications, let's look at various ways light can be generated. A simple and common form of light emitter is an ordinary light bulb. Ol' Thomas A. Edison was credited with bringing this device into practical reality. However, the physics upon which light bulbs are based has been understood for centuries. The word incandescent means to glow or illuminate. When any material is strongly heated, atoms from which the material is made become highly agitated, so agitated that they give up energy. This re-radiated energy is *not necessarily in the same form* as the energy which originally produced the agitation. Virtually every form of lighting is the conversion of energy from one form to another.

Incandescent light is literally light from heat. Whether I talk about the atomic fires of the sun or heating a piece of steel to white hot with a torch, the principles are the same. The challenge for Thomas Edison was to find materials and a method for fabrication of a lamp filament. Temperatures high enough to be a practical generator of light cause destructive stresses in any filament material you might choose. Early Edison lamps gave off a rather dull, red glow compared to modern lamps. He had to compromise the quality of light to achieve a reasonable life. I understand that to this day, Edison's home in Florida has functional lamps which he personally assembled!

Modern lamp filaments are made of tungsten, a very, very hard metal. Tungsten has a reasonable operating life when operated at "white hot" temperatures. Tungsten is also a rather poor conductor compared to copper. This is an asset for the lamp designer. Tungsten's electrical resistance makes a lamp filament react to a

flow of current by readily converting it to heat. The heat in turn produces incandescence. Incandescent light is very random in wavelength. The atoms and electrons around the atoms of tungsten vibrate in random patterns and produce a broad spectrum of emissions. Light from a hot filament is perceived as "white" which in fact is a mixture of many colors.

We mentioned earlier that tungsten is a very hard material. You may be familiar with tungsten-carbide, a popular material for fabrication of long lasting tools to cut steel! However, "hard" doesn't also mean "tough." A diamond, the hardest mineral known to nature, can be easily smashed with a hammer. Tungsten, like diamond, is also brittle. "Brittle" is but one word which says "not ductile." Ductile metals include copper, aluminum, and even iron. Pure iron is quite soft and easily shaped with blows from a hammer. Extruding fine wires from tungsten for early lamp production wasn't easy! Tungsten's brittle nature is detrimental to the life of an incandescent lamp; I'll tell you how to deal with it shortly.

While we're talking about lamp life, check out the graph in Figure 12-3. The curves depict a relationship between life, current draw, and light output as operating voltage of an incandescent lamp is varied. Note that all curves cross in the middle at the intersection of 100% operating voltage and 1X life, current and candlepower. The curves are logarithmic. Accurate answers are difficult to read with them so I have included a tabular list of data (Table 12-1) which are representative of the curves in Figure 12-3. Note first that Figure 12-3 and Table 12-1 illustrate operating current's low sensitivity to operating voltage. This depicts tungsten's high positive temperature coefficient of resistance. Dropping applied voltage to 50% of rated voltage results in a current draw 68% of rated current. Increasing applied voltage to 150% of rated voltage yields a draw equal to 125% of rated current. Light output is affected more strongly. A light output 125% of rated occurs at only 107% of rated voltage; 68% of normal light requires application of 89% of rated voltage. Life values are strongly affected by applied voltage. Referring to the curves and Table 12-1 I note that 125% life may be achieved by dropping applied voltage to only 97%. Life drops to 68% somewhere around 103% of rated voltage.

Let's look at a second example application of this data. Suppose I have a lamp that is rated at 28 volts, 0.5 amps and 12 candlepower. Let us reduce applied voltage to 80% of normal or 22.4 volts. Start up the chart

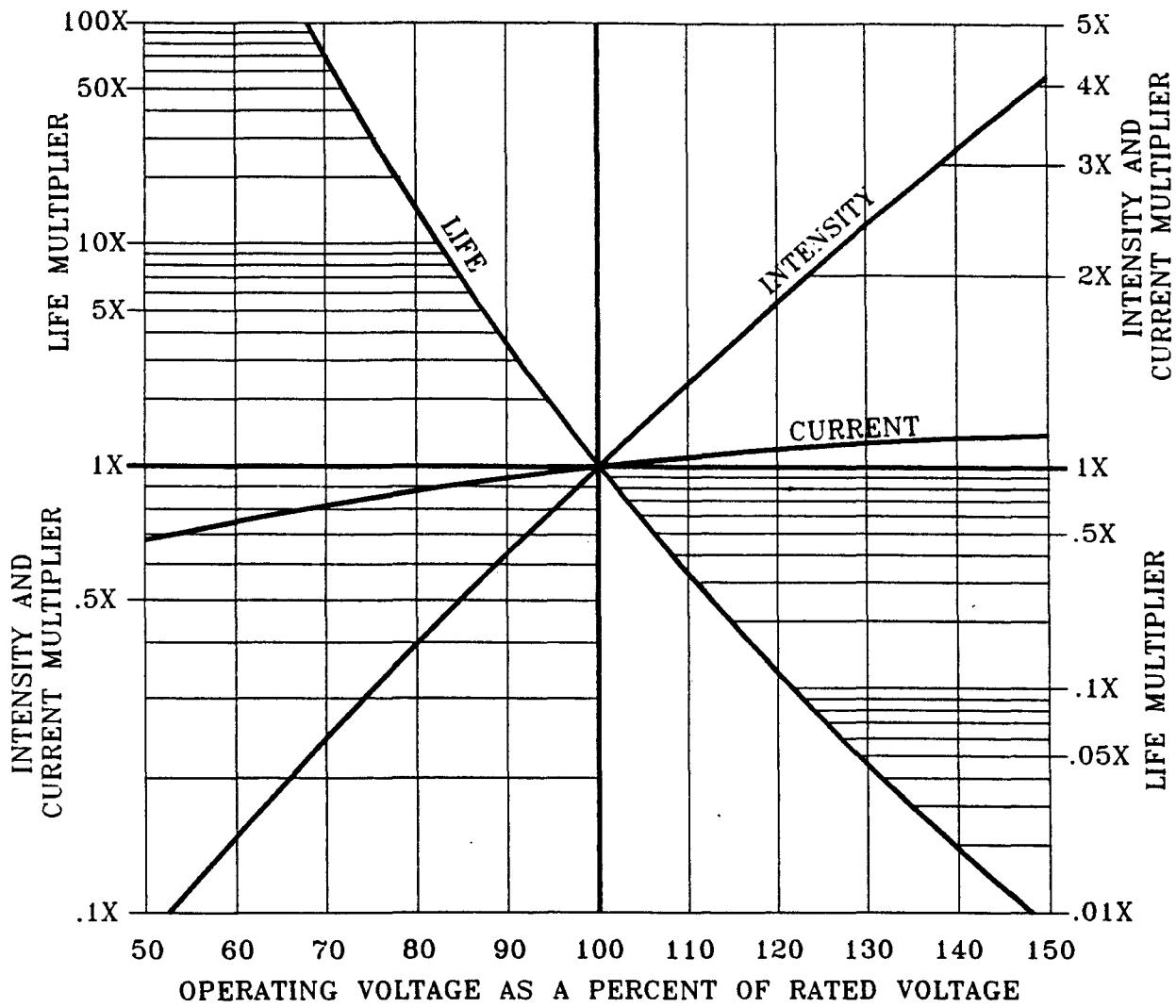


Figure 12-3. Incandescent Lamp Intensity, Current and Life Characteristics.

TABLE 12-1. Incandescent Lamp Characteristics

OPERATING VOLTAGE % OF RATED	LIFE MULT	INTENSITY MULT	CURRENT MULT
10			0.28
15			0.35
20			0.41
25			0.47
30		0.01	0.52
35		0.03	0.56
40		0.04	0.60
45		0.06	0.64
50	4095.99	0.09	0.68
55	1305.11	0.12	0.72
60	459.39	0.17	0.76
65	175.81	0.22	0.79
70	72.25	0.29	0.82
75	31.57	0.37	0.85
80	14.55	0.46	0.88
85	7.03	0.57	0.91
90	3.54	0.69	0.94
95	1.85	0.84	0.97
100	1.00	1.00	1.00
105	0.56	1.19	1.03
110	0.32	1.40	1.05
115	0.19	1.63	1.08
120	0.11	1.89	1.11
125	0.07	2.18	1.13
130	0.04	2.50	1.16
135	0.03	2.86	1.18
140	0.02	3.25	1.20
145	0.01	3.67	1.23
150		4.13	1.25
155		4.64	1.27
160		5.18	1.29

on the 80% voltage line to intersect the INTENSITY curve. From this point go left to read about 46 percent. This says that a reduction of 20% in operating voltage will drop light output by more than half. Continue up the 80% voltage line to intersect the CURRENT curve then left to read 88 percent. I can deduce that current draw will now be 0.88 (percent) x 0.5 (amps) = .44 amps. Continue up the 80% line to intersect the life curve; then left to read 15 times!

Now you know how so called "lifetime" lamp bulbs get

their claim to fame. For example: suppose I design a lamp to operate at 143 volts and 1 amp which would make it a 143-watt lamp by design. Now let's operate the lamp at 115 volts (80% of design voltage) and I find that the current has dropped to 0.88 amps. 0.88 (amps) times 115 (volt) equals 101 watts. I also note that it emits 46% of the light it did as a 143-watt lamp. But look what happened to life: if it had a 750-hour design life at 143 watts it can masquerade as a 100-watt lamp with a 11,250-hour design life. However, compare a "lifetime" lamp illuminated side by side with a regular lamp of the same wattage and you will note that lifetime lamps are not as "white" in the appearance of emitted light. They operate at lower temperatures than regular lamps; their color shifts more to red and less to blue. Moreover, the lifetime lamp develops less light per watt of power consumed. Most people find the regular lamps more pleasing to live with; the "lifetime" lamps are not exactly barnburners in the marketplace. I'll use these data on lamp characteristics later in this section.

HIGH ENERGY GLOW DISCHARGE

Glow discharge lamps are the familiar "strobe" light used for anti-collision warning systems. Neon tubes used on signs are also glow discharge lamps. If you'll recall some high school physics and chemistry Atoms are built from clusters of neutrons and protons in the center called the nucleus. Electrons are positioned about the nucleus in orbits called "shells." The lightest atom is hydrogen with a single proton nucleus and a single electron in the first shell. The *heavy* dudes have names like uranium, plutonium, etc., with hundreds of pieces in their nuclei and like numbers of electrons whizzing about in their shells. Only electrons are of interest to us in discussing the glow discharge lamp.

Shells about a nucleus of an atom are fixed with respect to the nucleus. They exist whether or not they are occupied by electrons. Hydrogen with its single electron in the first shell has many shells above the first, they just happen to be empty. Each shell has a certain energy level associated with it. Now, let us suppose that we cause an electric current to flow in a space filled with a gas, say neon. As electrons are coaxed to flow from one atom to the next, they have to migrate up through a shell structure of one neon atom and then back down through the next. During descent through the shell structure, they give up a quantity of energy equal to that which originally displaced them from their

normal position within the atom. Curiously, the energy may be in a *different* form from that which pumped the electron up through the higher energy shells. For neon gas, one of the released energy forms may be observed as reddish-orange light. A tube filled with argon emits a blue to violet light. A xenon (ZeeNon) filled tube emits white light. White? White isn't a color, it's a combination of many colors.

Xenon atoms are much heavier than either neon or argon. It's also much more difficult to rip the electrons from the outer shells of a xenon atom. A voltage of 65-100 volts will ignite a glow discharge in a neon or argon lamp. Xenon lamps require 300 to 2000 volts for operation plus a trigger voltage of 2000-6000 volts! That should give us a clue as to relative differences in energies. Electrons fall through more combinations of shells in the xenon atom and each emits a different color of light. A combination of all colors emitted by a xenon glow discharge lamp appears white. Not all of the energy given up by descending electrons contributes to the white light we can see; xenon lamps emit components of "light" that extend well outside visible boundaries including copious amounts of ultra-violet.

Strobe lamps for aircraft position marking are similar to strobe lamps for cameras. A solid state power supply raises aircraft bus low voltage to a level of 300 to 400 volts for charging a capacitor. When xenon tubes are triggered a large current flows in the xenon gas. For a few milliseconds, the electrons about the atoms are violently stirred. Result: an intense, short duration pulse of white light. A basic strobe lighting circuit is illustrated in Figure 12-4.

We've now discussed the two predominant technologies used to produce light for aircraft applications. There are a few others which include:

LIGHT EMITTING DIODES OR LEDs.

These are solid state lamps used singly as on/off indicators. They are also used in groups to form characters on alpha-numerical displays. Some of the do-it-yourself avionics projects will use these lamps for indicators, i.e., lamps that are looked at directly for interpretation of what is displayed. The low cost, consumer class LEDs do not emit sufficient light for illumination of objects to be observed. Light emitted from an LED is a function of how it is manufactured. As of this writing, no "white" devices are available. Red, green and amber or yellow lamps are quite common. Blue ones exist but they are not yet low cost off-the-shelf components. I predict that

if blue lamps make some technical and economic strides forward, "white" solid state lamps will be available soon after. Take a close peek at a color television screen. Every color you observe, including white, is synthesized from controlled combinations of red, green and blue dots. Red and green LEDs are available now . . .

ELECTROLUMINESCENT.

This is a flat-panel light emitter. A witch's brew of chemicals is sandwiched between two conductors, one of which is transparent. When an a.c. voltage on the order of 40 to 100 volts is applied to the two conductors, the stuff in the middle glows. Examples of these lamps can be found as plug-in night lights. They are usually about 3" square and emit a soft green light. White, blue and yellow are other E.L. colors. Liquid crystal display (LCD) arrays on loran receivers are often back-lit with E.L. panel light. The classier singles like the A36 Bonanzas and the Barons use E.L. to illuminate switch panel legends below the instruments.

LOW ENERGY GLOW DISCHARGE.

These are little cousins to xenon tubes used in anti-collision lights. Small neon lamps are found in spark plug testers, magneto synchronizers and wall switch plates. They don't put out much light nor do they require much energy to illuminate them. Small tubes filled with argon have been used to generate small amounts of ultraviolet light to illuminate alarm clock faces painted with fluorescent paints. Narco and King use glow discharge technologies for frequency and DME readouts on their radios.

FLUORESCENT TUBES.

These are variations on a theme. First, they are glow discharge lamp. A glass tube is filled with a mixture of argon gas. When a current passes through the gas it emits ultraviolet light. U.V. excites a coating on the inside surface of the tube, causing them to glow in a variety of colors which appear white. Sub-Miniature versions of the large room illumination lamps are used in some high dollar instruments for face lighting. Miniature versions are used in camping flashlights and recreational vehicles. These lamps are excited by high voltage alternating current. Forty volts or so for the itty bitty guys; 400 volts or more for 8-footers on the ceiling. A special transformer called a ballast is used to generate and control current needed to properly illuminate these lamps.

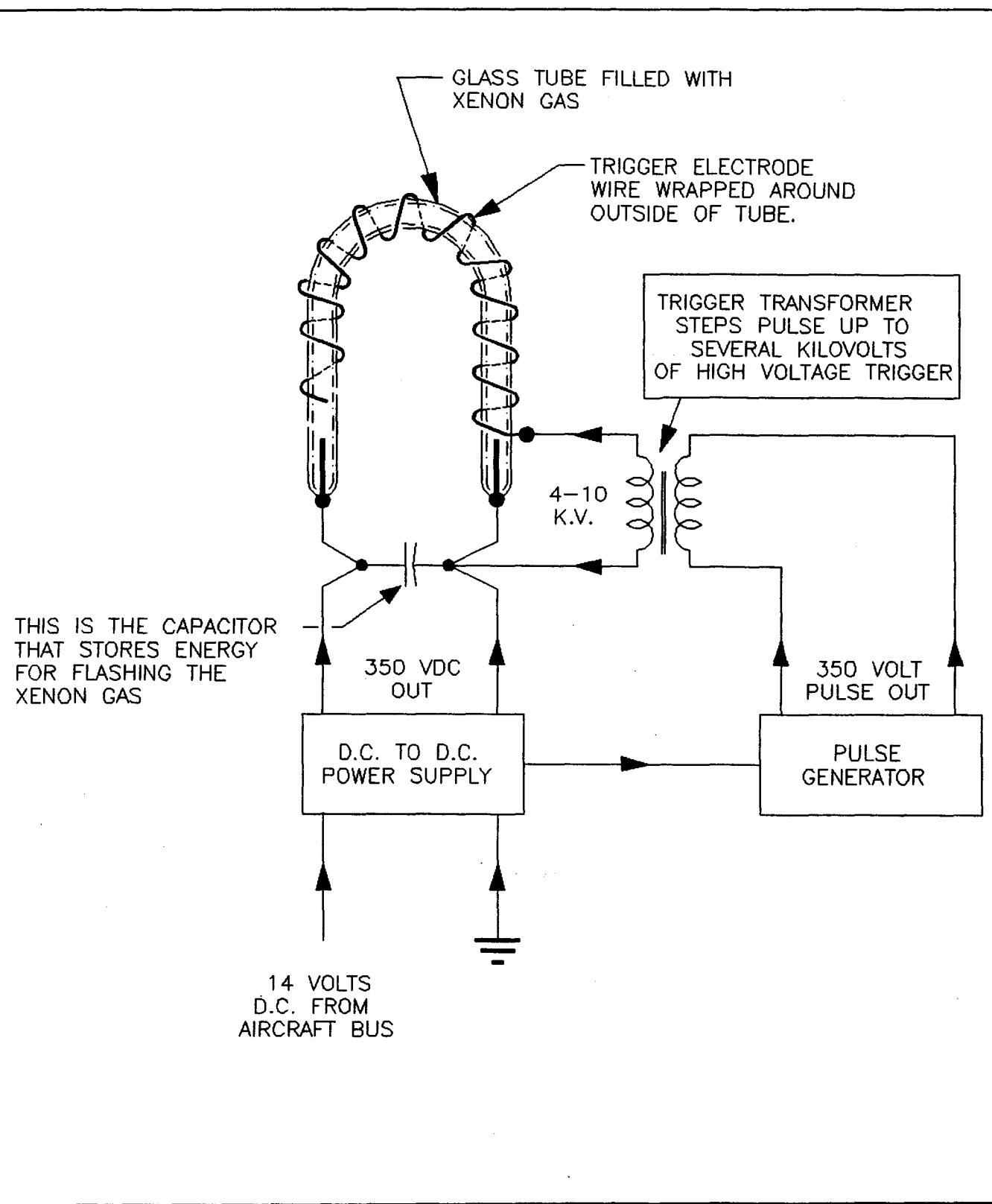


Figure 12-4. Simplified Schematic of Strobe Light System.

The previous four types of lamps have limited, specialized applications in airplanes. Generally, if a lamp isn't a xenon glow discharge lamp on the tips of wing and fin, it's going to be an incandescent lamp.

LANDING AND TAXI LIGHTS

The highest wattage lamp on an airplane is a landing lamp. It is also the most expensive lamp to replace. Xenon tubes in a strobe can be pretty pricey too. Fortunately, they don't seem to fail quite as often as landing lamps. During our short tenure as airport owners I don't think any spare parts purchases were more surprising than some of the landing light bulbs we replaced! I'll discuss how to increase bulb life in order to avoid buying any more of these critters than you have to.

One of the toughest things to do to your landing light is *turn it on!* We've all observed that most light bulbs burn out when first energized. A flash and perhaps a tinkle inside and the varmint heads out for wherever all good bulbs go when they die. The chapter on switches describes a lamp bulb's low resistance when the filament is cold. Application of power to a cold filament causes a large inrush current followed by a *rapid* rise in filament temperature. Engineers call it thermal shock. Where landing lamps are concerned, I call it *piggybank shock*. As lamps acquire more hours of service, filaments evaporate and get thinner. Their ability to survive thermal shock at turn-on is slowly degraded until ...

Another insult you can inflict upon your landing lamp is to *pound on it*. Airplane engines are well known for their ability to shake things. Furthermore, tungsten lamp filament brittleness makes it vulnerable to vibration. While researching literature for this section I found that somewhere around 400 degrees F tungsten changes from brittle to a more ductile state. A lamp's filament is much less vulnerable to vibration damage when its temperature is maintained above 400 degrees. Later paragraphs on lighting controls will discuss ways to substantially reduce effects of both thermal shock and vibration.

If you've got a certified aircraft, you pretty much have to replace dead lamps with the same part number the ship was supplied with. If you are building an airplane, consider halogen cycle, automotive headlamps as landing and taxi lamps. Walking down the aisle of a parts store a few days ago, I observed some really compact, rectangular, halogen headlamps. Now, if these bulbs are

sufficient to illuminate the pavement ahead of your 65 MPH car, why not your airplane touching down at 50 MPH?

Automotive headlamps have other attractive features. They can be had with **TWO** filaments; one for high beam, one for low. The high beam has a narrower focus and higher aim angle than the low beam. Consider adjusting the lamp for optimum angle in the landing configuration with the high beam filament illuminated. Then use the low beam filament for taxi. On my Aries wagon, pulling back slightly on the turn signal stalk will illuminate both high and low beams, what a blaze! Suppose you use high beam in approach, ADD low beam during flare/rollout and use low beam for taxi. To my way of thinking, halogen headlamps on each wing fed with life-enhancement controls and separate switches yields a versatile, dual landing light system. Total cost of components for this system would be less than retail for a single, 150-watt "aircraft" lamp. Better yet, spare lamps can be had from K-Mart for about \$10 each! A single lamp installed in your airplane has the advantage of dual filaments. Low beam illumination might be a *distant second* to high beam for landing but I think it would do in a pinch. How about that? Landing lights with built in backup!

Alternatives to OEM, sealed halogen lamp assemblies are aftermarket driving lights. J. C. Whitney catalog lists several 55-watt devices for under \$20. Replacement bulbs are less than \$4. I would like to hear from anyone who elects to develop a landing light system for their airplane using poor-man's parts. I'll compile data on what works and what doesn't for later inclusion to these pages.

Believe me folks, modern halogen headlamps are 10 times the lamp that says "aircraft" on it. Aircraft sealed beams were designed in the 40's and sales volumes are steadily decreasing. Costs will continue to rise as numbers of certified single engine airplanes dwindle. Further, they are not likely to receive any technological updates; who would put development dollars into a dying market? On the other hand, lamps for cars have a steadily increasing market; demand for leading edge technology is high. Need I say more?

POSITION LIGHTS

Some folk call them "nav lights." Wonder where they got that term? If "nav" lights are turned off in the dark are you more likely to get lost? Position lights take

more total energy to operate than landing lights and they don't even help you see where you're going!

That's a tricky statement which I should explain: position lamp bulbs on a 14-volt airplane draw about 2 amps each. So, 6 amps times 14 volts is 84 watts. A two-hour flight times 84 watts is 168 watt-hours. A 100-watt landing light might be on for 10 minutes during that same flight for a total of only 16.5 watt-hours. "Energy" is an accumulative value. "Power" is an instantaneous or rate value. For example: burn a 100-watt bulb for two hours and it will consume power at the rate of 100 watts. Only after you are told how long the bulb is illuminated can you deduce a total energy consumption of 0.2 kilowatt hours. I'll elaborate on this distinction further when I write about strobe lights.

Lamps used as position lights are anything but modern. They have roots in the same idea patch that grew the "aircraft" sealed beam landing light. Position lamps for 14-volt airplanes list for as much as \$20.00. At two amps or less draw it cannot develop more than 32 candlepower. I see in my engineering data book on miniature lamps that the #1076 lamp used in the front turn signal slot on my car is rated at 1.8 amps, 32 candlepower and lives in the lab for 200 hours. I buy these at the corner parts store for 85 cents! "Foul!", sez the guy at Gold Plated Airparts, un-Incorporated, "They're not the same kind of bulb." He says I am comparing apples with oranges; real position lamps have built in mirrors!

Oh yes, pardon me. They *are* different in that respect. But, should a little piece of mirror be worth \$19.00? In all fairness, the mirrored position light bulb *was* a wondrous idea, a step forward in illumination technology, *40 years ago*. The internally mirrored position lamps are experiencing the same economic pressures as sealed-beam landing lamps. Consider modifying position light fixtures to accept the lower cost bulb and mount a piece of mirror behind the bulb to reflect light headed toward the wing back out into the environment. There may be a halogen cycle lamp in the 24-watt class that emits more candlepower per watt. I'll research the topic and if a suitable part can be found, the information will be passed along via a Hot Flash newsletter.

ANTI-COLLISION LIGHTS, INCANDESCENT

When airplanes became so numerous that they began running into each other in the dark, somebody decided that pilots needed a better way to see other airplanes after the sun went down. The candlepower of the smoking hot little position lights could not provide

sufficient visibility for alerting pilots to stay away from each other. One answer to the problem was obvious: **BIGGER** lamps. Not an attractive answer when the position lights alone had already eaten up a substantial portion of the 20 amp generator's output!

Gross candle-power alone was not the answer, the output of the electrical system just wouldn't handle it. Suppose we took the illumination of a fairly ordinary lamp bulb and focused it through a series of mirrors and lenses so as to concentrate the illumination in one direction. A properly designed optical system wrapped around a 25 watt lamp would make it look like a much larger lamp in one direction. Now, let's put the lamp in the middle of a rotation system so that the optics can be spun around the lamp, thus sweeping the horizon around the aircraft with a narrow beam. Wow! Just like beacons that mark airports on the ground, we could now create a short, intense pulse of light that solicits attention from distant observers. Thus was born the electro-mechanical, rotating anti-collision beacons found on thousands of airplanes today.

Rotating beacons are elegant ideas with respect to conservation of energy. You can make a small light do the job of a much bigger one but the thing is rather complex. It has a motor with brushes, gears and bearings that wear out. Motors also make noises in radios. Rotating beacons are often mounted on top of vertical fins (quake city!) where bulb life is miserable to poor, but they do a good job while they are working.

Some time in the late 60's, electrical systems began to grow like Kudzu in Georgia and 60-amp alternators were installed in the lowliest of Cessna 150's. About then, an idea of **BIGGER** lamps was revisited with more success. A company called Aeroflash wrapped a special lens around a 150-watt halogen lamp and fitted it with a solid state flasher. The Feds looked at the "beam" candlepower and pronounced these devices *equal* to the rotating beacon. It was really "disk" candle power since it radiated equally in all directions.

I was working at Cessna when Aeroflash systems were first certified onto production airplanes. I was not impressed with them. The lamp filament was a massive thing that took a lengthy time to heat up and cool off. Observing an Aeroflash beacon side by side with a Whelan or Grimes rotating beacon shows they are not "equal." Sharp pulses of light that come from rotating optics systems are more attention-getting than a *fade in, fade out* appearance of the Aeroflash. The Feds rated beacons purely on gross illumination. Rate-of-rise and

fall in the observed flash was not a specified characteristic.

Strobe lights were available at that time too but a strobe was 3 to 5 times the cost of the Aeroflash installation. Strobes were "Cadillacs" of the anti-collision systems in 1968. Aeroflash beacons came complete with new engineering problems to solve at no extra charge. Each time that 150 watt lamp energized, a large inrush current pulse whacked the system. Instrument panel lights flickered every time the beacon lit up; an hour of that was enough to make you give up night flying! The 150-watt halogen bulbs were more expensive than the bulb for a rotating beacon but they did seem to last longer.

The panel light flicker problem was "solved" later by adding a resistor. Power was shunted to a 1.5 ohm resistor during times when the power was removed from the halogen lamp. System current drain compared to the single bulb configuration was smoother but total energy requirements doubled! An attempt was made to use two lamps alternating like a railway crossing signal. A twin lamp system was difficult to install for effective presentation. If both lamps were visible to another aircraft they appeared as a single, continuously illuminated lamp until you were close enough to perceive them as two alternating lamps. I am not aware of any airplane that has been certified with a dual lamp Aeroflash system. With either approach panel light flicker was reduced but not eliminated.

Today, the white strobe is the anti-collision warning system of choice. It produces bright, sharply defined pulses of light. VERY attention getting. But they come with their own sins as we shall see...

ANTI-COLLISION LIGHTS, STROBE

Xenon strobes are probably the best thing that's happened to night flight safety since lights were first installed on airplanes. We've already compared glow discharge lamp operation with other light emitters. Now let's talk about the applications.

A xenon glow discharge lamp, while obviously very bright, wouldn't make a very good landing light. The device is not capable of emitting a continuous light. Several hundred volts of ionization potential is required to "light the fires" in xenon gas filled tubes. Further, the current that flows during the light pulse is on the order of 3 to 10 amps. *Let's see, 5 amps times 300 volts is 1500 watts!* Wait a second, how can we supply that kind

of power from an alternator that is capable of say 14 volts at 30 amps for a grand total of 420 watts?

Easy. In earlier paragraphs on position lights a distinction was made between energy and power. I said that power was an instantaneous quantity and that energy is time dependent. The strobe lamp is obviously illuminated for a very short time. It's measured in milliseconds. Let us look at the mechanism that supplies the energy to flash a strobe.

The strobe on a wingtip is quite similar to a flashgun on a camera. After a picture is taken, you wait several seconds before a light illuminates to indicate flashgun readiness for next exposure. While you are waiting, a capacitor is charging up to the lamp's design operating voltage. Lamps can be had with operating potentials in the thousands of volts but garden variety flash tubes for cameras or aircraft strobes require 300 to 400 volts.

The potential energy available to flash a strobe lamp is computed by multiplying the size of the capacitor times the square of the operating voltage and dividing by two. The quantity you get with this exercise is measured in joules (pronounced "jewels"). A joule is a unit of measure like the amp, ohm or volt. In this case a joule is a measure of energy in watt-seconds.

Suppose we have a capacitor marked as 200 microfarads. Let's further suppose we charge the capacitor up to 320 volts and connect a flash lamp across it. When the lamp is triggered, we will liberate 10.24 joules of energy. *[320 (volts) squared times 0.000200 (farads) divided by 2 = 10.24]* If you look in any catalog that advertises aircraft strobe systems you will find power supplies rated in watt-seconds or joules. Now you know how they figure the rating. You can increase the power output by either raising the voltage or increasing the size of the capacitor. When the lamp is triggered, the light will last for only a few milliseconds. If our 10.24 watt-second example is discharged in 10 milliseconds, the peak power is *10.24 (joules) divided by .010 (seconds)* equals 1024 watts!

Mechanical complexity of rotating beacons has been replaced with electronic complexity in strobes. The d.c. power from ship's bus is first converted to a.c. power by some very busy transistors. The a.c. is stepped up to a higher voltage and rectified back into d.c. so the flash capacitor can be charged. Power supplies used in contemporary strobe assemblies are rather antiquated now; they operate in the 500 to 2000 cycles per second range. In the section on alternators, I said

that modern alternators got so small because they operated at higher internal frequencies. Whelan and Grimes folk both need to upgrade their power supplies to operate at 50,000 to 100,000 cycles per second. Components for the task are on the shelf and have been for some time. Power supply volumes and weights should drop to 1/4th their present values, or smaller. Strobe light power supplies will generate annoying noises in radios if not properly designed and installed. More on this in the section on electrical system noise management.

How much energy does it take to run our 10.24 watt-second strobe light system? Well, we need to flash the thing about 70 times per minute or once every 860 milliseconds. [*10.24 watt-seconds divided by .86 seconds places the average power draw at 11.9 watts.*] No energy conversion system is 100% efficient; let's assume 80% for our hypothetical strobe. [*11.9 divided by .80 is right at 15 watts. The average current draw of this system would be 15 divided by 13.8 volts or 1.1 amps.*] The neat thing is that you get the illuminating power of a 1000 watt lamp with a 15 watt power budget. All this without moving parts or the special lenses commonplace with incandescent beacons.

BIG FLASHES VERSUS LITTLE FLASHES

For short flashes of light (less than 100 milliseconds) the perceived brightness of a lamp is proportional to energy, not peak power. The human eye integrates with approximately a 100 millisecond time constant. So, consider a case of two strobes: a 5 watt-second unit operating side by side with a 10 watt-second unit. Further suppose that each develops 1000 watts peak power. The 10 watt-second unit will appear brighter.

What's all this mean in terms of utility? There was an article in Sport Aviation a number of years ago for a homebred strobe. It used a 4 micro-farad capacitor charged to about 400 volts. [*400 (volts) squared times .000004 (farads) and divided by 2 is only .32 joules!*] How could this puny energy level produce a useful flash in a field of monster production strobes that start at 10 joules and go up from there? Fortunately, while the human eye can perceive a difference between 5 and 10 watt-second units the eye's overall sensitivity characteristic is logarithmic. Without going into a long winded explanation of logarithmic, let me assure you that a .32 watt-second unit doesn't appear to be 1/30th the intensity of a 10 watt-second unit. When that little .32 watt-second device is out there flashing

away against a black sky, believe me, it's quite an attention getter. Many IA's are issuing Form 337 mods to put strobes of any size on airplanes not originally certified with strobes. They agree with the idea that any enhancement to existing certified night lighting is useful. Moral of the story: don't pass up a chance to bolt a little guy to your airplane especially if it's a bargain. Any strobe is 1000% better than no strobe; you can always put on a bigger one later, after you pay off the car or the kid's braces . . .

INSTRUMENT PANEL LIGHTING

I headed the electrical-avionics group during early development of the Piaggio P-180, twin turboprop; it was the GP-180 while Learjet was still involved. Instrument panel lighting for that airplane was at best a challenge; some called it a nightmare! The airplane had a combination of: E.L. backlit panels, 5-volt embedded incandescent backlit panels, 5-volt internal instrument lights, 28-volt internal instrument lights, 28-volt post lights, glow discharge radio displays, and cathode ray tube EFIS displays. The task was to orchestrate dimming controls to accommodate the wide range of technologies. Mixed technologies operated from a single control had to track each other as close as possible from minimum to maximum intensity. Fortunately, few of you will ever have that size of task and I hope I never will again!

Few design tasks on a homebuilt are as personal to the builder as panel lighting. I've seen some gorgeous panels that sprouted post lights like fungus; virtually every instrument, control, and panel legend was provided illumination from one or more post lights. Post light assemblies are listed in many aircraft parts catalogs; none of them are cheap. However, they are probably the most versatile product for putting light right where you want it. The concept of lighting virtually everything has a firm foundation in certified aircraft design. As a homebuilder, you have a distinct advantage over the certified aircraft pilot. You decide where all the controls are going to be mounted. You fly the same ship most of the time. You can probably operate the controls in your airplane blindfolded! So, why light up everything like you've never seen it before?

A complete set of post lights for a full IFR panel and average set of controls might require 20 to 30 lights and a panel lighting load of up to 2.5 amps in a 14-volt system. One to three lamps might suffice to flood the flight instruments and radio panels for a current budget of only 0.25 amps! Except for the interval from sunset

to total darkness, I am personally most comfortable with *very small* amounts of light on the flight instruments and radio readouts. I keep a low intensity flashlight in my pocket for map reading and temporary added illumination of cockpit controls. Reflections on the cockpit glass are minimized and my night vision is at its best. During alternator failure, minimum panel flood lighting maximizes battery life and improves your chances of getting on the ground with essential equipment still functioning. So consider a couple of floods, on each side of the cockpit or perhaps under your glare shield. A two lamp panel flood lighting system requires as little as 160 milliamps total current when the lamps are on bright!

Irrespective of how many lamps ultimately illuminate your instrument panel, an adjustable dimming control is essential. Dimming control techniques will be discussed later in this section.

LIGHTING CONTROLS

Most of the lights we work with daily have ordinary switches to provide simple on/off control. If we knew nothing about the contrary nature of tungsten filaments we might well assume that most incandescent lamps on an airplane would perform as desired with a common switch for control. Indeed, except for instrument lights which are dimmable, virtually every production airplane flying today uses no lamp life enhancing controls.

Let's define two goals for achieving better lamp performance in airplanes. Earlier in this chapter, I stated that if you turn a lamp on *gently*, a filament will be spared the stresses of thermal shock which result from simply closing a switch to apply power. I further stated that if a filament were maintained in a "warm" state, 400 degrees or more, it was in a ductile state; less susceptible to vibration. The goals are: (1) reduce thermal stresses at turn-on and (2) improve resistance to vibration. . . .

KEEP 'EM WARM - EVEN IN THE SUMMERTIME

The prescription for reducing thermal shock and improving vibration resistance is to keep filaments warm, even when the lamps are not being used for illumination. This is done by applying a small amount of power, usually less than 2 percent of the lamp's operating wattage, at all times. I've done some work with 300-

watt locomotive headlamps. These are 30-volt lamps that draw 10 amps. Two volts applied to these lamps causes them to draw 1 amp for a power level of only 2 watts. At this power level the filament is heated to a dull red glow! Temperatures that emit dull red are much higher than the minimum required to keep a filament in its ductile state. I can deduce another interesting fact from this experiment. The locomotive headlamp has a measured cold resistance of 0.15 ohms. Sudden application of 30 volts will cause 200 amps of inrush current to flow. However, with 2 volts applied, the lamp draws 1 amp. Its resistance has, therefore, increased from 0.15 to 2 ohms! If I apply 30 volts to the warm filament I note that the inrush will now be 15 instead of 200 amps! I may conclude that keeping all the lamps in the airplane warm (to the tune of 2 volts for a 28-volt lamp and 1.5 volts for a 14-volt lamp), will cause filaments will last much longer and inrush currents for large lamps will be substantially reduced.

Let's consider a hypothetical airplane with four, incandescent lighting circuits consisting of a landing light, position lights, a string of 12 dimmable instrument lamps on the panel and a single dimmable panel flood and map light. Figure 12-5 shows the resistor method for keeping the filaments warm in all four circuits. *Note that while the voltage across the lamps is low, the currents are not insignificant.* Consider the landing light circuit: 1.5 volts at 1.5 amps across the landing light heats it to a level of 2.25 watts. The voltage drop across the resistor is 13.8 minus 1.5 or 12.3 volts. The power dissipated in the resistor is 12.3 volts times 1.5 amps or about 19 watts! The total system drain for all four circuits is $1.5 + 0.9 + 0.3 + 0.1$ for a total of 2.8 amps and 38.6 watts.

If you've got a 30 amp alternator, then you have dedicated almost 10% of your alternator output to just keeping the light bulbs warm. This may or may not be significant in normal operations but if the alternator fails the 2.8 amps of keepwarm current cannot be considered to be essential load. I suggest that a keepwarm supply breaker be installed and wired as shown in Figure 12-5. If this breaker is on the non-essential bus with a switching system similar to those shown in Appendix Z, then the keepwarm loads are automatically shed when essential bus selector switch is in the "EMERGENCY" position. If you do not have a split bus system, then make the keepwarm breaker a push-pull device so that you can open it up and shed the keepwarm loads in case of alternator failure.

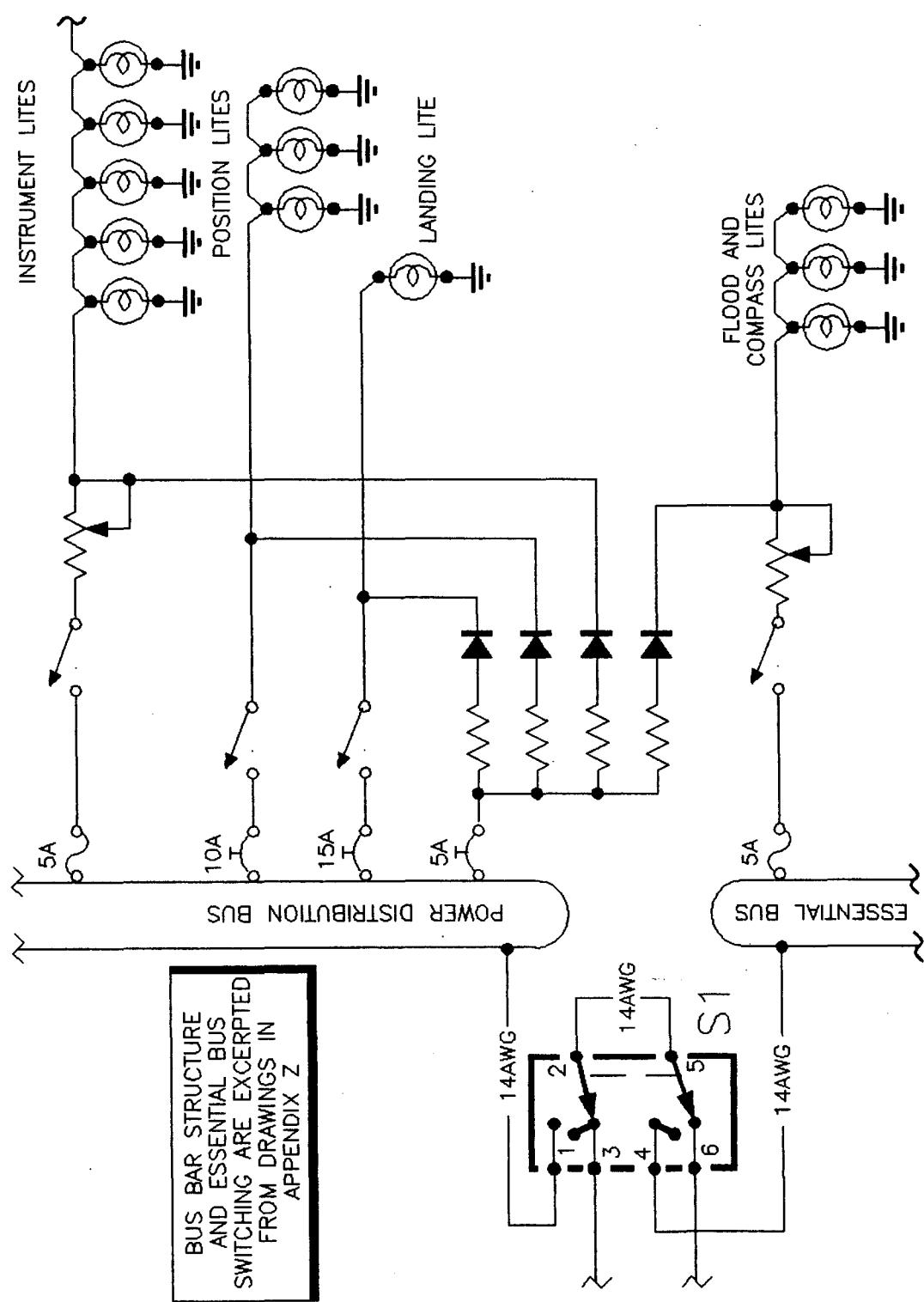


Figure 12-5. Keepwarm System using Resistors.

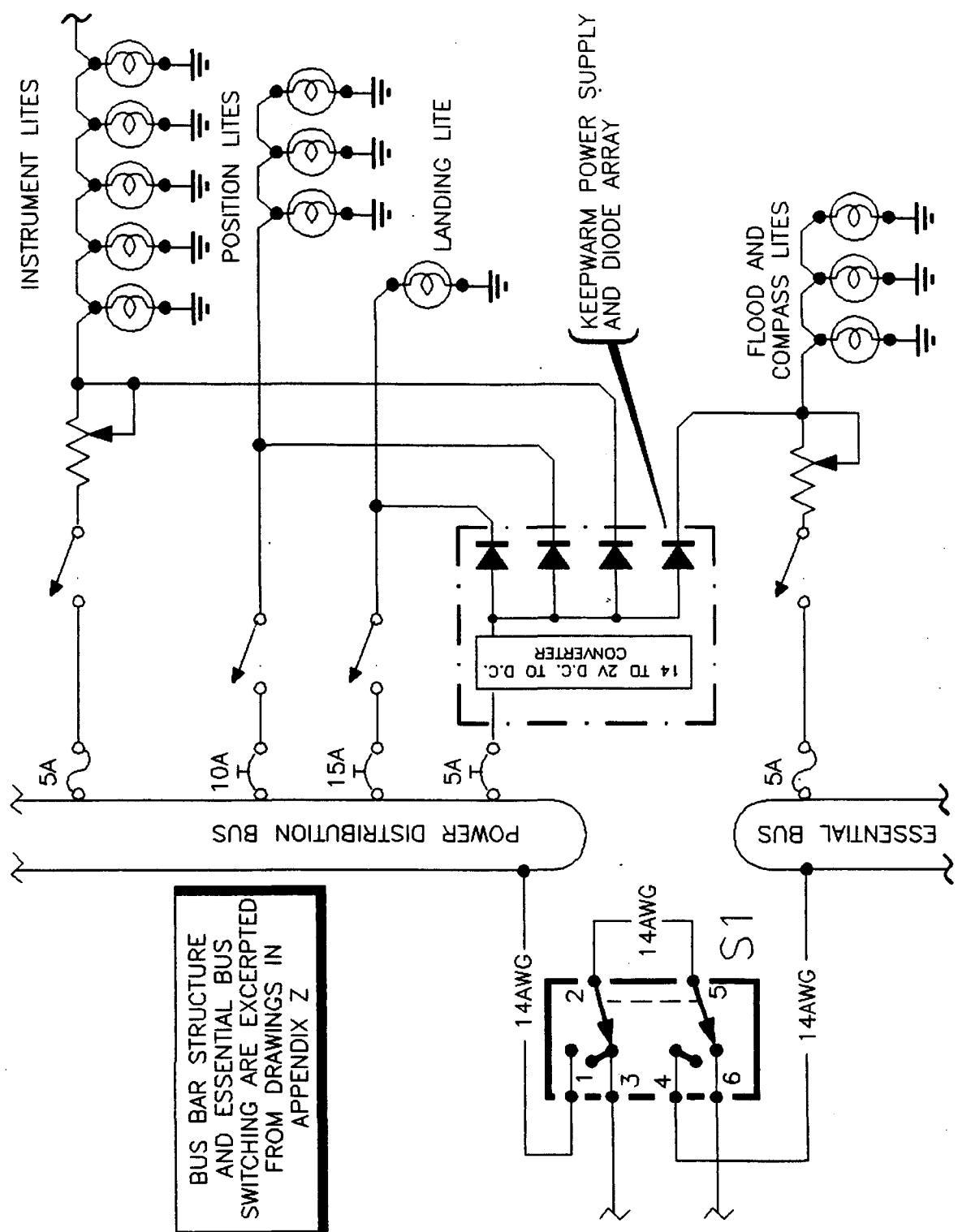


Figure 12-6. Keepwarm System using a D.C. to D.C. Converter.

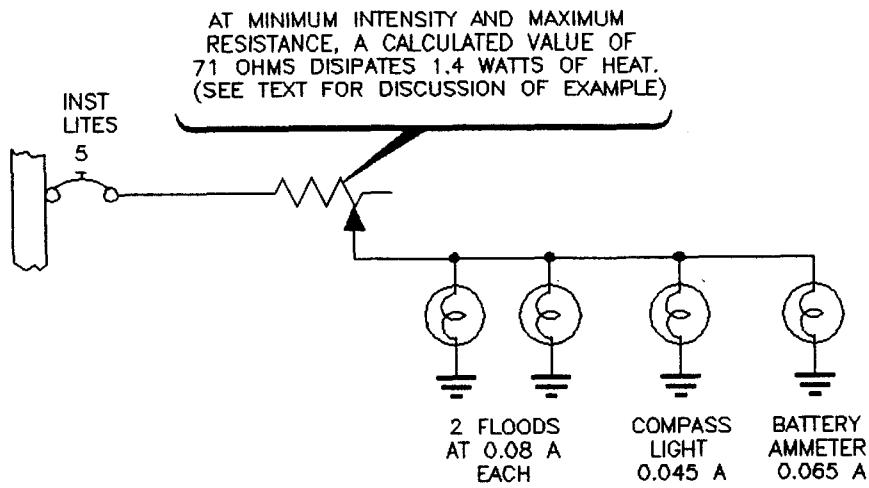


Figure 12-7. Example of Dimming Control using a Rheostat.

Using a resistor to develop keepwarm voltage is certainly simple but it's not very efficient. In the previous example, a resistor which maintains 2.3 watts in a landing lamp will itself dump 19 watts as wasted heat! What's needed is a gadget which will produce a keepwarm voltage that doesn't waste so much energy. The name of the gadget is a *d.c. to d.c. converter*. Strobe lights use 'em to transform 14 volts up to 350 volts for charging energy storage capacitors. Why not use one to develop a two-volt keepwarm source? A *d.c. to d.c. converter* running at 50% efficiency would keep the lamps warm in our hypothetical airplane with a total budget of only 11.2 watts. That's a lot less than the 38.6 watts consumed by the resistor keepwarm method. A keepwarm power supply will be added to the list of do-it-yourself avionics projects. Its application is illustrated in Figure 12-6.

INSTRUMENT LIGHT DIMMING

If your dimmable instrument or map lights are single or perhaps dual bulb floods, you may wish to consider the ordinary rheostat as a control device. A rheostat is a class of adjustable resistor. It is designed to be mount-

ed on a panel and operated by a knob. For small systems they are simple, inexpensive and don't take up a lot of panel space. Wiring for a rheostat dimming system is shown in Figure 12-7. Here is how you select a variable resistor for a lamp dimming task: Let us suppose that panel floods consist of two 14.0-volt lamps rated at 0.08 amps each. On the same circuit, we're going to includ an internal compass light at 0.045 amps and one internally lit gage at 0.065 amps. Our full voltage lighting load would be $0.045 + 0.065 + 2 \times 0.080$ for a total 0.270 amps. Referring to Table 12-1, let's assume that minimum intensity setting on the rheostat will be at 1% of normal light output. Looking down the intensity column to find 0.01, I find that the applied voltage needs to be 30% or 4 volts. At this setting the lamps will draw 52% of their normal rated current; $0.270 \text{ (amps)} \times 0.52 \text{ is } 0.140 \text{ amps}$. If I elect not to turn the lamps completely off, then this low intensity setting will insure keepwarm power to enhance lamp longevity.

Armed with this information, I now need to calculate the value of resistance that will drop a nominal 13.8 volt

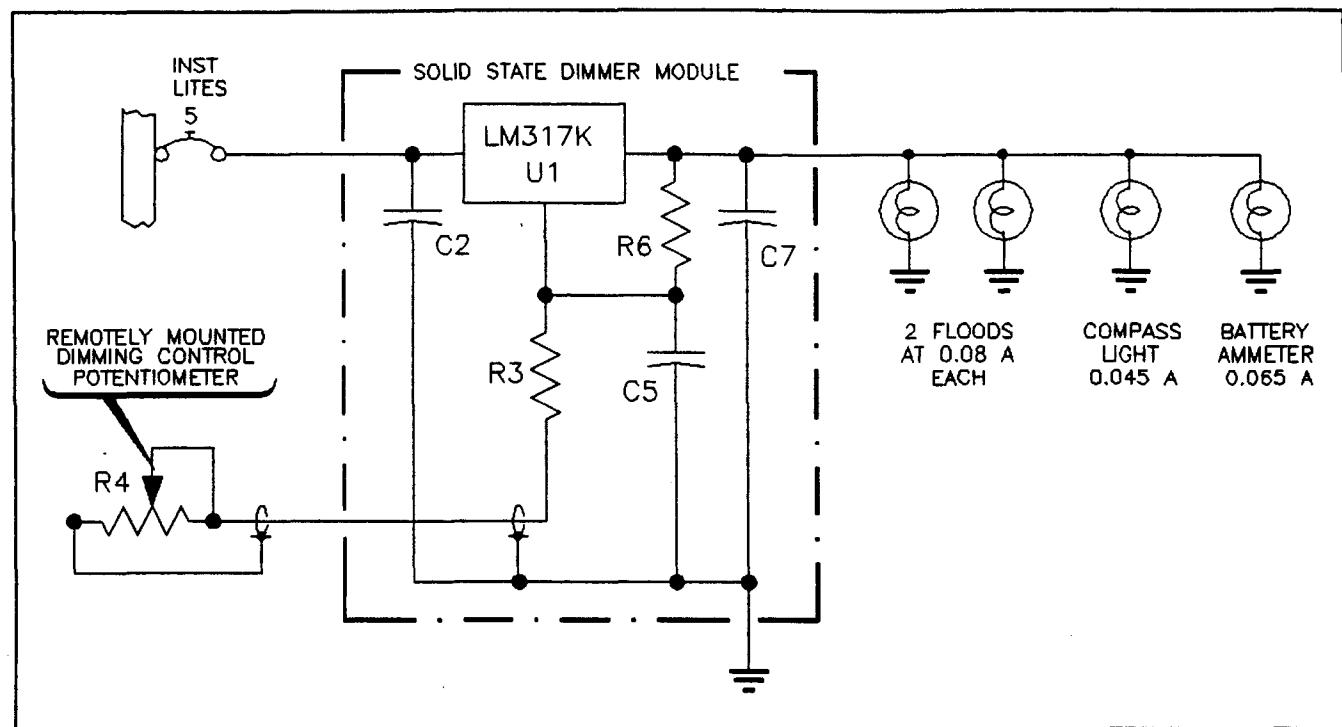


Figure 12-8. Example of Dimming Control using Solid State Dimmer Circuit.

bus voltage down to 4 volts when loaded with 0.138 amps. Referring to the formula in Section 1: Resistance = Volts/Amps. The voltage dropped across the rheostat will be 13.8 minus 4 or 9.8 volts. $9.8 \text{ (volts)} / 0.140 \text{ (amps)} = 70 \text{ (ohms)}$. Now, what size rheostat? A 75 ohm device can be purchased in any size from about 5 watts to hundreds of watts. Let us calculate power dissipated by a rheostat in our hypothetical design problem. The rheostat dissipates the most power when the lamps are at minimum intensity. Power in a resistor is calculated by multiplying voltage drop (9.8 volts) times the current through it (0.138 amps) to get 1.35 watts. Well below 5 watts; the smallest wire wound rheostats or potentiometers in the catalogs. Further, our calculated value of 70 ohms will have to be compromised by ordering the nearest common value offered. Seventy-five ohm devices are not too difficult to find, 100-ohm devices are quite common.

Suppose you find a heck of a deal on a 50-ohm device but it makes your lights burn too bright at the maximum dim position. Consider *adding dummy lights* to the system that are not visible in the cockpit. The addition of one or more lamps to the string which are enclosed with a light tight-housing will make the 50-ohm device perform as desired. It may be much easier to tailor the system to a rheostat than to find a rheostat which exactly matches your calculated values.

An alternative dimming control is illustrated in Figure 12-8. This circuit has some decided advantages over the simple rheostat and they are: (1) the controlling device mounted on your panel can be a very small potentiometer (check out the Clarostat RV6 series pots in the Digikey catalog), (2) the major power dissipating component is an integrated circuit mounted on a remotely located heatsink, (3) dimming characteristics provide smoothly varied lamp intensity with respect to dimming knob position, (4) the electronic circuit is load current and supply voltage independent.

The LM317 is a power integrated circuit, variable voltage regulator. The LM317 is an active device designed to *maintain a constant output voltage irrespective of variations of input voltage and output load*. This means that pulses of current from strobes will not cause the panel lights to flash or flicker. It also means that if

one bulb in a multiple string (such as a dozen post and eyebrow lights) burns out, remaining bulbs will be unaffected by changes in dimming circuit load.

The LM317 comes in two packages which are suitable for dimmable lighting controls and both type both look like power transistors. I recommend the larger LM317K be used for all applications. It is mechanically more rugged, easier to mount and only moderately more expensive. This system will handle virtually all dimming loads with the same circuit components except for the size of heat sink upon which the LM317K is mounted.

The minimum output voltage from the LM317 is 1.2 volts. This means setting the dimming control pot to minimum (zero ohms) will keep the panel lamps warm without need for any special keep-warm circuitry. However, consider the following: 1.2 volts on a 12-volt lamp will not cause any usable light output. If your dimming control pot takes lamp voltage completely down to 1.2 volts, the control must be moved through a large percentage of total rotation *before any light is visible from the panel lamps*. I recommend that dimming controls be scaled so that full counter-clockwise rotation leaves the lamps powered up to about 4 volts as I did in the rheostat calculation earlier. Clockwise rotation will then provide an immediate increase in visible light from the instrument lamps.

LAMP SELECTION

A number of catalogs listed in Appendix A contain listings for incandescent lamps. Some listings will state an application for the lamp. Stated applications almost always refer a purpose for which a lamp was designed. It is not forbidden to use a lamp for other purposes. Indeed, any lamp is fair game for use in your airplane.

Some general rules of caution: avoid using lamps with screw-in bases. These can rattle loose in their fixtures to become an in-flight nuisance at best. Worse, a loose lamp could cause misinterpretation of an indication that the lamp is expected to provide. Bayonet lock bases are good. Flanged base lamps are excellent also; their fixtures are usually designed to be used in airplanes or other vehicular applications. Most of the time, lamp selection is driven more strongly by the fixture it fits into than by the characteristics of the lamp itself. For example, you might find some nifty fixtures in the Fly Market at OSH that look as if they would make good instrument panel floods. The task is then to find a lamp that fits the fixture, and provides sufficient (but not too much) light.

If you have some small instrument, like a battery ammeter or bus voltmeter tucked away in some corner of your panel, consider installing your own internal lighting. Radio Shack stocks some very small, 12-volt lamps with wire leads. I've installed these lamps in the tiny, 1.5" square meters with good success. The instrument seldom needs full output from such lamps to be visible so include a resistor in series with the lamp to limit its brightness and multiply its life. It is unlikely that properly installed internal lamps will ever need replacement.

Lamp selection and lighting system design is a task that needs to be approached with an open mind. Be ready to try something a little different and keep refining the design until it is really right. If you develop something really neat that you'd like to share with your fellow subscribers, let us know. Distribution of good ideas is part of the 'Connection's reason for existence.

Antennas and Feedlines

Antennas have been around since before Marconi's feeble signals were first received from across the Atlantic ocean in 1901. As a class of device, antennas are quite simple in theory of operation and methods of construction. Antennas used on airplanes are certainly very simple. None-the-less, there's a sort of aura about antennas that borders on mystical. After all, here's a simple piece of conductive material that literally launches energy from transmitters into the atmosphere. Still more amazing, the same antenna will gather tiny, 0.0000000000000002 watt signals from the atmosphere and conduct them to a feedline for transport to a receiver.

Not too many years ago, in fact as late as 1953, books referred to a substance called "ether." It was thought to be a medium through which electromagnetic waves would conduct and was used to give foundation to suspect theories on propagation of light and radio. Scientists have now abandoned the concept of the "ether" but they didn't replace it with a more suitable term. I think they should have simply changed the definition of "ether" to include atmosphere and space for indeed, both radio and light travel readily in each medium.

WHAT IS THIS RADIATION STUFF?

Recall from chapter 7, a magnetic field is generated every time electrons flow. Electrons will flow whenever a conducting path is provided between different electrostatic potentials. The converse is true also. If a magnet is shoved into a coil of wire you can sense a voltage being generated as the magnet moves past turns of wire. If voltage is conducted away on wires to do work then it may be called an electro-motive force. If the terminals of our experiment coil are not connected, the voltage is still there but it might be called electro-static. Alternators use very strong moving magnetic fields to generate large values of electromotive force or voltage.

But suppose our coil of wire experiment were conducted with steel wire versus copper wire. The electrostatic force would be the same but steel's higher resistance

would produce some losses if you try to draw current. Consider further that if you wind our coil with some exotic wire with a very high resistance. Again, if you draw no current a measurement of electrostatic potential would be the same but the ability to draw it off is nearly zero. Now suppose the wire has infinite resistance (wire made from air if you will). It's no leap of faith to acknowledge that an electrostatic potential is still there in spite of the fact that no conductor exists to carry it elsewhere. The major difference between our somewhat static demonstrations of magnetic and electric fields and propagating radio or light energy is frequency. If voltage fields or magnetic fields are generated in a cyclical or periodic manner, they produce a wave capable propagating energy and requires no conductor to do so.

Figure 13-1 is an excerpt from Figure 12-2. In chapter 12 we were interested in wavelengths and frequencies of light. Both figures speak of other electromagnetic emitters, namely well known radio communication and navigation aids. Each service has a frequency range and a wavelength range. For example, localizer, VOR and VHF communications frequencies lay between 108 and 135 megahertz which corresponds to a wavelength of 2.78 to 2.22 meters. These numbers are derived by dividing the speed of light (299,999,997 meters per second) by frequency in Hertz (108,000,000) which yields a wavelength of 2.78 meters. In each example, the transmitter generates a cyclical electromotive and/or magnetomotive forces (remember, you can't have one without the other!) which are conducted along feedlines to antennas.

On the antenna they become electrostatic and magnetostatic fields with cyclical properties measured in hundreds of millions of excursions per second. Once placed on the antenna, energy propagates freely into space around the antenna. The fact that simple wires, stuck into the air will do such amazing things has often prompted fertile imaginations to believe that more complex designs might do even better. I recall strange devices that used to sit on top of people's television receivers in the 50's and 60's. They were true *objects*

THE "RADIO" SPECTRUM

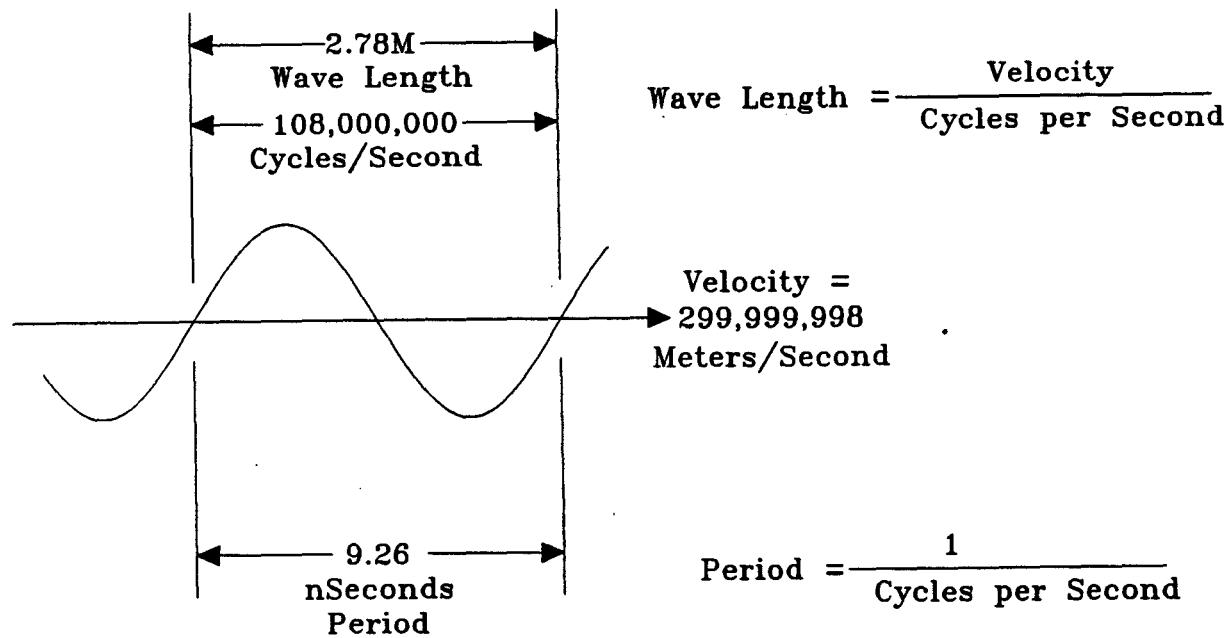
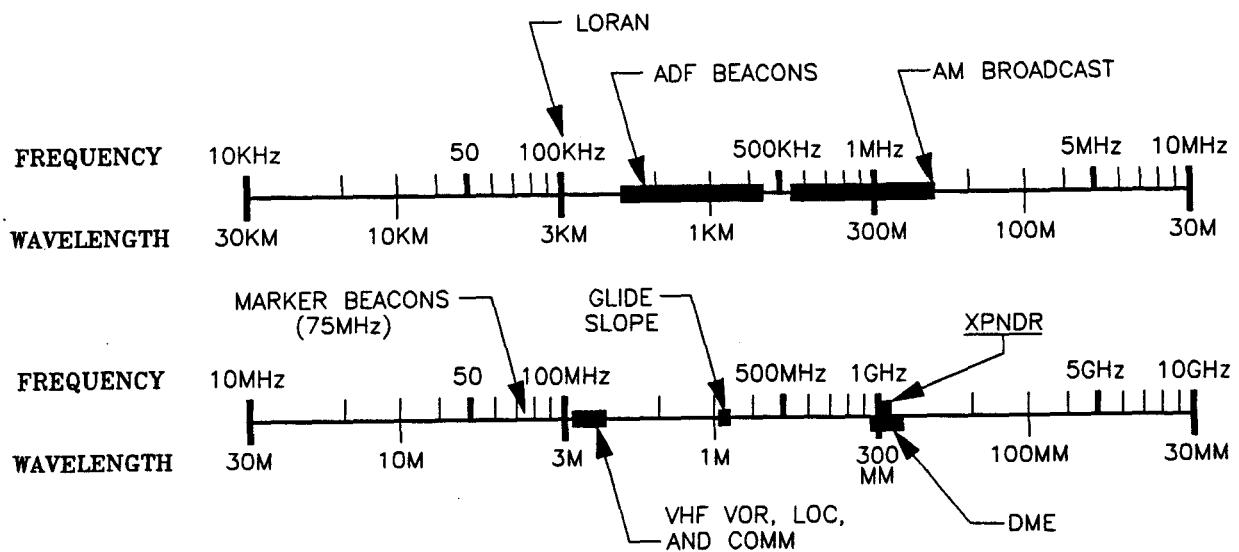


Figure 13-1. Radio Spectrum and Wavelength.

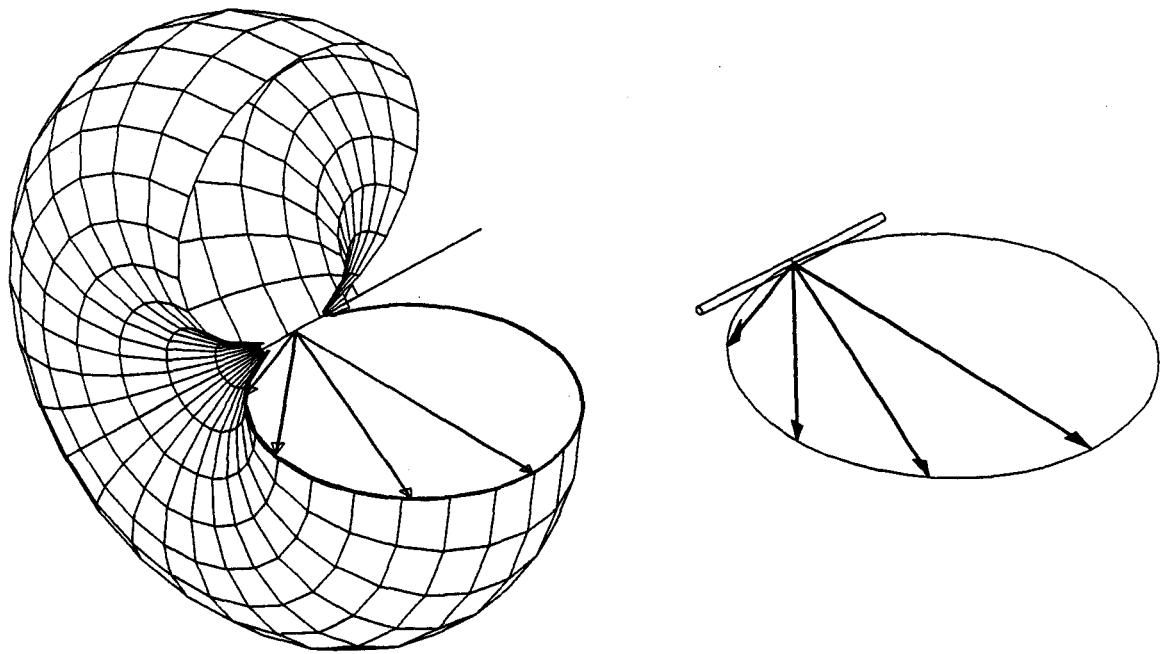


Figure 13-2. Three-D and "Slice" Views of Dipole Radiation Pattern.

d'art. Simple "rabbit ears" simply had to be outperformed by these gold anodized, multi-jointed testimonies to the metal smith's art!

Citizen's band antennas suffered from equivalent maladies. During the heyday of citizen's band activity in the 60's and 70's many an operator paid dearly for what he believed would provide that "little edge" over his neighbor's signal. The most noteworthy feature for some designs was the prodigious rate at which they blew away in Kansas storms compared to their simpler brethren.

Figure 13-2 shows a simple dipole antenna with a slice out of its radiation (or reception) pattern on the right. The arrows are signal strength vectors. The arrow points the direction from which the signal is to be observed. The length of the arrow shaft is proportional to signal strength radiated in that direction. Note the longest arrow extends outward from center of the antenna at right angles. As the arrows rotate more toward the ends, they get shorter. An arrow pointing off the end of the antenna would have zero length. Obviously, the best place to receive a signal is broad-side to this antenna. Sharp nulls do exist off the ends. The view on the right is a single slice through a three-dimensional radiation pattern which wraps completely around the antenna as

shown on the left.

If you transmit with this antenna, most energy would radiate in directions other than toward an intended receiver. Figure 13-3 shows parasitic elements placed adjacent to the radiator. These elements focus otherwise errant energy into a major lobe out the front. This basic antenna shape is very familiar to all; similar devices stick from the tops of houses and buildings everywhere. The parasitic elements are called "directors" and "reflectors." Even their names suggest an ability to modify energy patterns.

Some antennas are said to have "gain" over it's poorer performing cousins. The word gain is somewhat misleading. The same word is used to describe amplifier performance; 10 volts out for 0.4 volts in says the device has a voltage gain of 25. Does this mean an antenna with gain amplifies your outgoing or incoming signal? Not really. No energy is added created; available energy is simply focused. A similar situation exists with more familiar devices. For example, a modern halogen lamp flashlight may produce a light visible at perhaps 5 miles away. If the bare bulb with no reflector were simply held up in the dark from such a distance, I dare say it would be invisible. In both cases, total radiated energy is the same. A reflector focuses at least half of available light in one direction.

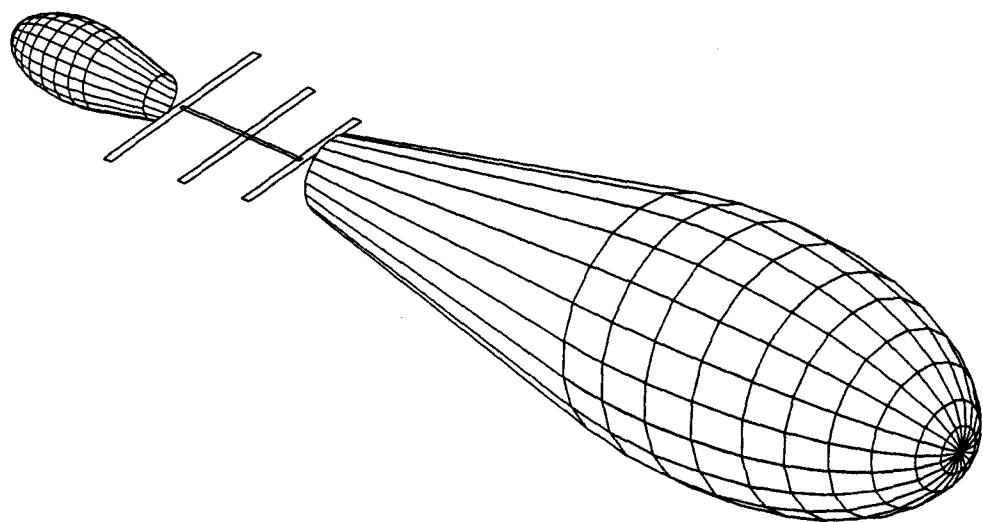


Figure 13-3. Parasitic Elements Focus Energy into "Beams".

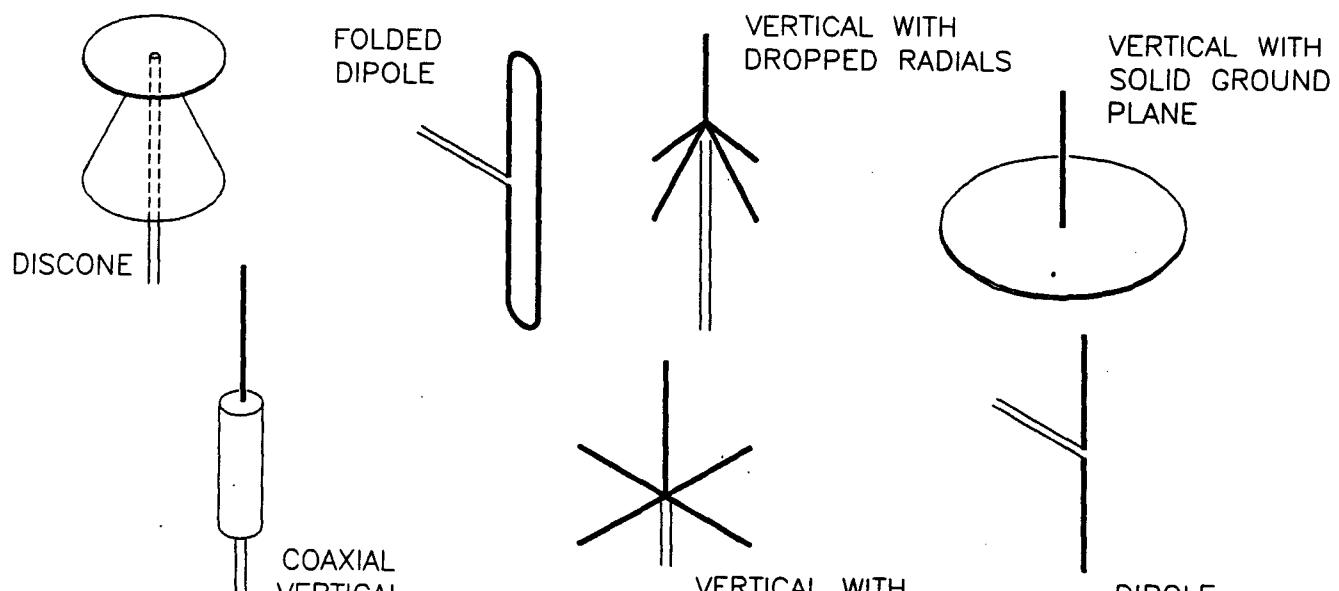


Figure 13-4. A Collection of "Vertical" Antennas.

Of course, if you are not positioned exactly in the beam at five miles, you might not see it even with a reflector. Parasitic elements added to antennas will modify a driven element's radiation pattern so as to concentrate transmitted energy. Therefore, antenna gain is a function of how well the antenna focuses available energy in the desired direction.

Multi-element antennas are often called "beams" and are rotated by remote control to point at a station of interest. Amateur radio and citizens band beams are evident in most communities. Television antennas in remote communities are often situated on tall towers and rotated as needed to receive distant signals. Fringe area television antennas tend to be large also with many parasitic elements. The longer the antenna, the more tightly focused is its beam which yields more gain.

"So what?" you might ask. "Rotated beams are not practical for service on airplanes. Why bother with them here?" The point to be observed is that judicious placement of conductors in the vicinity of an antenna will strongly modify the antenna's radiation pattern in a predictable and useful way. The converse is true also, random or careless placement of conductors in the vicinity of an antenna may strongly modify the antenna's radiation pattern in unpredictable and useless ways.

Figure 13-4 illustrates several different types of antennas. Each is uniquely constructed but interestingly enough, from a performance standpoint, all the illustrated antennas perform nearly the same! There are small differences but you would be unable to detect the "hotter" design simply by listening to signals received on it. Laboratory equipment is required to accurately quantify the differences. There are several features common to the antennas illustrated. Except for the discone, they are all "resonant" antennas and all vertically polarized. The "vertical" aspect of these antennas is rather apparent from just looking at them (except perhaps for the discone). None of these antennas has parasitic elements so their radiation patterns are "omni directional." This means that all these antennas transmit and receive from any direction.

IT'S ALWAYS BEST TO RESONATE

The "resonant" feature requires a little explanation. Resonance is most easily conceptualized as response which repeats an external stimulus. At more pedestrian frequencies, like those you can hear, I can think of many examples of resonant response. I recall a photography job for a music store several years ago when a show-

room full of grand pianos were being demonstrated. When the pianist played a single chord loudly and then muted her instrument, I could hear the chord carry on from several instruments around it. Strings tuned to the same frequencies being played would begin to vibrate in resonance with the applied stimulus. In this case, sounds from the played piano. Pipe organs use resonant tubes excited by a stream of air to produce notes of music. Each pipe's or string's resonant frequency is predictable if you know the laws of physics which govern its performance.

The basic dipole antenna is resonant when its length is equal to $1/2$ wavelength for the frequency of interest. Figure 13-5 shows a dipole antenna with an adjacent graph. The graph depicts voltage and current distribution along the antenna's length when excited with energy at its resonant frequency. Note that voltage is highest at the ends while current is highest in the center. The high current point or center turns out to be the easiest place to make connections with feedline to conduct energy to or from the antenna. I'll point out here that the lion's share of energy from an antenna radiates from the highest current points; in the center. Therefore, if you ever need to mount a dipole in restricted space, it's okay to bend up to 30% or so of the length at each end with little effect on radiation pattern or antenna efficiency. I can put 85-foot ham antennas in my 65-foot long attic; a 10-foot dogleg in each end makes it fit!

Antennas for airplanes are almost always "resonant" meaning that they are cut to length for the frequency of interest, well, almost. Marker beacons and LORAN are the only services that work on a single frequency. Therefore, their antennas may be optimized at a single frequency. All other services such as VHF communications, VOR navigation, DME, Transponder, ADF, and glideslope operate on a range of frequencies. Bandwidth is a term used to describe the useful operating frequency range for antennas. For airplanes, optimum antenna designs are not necessary. Systems which operate above 100 MHz are essentially line of sight services. Since airplanes operate high off the ground and away most manmade noises, they enjoy adequate access to facilities in spite of less than ideal antenna situations. This is fortunate because optimized antennas, and antennas with "gain" usually mean larger size, more weight and more expense or restrictions to an otherwise omnidirectional performance pattern.

There are a number of factors which interact with antenna length to determine its point of resonance. One important factor has to do with length to diameter ratio.

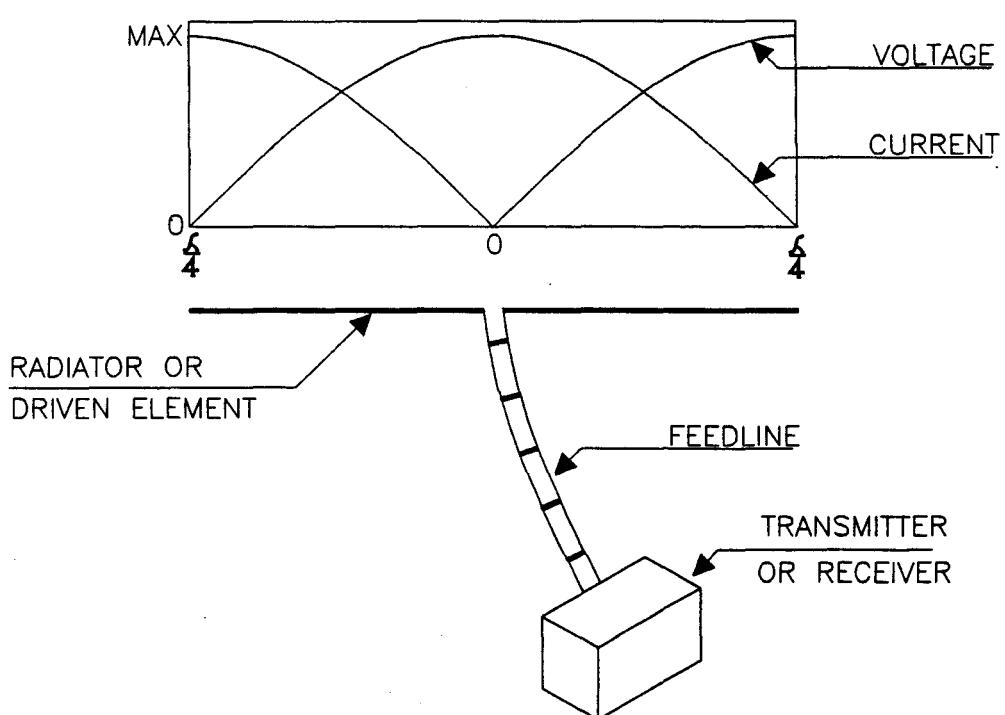


Figure 13-5. Half-Wave Voltage & Current Distribution.

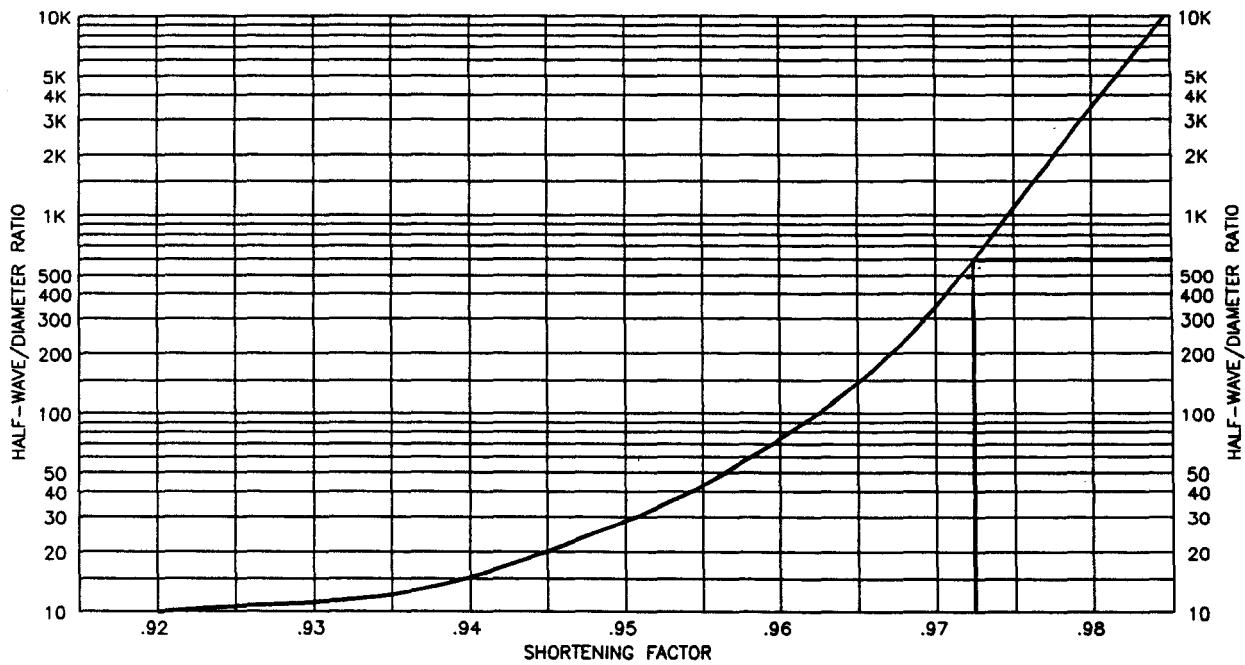


Figure 13-6. Length/Diameter Ratio Shortening Factor.

Only an antenna of zero diameter will be resonant at it's free space calculated length. Figure 13-6 shows a graph for shortening an antenna to compensate for its diameter. The vertical scale is half-wave-length to diameter ratio. Let's use marker beacon antennas as a handy example. 300 (million meters/second) divided by 75 (million cycles per second) yields 4 meters per cycle (a full wave length). A meter is 39.37 inches long so a half-wave antenna at 75 MHz is 39.37 times 4 divided by 2 or 78.75 inches. Not having any zero diameter wire to make the antenna from, let's select .125" brass rod. 78.75 inches divided by .125 inches yields 629 for a half-wave/diameter ratio. Entering the graph at 600 and travel horizontally to intersect the graph, then down to .972 along the bottom. 78.75 inches times .972 yields 76.5 inches. Hold on, before you get out your yardstick and hacksaw, know that proximity to other conductors adds capacitance to the resonance equation causing the resonant frequency to shift lower. This requires the antenna to be further shortened still. Capacity due to adjacent structures is really significant when antennas are bent so as to become more parallel with their mounting surface. Examples of this type will occur several times in the following discussions. So, when you make a measurement of someone's hot performing antenna and it appears "short" with respect to calculated length, know that there is a good reason for it. If the antenna seems to be "right on", it probably "isn't."

Years ago, most single engine manufacturers fabricated their own comm, omni, glide slope, marker beacon and ADF sense antennas. Comm antennas were steel rods poked through the skin on ceramic cone insulators. Glide slope antennas were simple dipoles mounted at the top of the windshield. "Sled runners" were to be found on the belly of airplanes with marker beacon receivers. A single copper-clad steel wire was stretched from cabin top to vertical fin tip for ADF receivers. I don't think any airframe folk undertook to build DME or Transponder antennas but they could have. DMEs and Transponders were rare installations during the heyday of airframe built antennas. About everyone buys antennas nowadays but that doesn't mean you have to.

Things to consider for antenna selection include performance, strength, drag, esthetics, cost and ease of installation. On the performance side, commercially built antennas work about the same as homebred devices. There just isn't much you can do to improve on basic physics of these things. However, poor grounding on a 1/4-wave vertical can cause an otherwise adequate

antenna to perform badly, purchased or fabricated. Commercially built communications and VOR antennas will sometimes include some form of matching network in their base which is of marginal benefit (we'll discuss it later). The word "drag" brings everyone but J-3 owners right up in their chairs! For both esthetics and drag considerations, composite airplane builders may build antennas inside the structure during fabrication of the airplane. I don't personally get too excited about drag from antennas. I've seen the numbers crunched by some pretty good aero guys and antennas simply are not a big issue with respect to aircraft performance. A word of caution for antennas built into composite airframes . . . If the antenna is to be buried into a canard or wing and glassed over, make sure you build it solidly. The antenna cannot be repaired later when some joint goes bad or a wire breaks.

Strength and ease of installation are mechanical issues. Strength has to be considered for an antenna sticking out into a 200+ MPH airstream. Making proper mechanical connections between antenna and airframe requires attention to potential failure modes. Jim Wier, formerly of RST electronics, has written a number of articles on antenna fabrication for both metal and composite airframes (See notes at end of this chapter). You may wish to acquire them. I don't agree with everything Jim has written but his fundamentals of antenna fabrication and installation are solid and his writing is fun to read.

If cost in dollars is a factor, then do consider building your own. If cost in hours is an issue, it may be a toss-up between build or buy.

Table 13-1 lists common type of antennas found on airplanes categorized by service. Each service denotes style, frequency range and operating mode. More explanation of style and mode will be forthcoming in detail discussions for each antenna.

WE HAVEN'T FORGOTTEN GPS

I had occasion to work with GPS systems on an RPV project a number of years ago. I thought I was in a good position to expound on GPS antennas when I began this chapter. I was researching a few questions of my own on GPS and discovered that there was too much I didn't know about the system to write with confidence now. We'll add discussions on GPS antenna systems in later revisions to this chapter.

Service	Antenna Style	Freq.	Antenna Operating Mode
VHF Comm	1/4 Wave Vertical w/Ground-Plane	118-136 Mhz	Resonant E-Field
Transponder	1/4 Wave Vertical w/Ground-Plane	1030-1090Mhz	Resonant E-Field
DME	1/4 Wave Vertical w/Ground-Plane	950-1225Mhz	Resonant E-Field
VHF VOR	1/2 Wave Horizontal Dipole	108-118 Mhz	Resonant E-Field
Glide Slope	1/2 Wave Horizontal Dipole	329-335 MHz	Resonant E-Field
Marker Beacon	1/4 Wave Horizontal w/Ground-Plane	75Mhz	Resonant E-Field
LORAN	Random Length Wire	100 KHz	Non-Resonant E-Field
ADF Sense	Random Length Wire	200-1600Khz	Non-Resonant E-Field
ADF Loop	Ferrite Core Loop	200-1600Khz	Non-Resonant H-Field

Table 13-1. Antenna Styles and Operating Modes

QUARTER-WAVE GROUND PLANE ANTENNAS (or HOW TO GET "GROUNDED" AT 5000 FEET)

The first three antennas listed in Table 13-1 are quarter-wave ground-plane type antennas. In the table and throughout this chapter, the term ground-plane appears frequently. It is always associated with discussions of quarter-wave vertical antennas. Back when Marconi and associates were exploring new territory in the early days of radio, it was a well known fact that transmitting and receiving "aerials" performed better when used in conjunction with a "ground." The term was quite literal in those days; connections to the earth were made by burying or driving long conductors into the ground. In an earlier chapter on grounding, we discussed three types of grounds in airplanes that, for the most part, have nothing to do with each other. Grounds for antennas is one of them.

Looking at half-wave dipole antennas in preceding fig-

ures, we note the balanced nature of their design. Currents and voltages of equal amplitude exist on either side of a center feed point. Dipoles need no ground or ground-plane because they are balanced. A quarter-wave antenna is un-balanced. In order to drive energy into the base, you must have some connection for the other side of the feedline and a ground is it. On metal airplanes, the airframe skin is used to provide a ground, on composite airplanes, or on tops of antenna masts, some form of artificial ground or ground-plane is needed. A satisfactory replacement for good connections to mother earth is a series of radials which are the same length as the antenna. Quarter-wave ground-plane antennas seen around airports and on tops of towers and buildings generally have four radials spaced evenly about the base of the antenna. Purists may add four to six more but differences in performance are slight, differences in weight and cost are great. That is until you build an antenna for very high frequencies, like a DME or Transponder antenna. Here it is more practical to .co

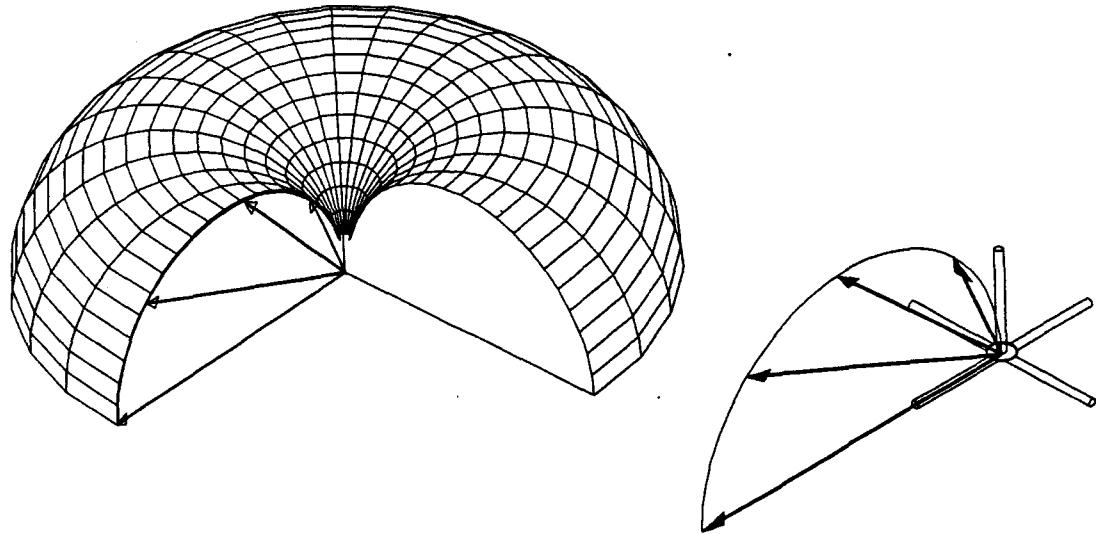


Figure 13-7. Three-D and "Slice" Views of 1/4-Wave Ground Plane Radiation Pattern.

make a ground-plane from an infinite number of 1/4 wave radials; like a solid disk of aluminum or copper.

The quarter wave antenna is 1/2 of a half wave. It has a slight performance loss over the half wave dipole but it is much easier to mount on an airplane than a vertically polarized, half wave dipole. Polarization is a term used to describe how the antenna couples to electromagnetic fields zipping through space all around us. Generally speaking, if an antenna's voltage gradient is vertical to the surface of the earth, the antenna is said to be vertically polarized. Best performance between two stations is achieved when they use the same polarization. Television and FM broadcast stations transmit horizontal polarized waves, therefore, antennas used to receive these services lay flat. *[In recent years, FCC has mandated FM stations to ADD vertically polarized components to their radiated signals to accommodate a proliferation of automobile receivers.]* Ground facilities for VHF communications use quarter-wave verticals with ground-planes. It behooves you to mount a VHF Comm antenna with the most vertical orientation possible on their airplane.

Figure 13-7 shows the radiation pattern from a 1/4-

wave, ground-plane antenna. Note this pattern is a subset of the single slice and 3-D models shown for the 1/2-wave dipole in earlier figures. Unlike a horizontally disposed dipole, with a radiation pattern that includes ground and sky, the 1/4-wave vertical has a very desirable omni directional pattern. Response for this antenna peaks on the horizon; very appropriate for DME, Transponder and Communications services.

When pilots were first given the ability to speak to the ground via radio, their transmitters operated around 2-5 Mhz as I recall. High performance antennas for these frequencies are difficult to obtain on an airplane. A quarter-wave resonant antenna would be 50-feet long! However, you needed to talk only a few miles during approach to an airport so shortened, low efficiency antennas sufficed. Antennas for the 2-30 MHz range are referred to as HF antennas. Energy emissions in this range are noted for an ability to propagate long distances. HF transceivers are often installed in aircraft which cross oceans or travel to remote locations. The most efficient antennas are long-wire antennas up to 2000' long which are literally reeled out in flight and retracted for landing. The Voyager Around-the-World aircraft carried an HF installation. The "stinger" which

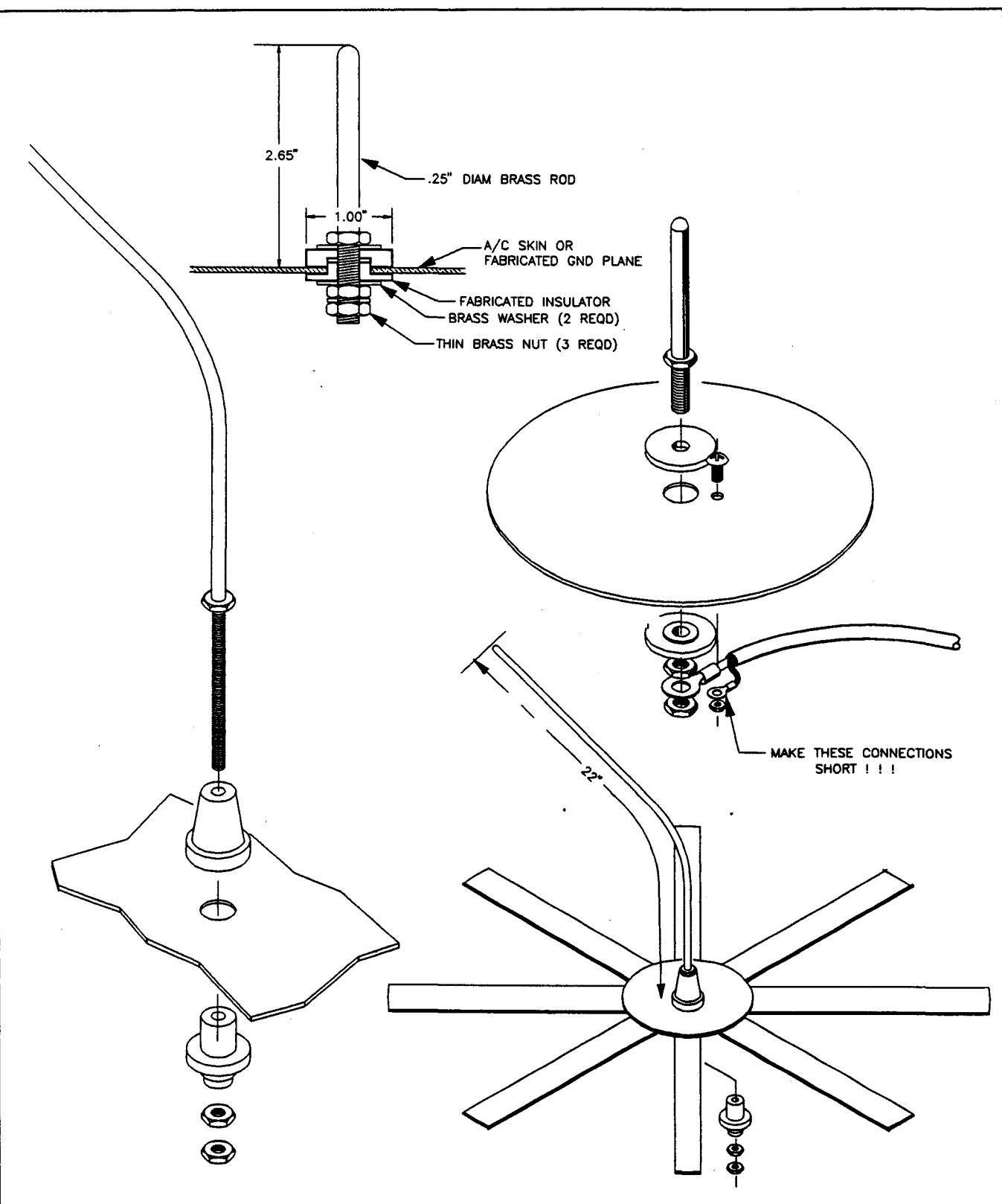


Figure 13-8. Variations on the Quarter-Wave Ground Plane.

protrudes from the left boom is the total length of Voyagers HF antenna. King Radio built some fancy footwork into the base of this antenna to optimize it's performance but it was still a compromise from a resonant, multi-wavelength trailing wire.

In the 40's, the FCC allocated VHF spectrum space in the 108-130 MHz range (just above the FM broadcast band) for radio navigation and communications. This was a welcome change in terms of antenna efficiencies but radio designers were pressed harder. In those days 100 MHz was an edge to the frontier. Vacuum tubes that operated well at VHF frequencies were harder to build. None-the-less, the new system caught on quickly. The higher frequencies were almost totally free of atmospheric noises and "skip" from other services around the world. The line of site nature of VHF systems seemed to be made for airplanes. Antennas from that day through the present are simple quarter-wave, base-fed sticks poked through the skin of the airplane.

ROLLING YOUR OWN IN QUARTER-WAVE ANTENNAS

Figure 13-8 shows several variations on the quarter-wave antenna installation. The longer "whip" antenna would be suited to VHF Comm uses while the short stubby fellow is for DME or Transponder applications. Irrespective of application, all quarter-wave ground-plane antennas have these things in common: (1) They are one quarter wavelength at the center of operating frequency range. (2) They require an artificial ground consisting of (a) many square feet of aluminum airframe skin or (b) a practical number of quarter-wave radials. (3) They are fed with a coaxial cable feedline with the center conductor attached to the base of an insulated radiator and a shield "grounded" as close to the base as possible.

Deviations from flat ground-planes and straight radiators are permitted. The length is important with respect to obtaining a resonant antenna components. The high current areas in both radiator and ground plane have primary responsibility for determining performance. Therefore, if a rakish look is desired, the top half to two thirds of VHF Comm antennas may be bent backward up to 45 degrees from vertical. However, foxtails flown from the tip are not recommended. Further, if the surface which mounts the antenna is not a perfectly flat plane, little performance is lost.

In a composite airplane, VHF ground-planes can be

fabricated from radial strips of copper foil, soldered to a commoning disk at the base of the antenna. Make these strips 1" wide and trim them off 22" from the base of the vertical. 4 to 10 strips is recommended. These may be cemented to the underside of the skin and structure. By fabricating a commoning disk from copper, the entire assembly can be soldered. You might even consider soldering the feedline shield directly to the commoning disk. With the UHF antennas for DME and transponder, a ground-plane disk of copper (preferred) or aluminum, 5-1/2" in diameter is sufficient. Now, there is some hangar wisdom circulating around that suggests, "the bigger the ground the better. Tie every piece of metal in the airplane together for increased performance." In the case of ground-planes just described, we went to a lot of trouble to make them "resonant." Resonance is a function of length compared to operating frequency. No performance gains are to be expected by adding connections to other "grounds." Further, there is a risk of noise problems by conducting stray currents to the communications antenna system via bogus ground connections.

MOUNTINGS FOR QUARTER WAVE VERTICALS, METAL AIRPLANES

Mounts for quarter-wave verticals have two requirements: they have to be good insulating material and strong enough to hold the antenna to the airframe. For the little DME and transponder antennas, strength isn't a great problem. Figure 13-8 illustrates a single hole, two piece bushing. I like to make these little guys from Delrin. A very tough, machinable plastic available from suppliers in the form of 1" rod stock. Lexan, and polycarbonate are other good materials. Nylons should be avoided. Sunlight and oil degrades nylon. Nylon also absorbs moisture. A few minutes on a lathe will make several sets of these. I cut a raised boss on the lower half which extends through the skin (and doubler) into a recess on the upper half.

For longer antennas, you may purchase two-piece glazed ceramic feed-thru insulators like that shown in View B or fabricate a larger, sturdier version of the little guy in View A. For the larger fabricated base insulator, consider 1/2" Plexiglas or cloth filled phenolic. In both cases, doublers riveted to the skin are used to spread loads over a wide area of skin. If a rib or bulkhead is close by, build a flange on the doubler to include this structure as doubler support. When fabricating a base from 1/2" sheet stock drill a close fitting clearance hole for the radiator. Clamp up in the insulator really snug with the radiator mounting nuts.

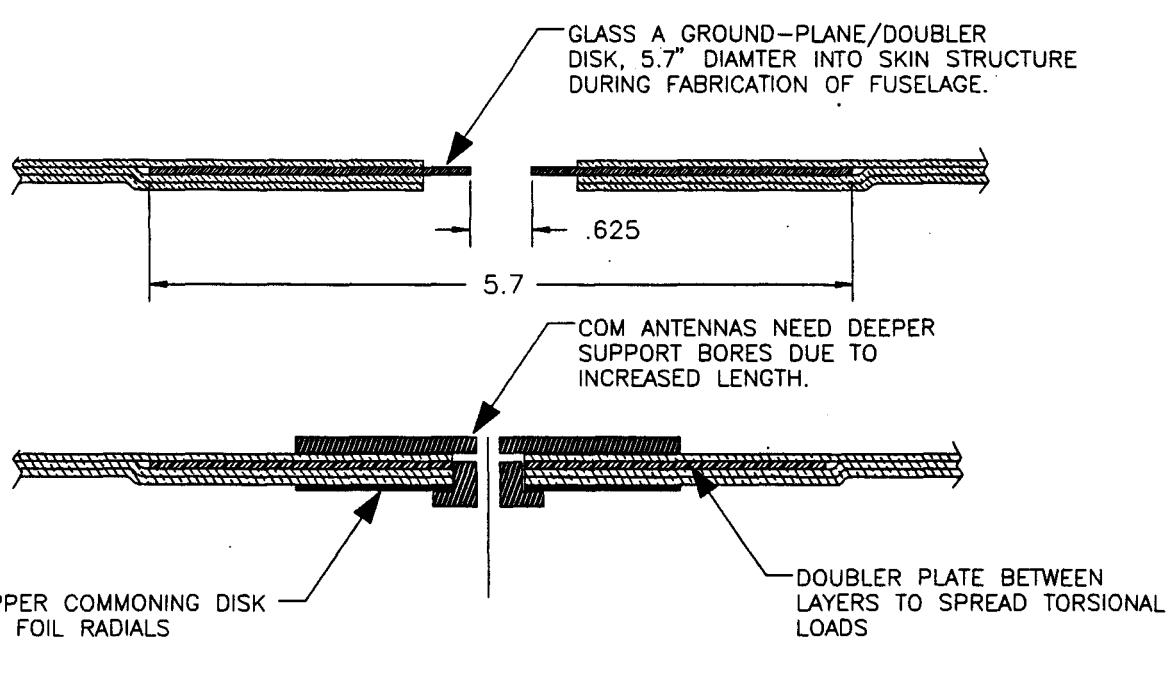


Figure 13-9. Embedded Ground Planes for Composite Airplanes.

MOUNTINGS FOR QUARTER WAVE VERTICALS, COMPOSITE AIRPLANES

Composite airplanes require a different approach. A few layers of BID glass and glue are a whole lot stiffer and tougher than .025" aluminum! Figure 13-9 shows DME and transponder ground-plane disks between layers of glass during fuselage fabrication. Many variations on this theme have been published by designers of composite airplanes so we won't go into a lot of details here. The most important difference between antenna installations on glass versus metal airplanes is an additional requirement for a resonant ground in the form of multiple 1/4-wave radials or a 1/2-wave diameter, ground-plane disk.

Copper foil in coiled tape form is available from 3M with an adhesive backing. Check with a 3M dealer for part number 1181 or 1245. Specify 1" width. The tape may be soldered to commoning disks at the base of 1/4-wave verticals or soldered directly to coax feedlines when ferrite beads are included on the feedline (see later paragraphs). The adhesive backing will hold the foil in place during installation but I wouldn't depend on it for long term support inside fuselages, etc. A layer of glass and resin over the finished foil is recommended.

TRANSPONDERS AND DME ANTENNAS, A HEALTH RISK?

I've read articles with admonishments to builders of plastic airplanes to mount transponder antennas far from the cabin as possible and/or provide shielding between the antenna and occupants. Aluminum foil applied under seat structures is recommended for very male concerns for protection of the "family jewels." The "200-watt" output rating of the transponder is often compared with the 600-watt rating of microwave ovens. While the peak power of your transponder may be 200 watts, the output occurs for microseconds at a time and only when replying to a radar interrogation. Average power at the antenna is only a few watts during pulse time. The 600-watt rating of your microwave is an average power directly related to an ability to cook. Your transponder can't warm anything up much less cook it. At Boeing in the 60's we worked on radar sets with 200,000 watts peak output. Average continuous power to the antenna was under 50 watts! I've not seen any studies in the engineering literature that confirm a hazard from this source. Energy densities as low as 5 milliwatts per cubic centimeter have been suggested as a threshold for

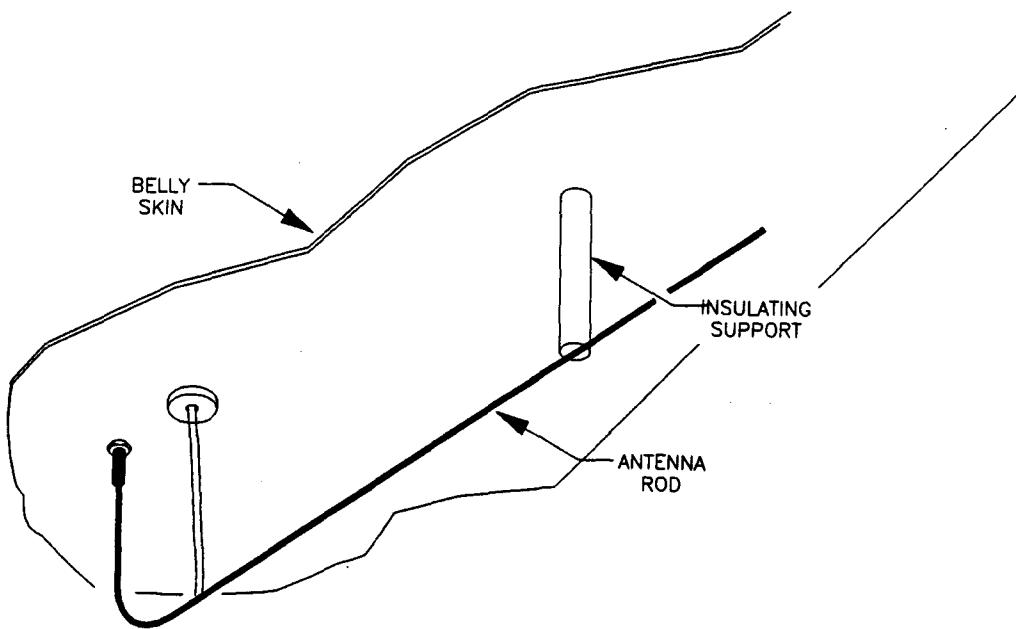


Figure 13-10. "Sled-Runner" Marker Beacon Antenna.

harm. Power delivered to any body parts from above a DME antenna ground plane will be well below this level. Most of the serious proponents of shielding take the "better safe than sorry route." Besides, if you are really worried about biological effects of electromagnetic radiation, the eyes are much more susceptible to damage. Mmmm, perhaps Bausch and Lomb would be interested in a new aviator's product. Grounded gold frames with screen wire shields embedded in the lenses? Shield your buns if it makes you feel better but don't loose any sleep over it if you don't.

MARKER BEACON ANTENNAS

Marker beacon transmitters put out about 5 watts into an antenna with a narrow beam directed straight up. Indeed some old books refer to them as "fan" markers in deference to the shape of their radiation patterns above the ground. At one time, 75 MHz marker transmitters were used for locators along traffic airways and high altitude performance was needed. Nowadays, one receives the outer marker from about 1000 feet up. Figure 13-10 illustrates the classic "sled-runner" may be seen on thousands of single engine airplanes. It extends vertically from the belly skin for about 4-6 inches then bends 90

degrees aft to be supported by an insulated post. A feedwire taps onto the antenna a few inches from its grounded attach point forward. Position of the tap is adjusted for best match to the 50-ohm feedline.

Newer antennas may be housed in molded plastic aerodynamic shapes with considerable shortening of length compared to sled-runners. This shortening does affect performance but performance isn't much of an issue from 1000 feet up! For plastic airplanes, just about any approximately 1/4 wave (about 75") of wire strung out as straight as possible in the tail cone will work nicely. Something of a "ground-plane" could be formed by wrapping a 75" conductor around the inside of the tail-cone parallel to station lines. This is an odd mutation of the neat dipoles and verticals we use elsewhere but it is permissible and understandable given the unusual length of the antenna and strong marker beacon signals.

HALF-WAVE DIPOLES

The next two antennas listed in table 13-1 are also resonant but these are horizontally polarized. VOR, localizer and glide Slope signals are radiated with horizontally polarized antenna systems.

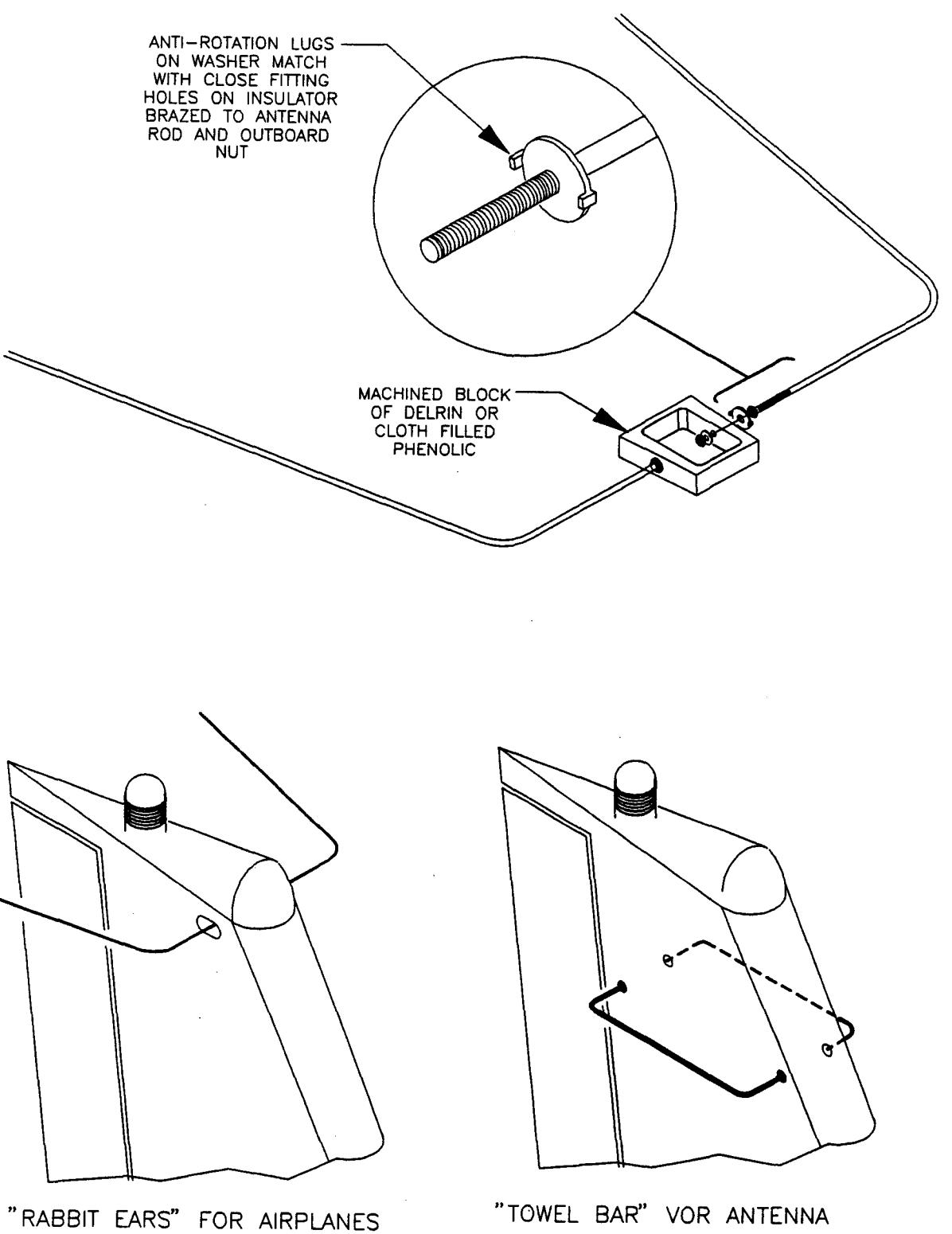


Figure 13-11. VOR Antennas

VOR/LOC ANTENNAS

VOR/LOC antennas are a pain in the you-know-what. They are twice the insulated elements as a communications antenna and they have to lay horizontal. The classic vertical fin installation requires a molded or machined insulator block not unlike that shown in Figure 13-11. The side surfaces are contoured to fit the inside surface of the vertical fin skin. Some form of mounting structure must be provided along with access for installation and maintenance. Quite often, VOR antennas are mounted on the vertical fin fairing itself which does make installation and maintenance access easier. These antennas are not difficult to construct but consider the following: A threaded stud stuck through an insulator block has almost no resistance to rotation under extremes of windage, temperature and vibration. Anti-rotation washers should be fabricated with tabs to engage holes in the insulator block. These can be brazed in place on the antenna rod along with the outboard nut before the rod is mounted and bent. This will keep the critter laying flat. Insulator blocks may be machined from Delrin or cloth filled phenolic with Delrin being the preferred material.

Figure 13-11 also illustrates the very common, swept back horizontal dipole and a relative newcomer to general aviation antennas. Nicknamed for their shape, they are called "towel bars." These are mounted in pairs on either side of a vertical fin and fed with a special feedline harness. If you are building a metal airplane, the vertical fin is a location of choice for the VOR/LOC antenna. Consider using a single antenna to drive two VOR receivers plus a glide slope receiver using a feedline signal splitter which we'll discuss later in this chapter.

THE WINGTIP ALTERNATIVE

I attended an RV forum in Fredericksburg and picked up a hand-out on a concealed wing tip VOR/LOC antenna developed by some RV builders. This "new" antenna, shown in figure 13-12, are a close cousin to the "sled-runner" marker beacon antennas. It is a quarter-wave, grounded base antenna with a "gamma matching" network for the coaxial feedline. This type of antenna has some obvious advantages over the classic dipoles hung out in the wind. First it is concealed and it is easier to build and install. However, it will suffer shadowing effects for signals arriving off the opposite wing. If this proves to be a problem, a second antenna on the opposite wing could be used to drive the #2 NAV receiver. Perhaps an antenna switch might be installed to permit selection of the antenna with the stronger signal.

CAUTION

A centered-needle ILS approach when receiving the localizer on a wing-tip antenna will place you off the runway centerline by 1/2 the wingspan of your airplane. Be prepared for a small side step maneuver toward the antenna when breaking out at minimums.

This type of antenna should be fitted to the airplane and adjusted for each installation. Folding the antenna back close to structure has a marked capacity effect cited earlier. These antennas are best trimmed in place. The RV gathering handout went into very specific construction details with an obvious goal of allowing one to reproduce the results with no test equipment. While writing this chapter I perceive a need to supply a small, mailable test set for 'Connection readers to make antenna adjustments in place on an airplane. If you are interested in pursuing wing tip antennas, get in touch with me and I'll work with you through your particular installation. In the mean time, I will put some thought into development of the test set to be made available to 'Connection subscribers. This test set will be capable of covering 75 to 350 Mhz for in-place trimming and matching of marker beacon, VHF COM, VOR/LOC and glide slope antennas.

GLIDE SLOPE ANTENNAS

Glide slope antennas are scaled down to about 1/3 size from VOR/LOC antennas. Figure 13-13 shows one method for fabricating a glide-sloped antenna. Lengths given are considerably shorter than calculated free-space. These antennas are often installed at the top of the windshield in single engine airplanes. The close proximity of windshield structure lowers the resonant frequency which requires further shortening of the antenna for best performance. Again, compared to VOR or COM antenna performance, glide slope antennas can be pretty sloppy. G.S. signals are seldom utilized more than 5 or 6 miles out from the end of the runway and G.S. transmitters are strong.

For pusher airplanes, glide slope antennas are good candidates for building into the nose or canard. Jim Wier's articles cited at the end of this section describe a number of alternatives for antenna fabrication and installation in plastic airplanes. Rather than duplicate his information here, I suggest you obtain the data package from RST. For high wing metal airplanes, the top of the

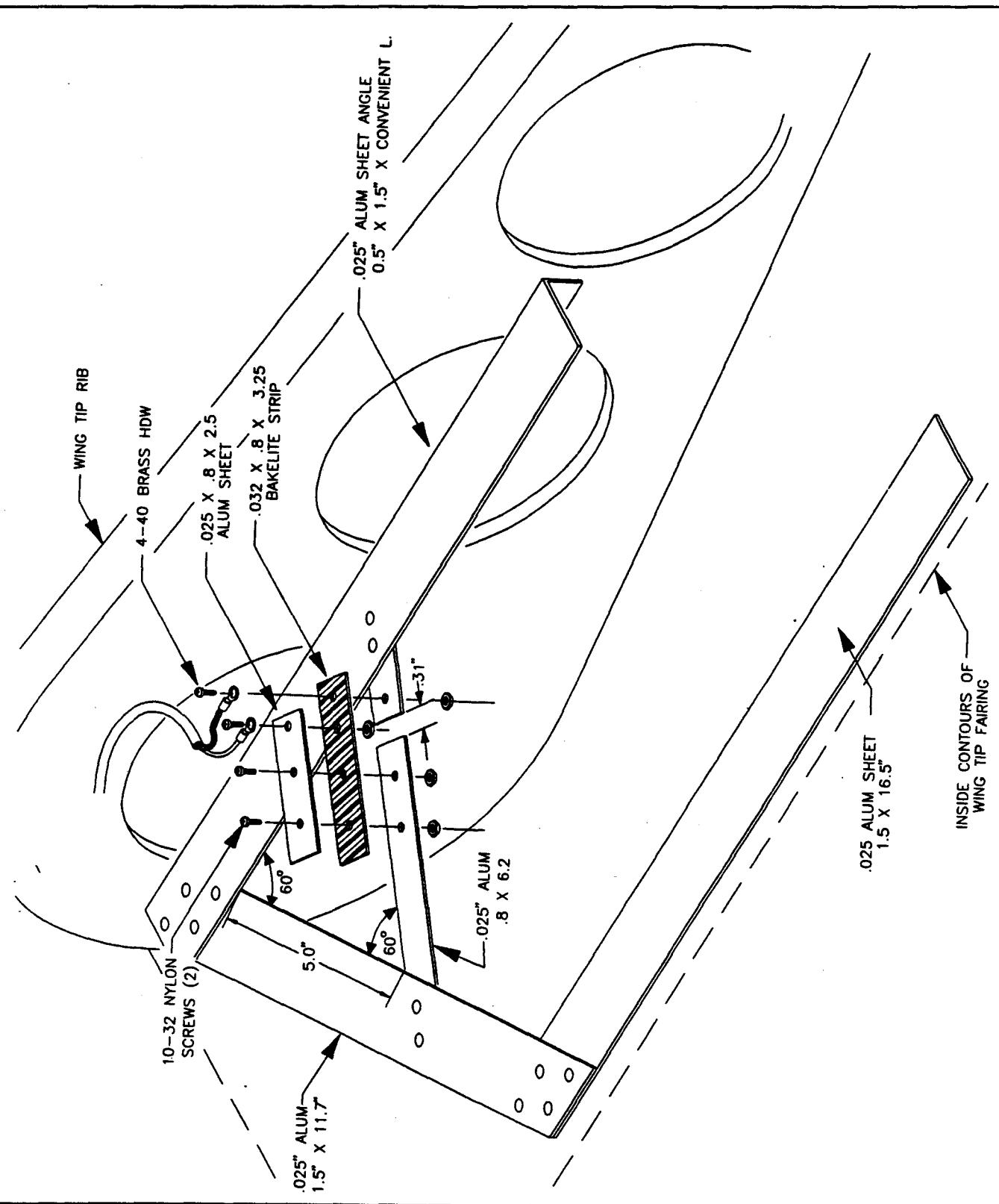


Figure 13-12. Wing-Tip VOR Antenna.

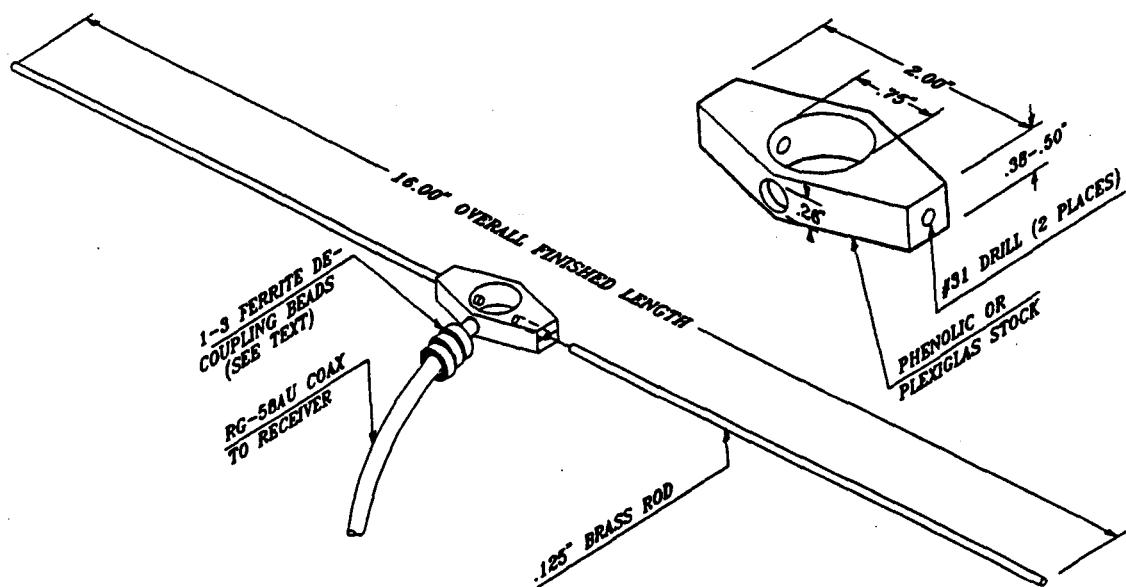


Figure 13-13. A Fabricated Glide Slope Antenna.

windshield is still a good bet. On low wing airplanes, consider a mounting a glide slope antenna on the plastic leading edge cover over a landing light. The light blocked by the antenna is negligible and, the antenna may have to be folded at the ends to stay inside the cutout length but it seems like a reasonable thing to consider. Of course, one could consider using a multi-set coupler as described in the next paragraph:

WHEN IS ONE ANTENNA IS BETTER THAN THREE?

The answer is, "when you can leave two of the three on the ground." For dual navigation and or navigation + glideslope installations, consider use of a feedline splitter to service multiple receivers with one antenna. This isn't a something for nothing situation, we're talking about sharing a finite amount of energy. In the case of dual VOR receivers, each receiver gets 1/2 the available signal. This does translate into a loss of range for both receivers compared to each having its own antenna. We're not talking about cutting range in half, it's more like taking 30% off at the fringes. Given the close proximity of most OMNI stations to each other, you may fly a long time and only over the desert southwest before you experience any degradation of utility due to feedline

splitter losses.

The other situation uses a VOR antenna for both VOR and Glide Slope. It turns out that dipoles perform fairly well on the third harmonic of their fundamental operating frequency. Hence, a VOR/LOC antenna with a 108-118 operating range could be expected to be a fair performer at 324-354 Mhz as well. G.S. receivers operate at 329-335 Mhz. Here the trade-offs are better. A two frequency splitter has fairly low losses for each frequency. Also, I believe splitters are available to supply two VOR/LOC receivers AND a Glide Slope receiver from a single antenna. Check with your local avionics shop and see what they recommend. You certainly don't want to carry more antennas than necessary!!!!

CAUTION

When using splitters, keep in mind that loss of one antenna or feedline will disable all receivers fed from the single antenna system. If complete redundancy is required by your design philosophy, splitters should not be used.

NON-RESONANT, E-FIELD ANTENNAS

Meet the worst antennas ever bolted to an airplane, LORAN and ADF sense antennas. In all fairness, they really can't help it. ADF frequencies (190 - 1600 KHz) and LORAN (100 KHz) have quarter wavelengths starting at a paltry 47 and ranging out to 400 meters! Unless you fly an AN-124 or a C-5, there just isn't enough good real estate to effect a good low-frequency antenna system on an airplane. None-the-less, there are techniques which provide useful compromise between the ideal and the useless.

Non-resonant, E-field antennas are very small compared to a wavelength at the frequency of interest. Two things happen with very short antennas: First, the amount of signal they are able to intercept is reduced and second, their feedpoint impedances are very high. Recall the discussion on internal resistance of batteries back in chapter 2, we spoke of an ability of a battery to deliver energy at high rates due to very low internal resistance. Obviously, if the internal resistance of your airplane battery went up to several thousand ohms and its open terminal voltage fell to a few microvolts, one would consider it quite dead and useless. Fortunately in this instance, we're not dealing so much with energy as we are with a small signal. Small signals, if handled carefully and applied to appropriate amplifiers, can be elevated to very useful levels.

An AM car radio antenna is an excellent example of a short E-field antenna. Since the feedpoint impedance is very high (like thousands of ohms!), 50-ohm coaxial cable would be inappropriate for use between the antenna base and receiver chassis. If you open the feedline on an old car radio aerial, you will find a very fine center conductor routed down a semi-rigid and oversized insulating tube around which a shield braid is formed. We get more on the special nature of this feedline later. Input circuitry of an automotive AM receiver is also designed to present a very high impedance (low current) load to the antenna. These conditions allow the signal of interest to propagate from wavefronts in air to the input of a receiver with minimal attenuation in spite of the high impedances involved.

Once inside the receiver enclosure, amplifiers and filters go a long way toward making an otherwise poor receiving system into a useful tool. ADF sense antennas have classically been 8 to 15 feet of wire strung from cabin top to leading edge of the vertical fin. Actually, this same wire would make a pretty good LORAN antenna as

well. I've heard that antenna couplers may be available which permit dual usage. However, LORAN receivers may take advantage of another technology known as the active antenna. Now here's an antenna that really does have gain. Well, actually the antenna is still just a passive piece of wire but there is an amplifier built into a little box right at the antenna's feedpoint. The amplifier does two things. It puts some gain on the signal and provides a low impedance output so that the signal will propagate adequately on ordinary 50-ohm coaxial feedline. Due to the single frequency nature of LORAN, it is possible to design a receiver front end that permits low impedance coax to be used with a passive antenna design. However, it's too easy to add the amplifier at the feedpoint and really do a better job of getting signals conducted from air and into the receiver.

ADF's are hold-overs from the early days of radio range stations which operated in the 190-450 KHz spectrum space. Even after the range stations were decommissioned in favor of VOR navigation, many of the transmitters were left on the air as low frequency beacons. Few homebuilders of compact airplanes are putting ADF systems in their ships. Further, given the rate at which GPS and LORAN are growing, one or both will replace the ADF as a non-precision approach aid in the foreseeable future. Meanwhile, making adequate installations of LORAN antennas is the plague of the moment, especially on composite ships.

There's no single magic potion for composite airplane LORAN antennas. Metal airplanes all seem to do well with the little whip (about 30 inches long) mounted on tail cone or in "sled-runner" fashion. A popular LORAN antenna for canard-pusher airplanes is illustrated in Figure 13-14. Most of the installed wiring is in the wing to provide a counterpoise ground. A short length of wire running up the tip sail is the actual antenna. Again, we hear some hangar-wisdom floating around that sez, "tie all the ground wires to every other loose piece of metal in the airplane, including electrical system ground."

When eight wires of about 8 feet in length are compared together with the 40-50 inch piece of wire that is the antenna, adding miscellaneous chunks of other "stuff" to the ground system holds little prospect for performance gains. It is more likely that noises from other system components cause by conduction and/or ground loops will be fed to the LORAN. Unless there is a compelling reason to do so, I keep antenna grounds separate from all others.

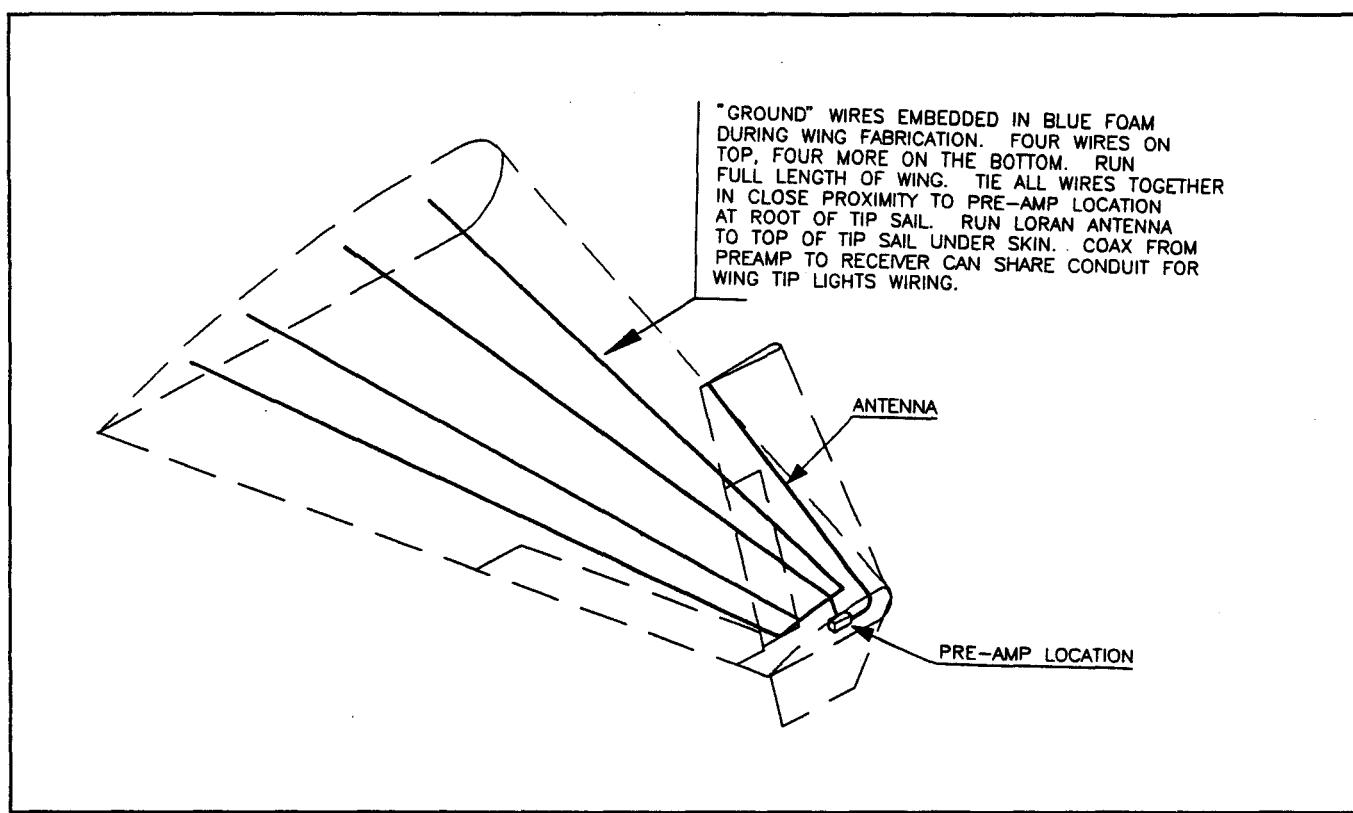


Figure 13-14. LORAN Antenna for Canard-Pusher Tip-Sails.

You can't have a LORAN antenna that's too long. Further, LORAN is vertically polarized so the most effective part of a LORAN antenna is that portion which is vertical to the surface of the earth. However, a long horizontal wire is better than a very short vertical wire. Experiment before deciding on a permanent installation. I would try a long wire running from wing tip to wing tip held on to the bottom with tape. Feed it from the center. At LORAN frequencies, there's nothing magic about grabbing the wire on the end. It seems to me that the best antenna for LORAN on plastic airplanes would be a version of the no moving parts ADF loop. A diversity or voting circuit to switch between multiple elements looking for the best signal would be in order. The problem is that plastic airplanes are a minority market, for now at least. With the heavy iron evaporating at 10,000 airplanes per year, I expect the LORAN people to take a serious look at engineering antennas for plastic airplanes. But they'd better hurry, before GPS blows them completely out of the water! The ADF loop is quite compact and operates in a unique mode as we'll see in the next few paragraphs:

NON-RESONANT, H-FIELD ANTENNAS (OR FINDING YOUR WAY HOME IN THE DARK!)

Like non-resonant, E-field antennas, H-field antennas are also much smaller than a wavelength at the frequency of interest. Further, they are characterized by their construction as having one or more turns of wire in the form of a "loop." Instead of sampling a small portion of a wavefront's electric field, loops sample the magnetic field. Loop antennas have been around just about as long as wire antennas. It didn't take early experimenters long to find out that special things would happen if the antenna were wound into a large coil instead of stretching it out between poles. As such antennas were rotated, a received signal was perceived to fade to nothing and then peak, two times per antenna revolution. It seems that when the antenna was broadside to the direction from which the signal was arriving, it had near zero response. 90 degrees of rotation would put the coils edgewise to the oncoming signal and maximum volume occurred.

My grandfather used a loop antenna to great advantage

in a radio we had on the farm when I was a kid. Some living room consoles of the late 30's and early 40's had loops which could be rotated by means of a front panel knob. AM stations around the country share their frequencies with several other stations. During the day, short-haul propagation hid the problem locally. However, out in the Boonies at night, an interfering, perhaps even stronger station on the same frequency could be nulled out by judicious loop adjustment.

The significance of this phenomenon was not lost on early pioneers of radio aboard ships. Loop antennas can be seen mounted on the radio shack of many ships. The antenna had two purposes. First, if you took a relative bearing on two or more stations with known locations, lines of bearing marked on a map would cross at your location at sea. Second, ships transmitting distress signals could be located by cooperating rescue ships who would trade bearing information as they steamed toward the distressed vessel. Even if only one ship had such antenna equipment it could be used to "home" in on the troubled ship. There was a problem when only one DF system was available. If two nulls were observed for each antenna revolution, how do you decide which way to go? Most times a distressed ship could give rough position data which would help rescuers resolve directional ambiguities. Occasionally, erroneous information would cause a rescuer to steam in the opposite direction with serious consequences for those who needed help. A marvelous story about rescues at sea can be had in a book by Farley Mowatt called Gray Seas Under. Radio DF equipment figured prominently throughout the story. Mowatt is a consummate story teller. I don't often pick up a book I can't put down but this was one of them. Check it out, you're in for a treat.

I helped an uncle install a manually rotatable loop on the belly of his Cessna 170 back about 1952. It had a speedometer type cable running from the loop gearbox up to a crank and bearing dial between the seats. With headphones on his low frequency receiver, he listened for the sharp null in received signal as the loop was rotated in flight. Since one usually knows approximately where they are, the null ambiguity could be resolved. Any town with an AM radio station could be used as a navigation aid.

Later, designers found that if you took a sample of the signal from a non-directional antenna and mixed it with the signal from the loop, the two nulls would remain sharp but the peaks would be markedly different. By rotating the antenna a full 360, the direction of the loudest peak would be noted and used to resolve the

proper null just 90 degrees away. The second antenna came to be called a "sense" antenna. Figure 13-15 illustrates the response pattern of a loop antenna with and without a sense sample. Manually rotated direction finding antennas soon gave way to devices driven by servo motors which automatically maintained the antenna in an unambiguous null condition on the received signal and the automatic direction finder (ADF) was born.

The first DF antennas for aircraft looked just like the devices shown in figure 13-16. As electronics capability grew, antennas could be made smaller and they were housed in tear-drop shaped housings for streamlining. By about 1960, they were small enough to be enclosed in a small plastic dome, usually on the belly. About this time the circular, air core construction was replaced by much smaller ferrite core, bar shaped devices. In figure 13-16 I have shown vertically polarized, E-field wavefront advancing on two loops oriented 90 degrees to each other. As you should expect by now, the horizontally polarized H-field is at right angles to the E-field. The H-field lines are in a proper orientation to couple nicely with the turns of wire in a loop antenna. However, when the loop is broadside to the oncoming wave front, each side of the loop develops equal but opposite voltages causing cancellation of the received signal at the feedline. A loop turned 90 degrees gets a different portion of the wavefront coupled to its wires for each instant in time which yields maximum signal.

Try this experiment with a little pocket AM radio: The antenna in most cheap radios is a piece of ferrite wound with many turns of wire. Tune the radio to a station several miles away and then rotate the radio while listening to the strength of received signals. When either end of the antenna core points to the station, the turns of wire are broadside to the oncoming wavefront and a null will be detected. Back in high school, about 1959, I managed to acquire a Regency TR-1 pocket radio. This was one of the first transistor radios on the market. I used to amaze my friends by having them tune the radio to any station and then put it into a sock and hand it back to me. I could tell them which station it was tuned to by appearing to wave it around a bit. Actually, I knew where the stations were located around the city and was listening for the nulls as I "waved". The parlor trick backfired when I tried to repeat it inside the building for the benefit of my electronics shop teacher. Steel and wiring in the structure badly distorted received signals and made "pocket radio direction finding" impossible.

Modern day loops used for ADF work don't have to be rotated mechanically. The antenna assembly on the belly

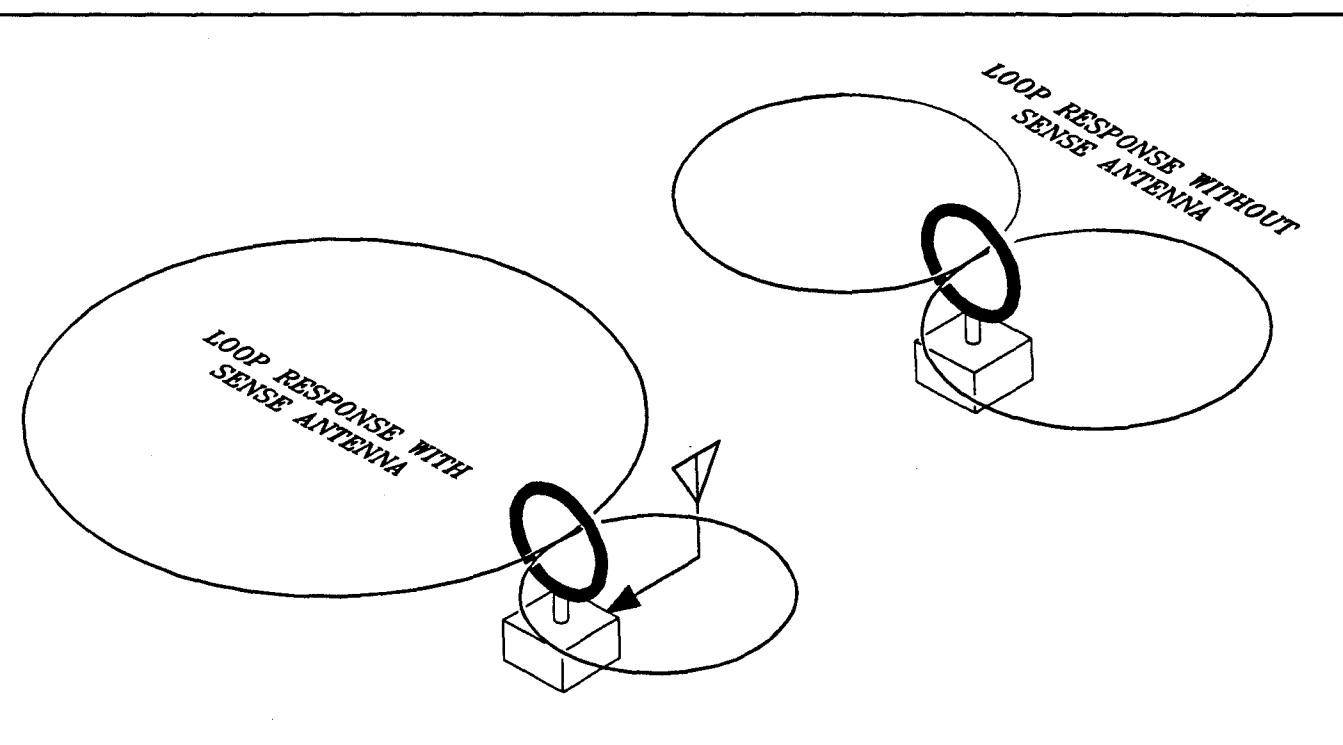


Figure 13-15. Loop Antenna Patterns.

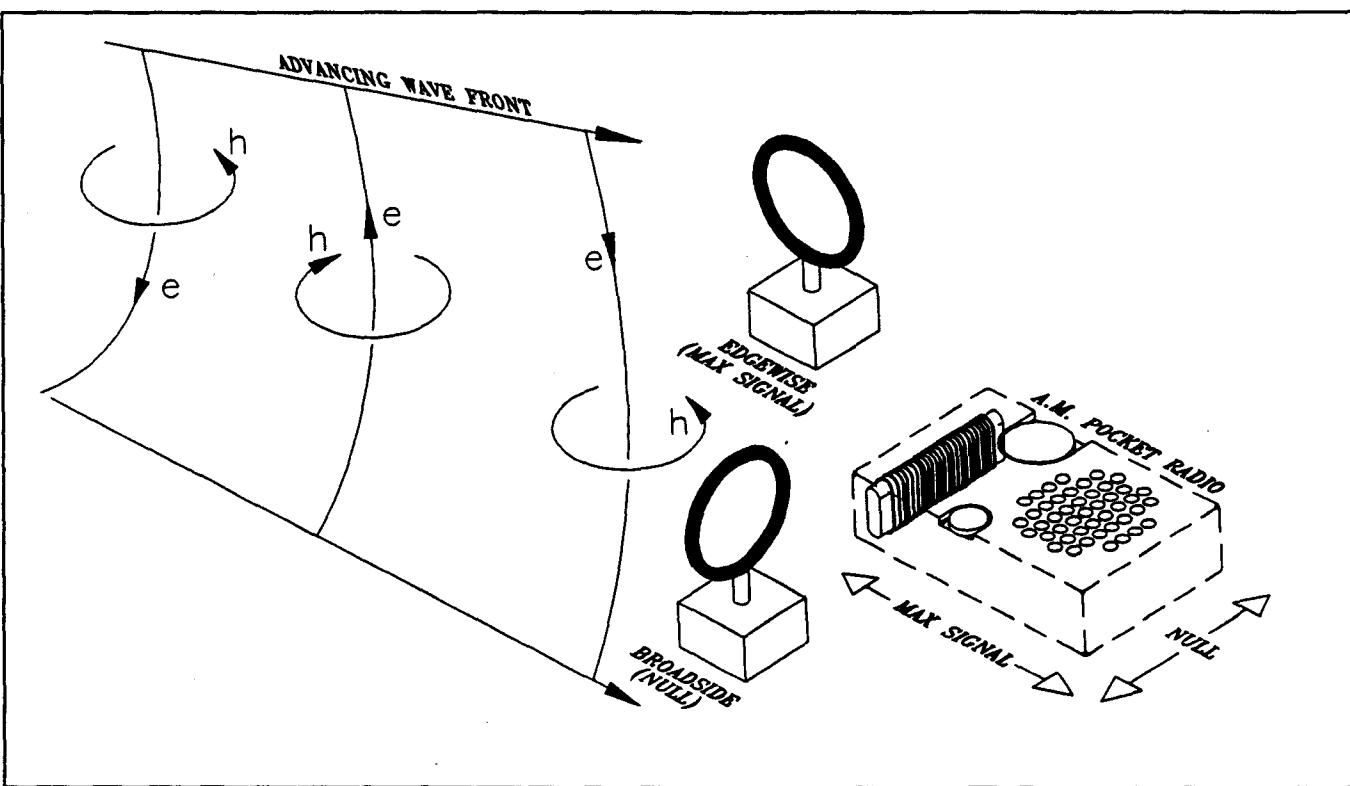


Figure 13-16. Direction Finding with Loop Antennas.

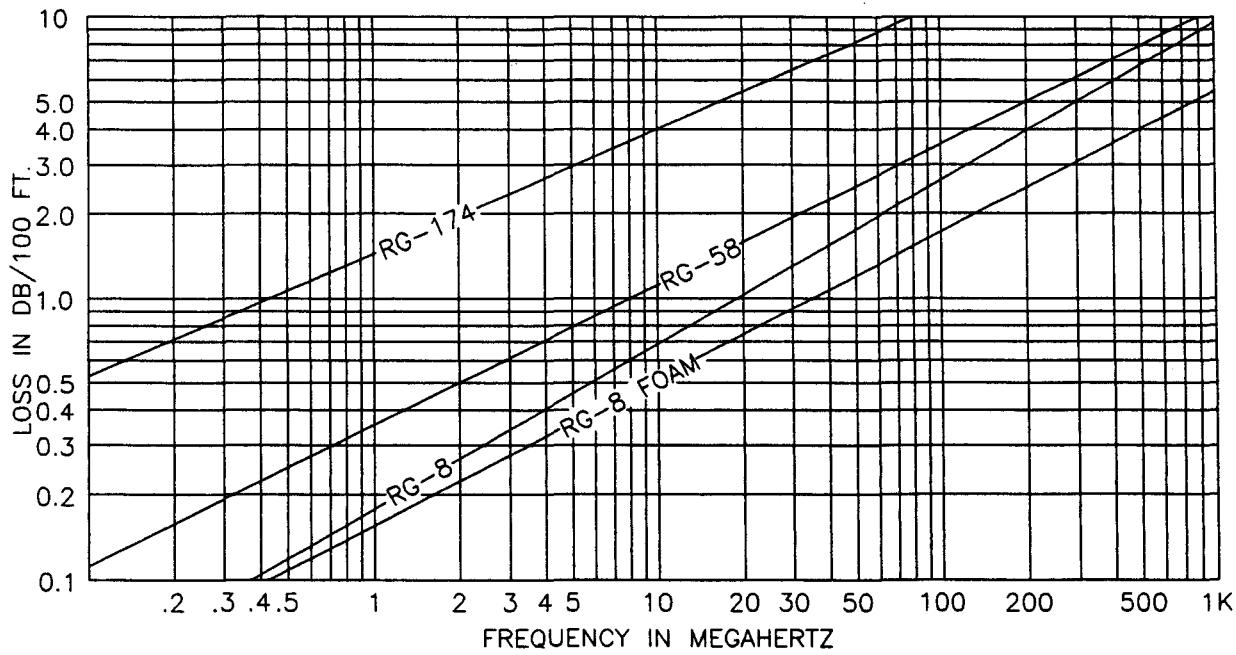


Figure 13-17. Losses versus Feedline Type and Frequency.

has two or three ferrite core coils, not unlike those found in the little pocket radio. All solid-state resolvers compare signals from a sense antenna with those from the ferrite "loops" and calculate direction of the oncoming wavefront electronically.

FEEDLINES: NOT YOUR ORDINARY SHIELDED WIRE

Radio frequency energy is seldom generated or gathered at the place where it is needed. Antennas may be located a considerable distance from a receiver or transmitter. The intervening wire is called a feedline. Unlike ordinary wire specified by gage, stranding and insulation, feedlines add specifications under headings of impedance, losses and power handling capabilities. Let's talk about impedance ratings which are always stated in ohms. Aha! We know about those critters; or do we? I've had more than one conversation with individuals who called about a defective roll of 50-ohm, coaxial cable they had just purchased. They "checked" the wire with an ohmmeter and it didn't read any where near 50 ohms! Had another fellow try to check some television twin-lead and he couldn't seem to read 300 ohms either. For coaxial cable impedance is a function of ratio of

inside conductor o.d. to outside conductor i.d. For parallel feedlines like television twinlead impedance is a function of ratio of conductor diameters to conductor spacing.

While the unit of measurement has the same name (ohms), techniques for measuring resistance versus impedance are different. Resistance is measured with a common ohmmeter. The simple hand held instrument has a battery, microammeter and some scaling resistors to measure current through the resistor to be tested. The volts divided by amps = ohms equation is solved and you read ohms directly from the meter scale. Impedance is an a.c. measurement. Further, it may include reactive components which cause impedance to vary with frequency. Reactive devices are capacitors and inductors which combine with resistors to make up complex impedances.

A LITTLE ENERGY GETS LOST ALONG THE WAY . . .

Irrespective of how you conduct energy from one place to another, it's nigh well impossible to transport it without some losses. We studied some examples of

resistive losses in the chapter on wire. Coax cables carrying radio energy has resistive losses like any other wire. Feedline materials suffer from additional losses due to insulation (or dielectric) quality. Furthermore, losses are directly related to operating frequency; higher frequencies suffer higher losses.

The ideal insulator for feedlines is air. Feedlines operating a very high frequencies or high power often use center conductors supported by occasional plastic spacers inside an outer jacket of copper pipe. Except for the center conductor and occasional spacers most of the volume inside the outer conductor is filled with air. However, to fabricate a practical feedline for running in wire bundles and under floorboards, a center-conductor is sleeved with plastic insulation and braided wire shielding is placed over the plastic for an outer conductor.

Depending on feedline size, center conductor insulation and length, coaxial cables for antennas will have some unavoidable losses. Generally speaking, the larger the coax, the lower will be its losses at any frequency. Figure 13-17 compares coaxial cables commonly used in avionics installations. Losses expressed in Db per 100 feet are seen to vary with operating frequency and cable type. *[Decibels, a very handy system for discussing power ratios]* We'll talk more about Db in the chapter on noise but for now, know that for each 3 Db power is diminished by 1/2, it follows that 6 Db loss means 1/4 power, 9 DB is 1/8th and 10 Db is 1/10th power, etc. This system allows you to work very large power ratios with rather ordinary numbers. For example: 60 Db describes a power ratio of 1 million to 1!

Referring to figure 13-17, we see typical losses for a few common coax cables. RG-174 is a very flexible, small cable about .1" in diameter. The first time I ever worked with some I was about ready to use it everywhere . . . until I looked up its performance at high frequencies. I've included it here as a comparison but I would not recommend its use in any but the most vexing space problems. Keep in mind that 50-ohm coax is 50-ohm coax. The radio cannot tell if you have more than one type of coax in the feedline. RG-174 could be considered for bringing glide slope signals off a windshield centerline antenna to a space over the upholstery. Once the coax is out of sight, appropriate connectors could be used to switch to RG-58 for the rest of the run. Use RG-174 in short runs, a few inches only, before transitioning to "better" stuff. At 300 MHz, RG-174 has a loss of 22 Db per 100 feet. A 1-foot piece would, therefore, have a loss of .22 Db which would be acceptable. RG-58 can be used for 95% of all installations.

Even 1000 MHz DME and transponder signals are not seriously affected by short runs (less than 10'). However, if you want the very best performance from these two radios, use RG-8 Foam type coax for feedlines. Purchase this coax from a two-way radio service firm. The so called RG-8X foam coax sold by Radio Shack and others should not be used in an airplane. Radio Shack's RG-58 is okay. RG-59 is a 70-ohm coax for television systems and not suited for aircraft antennas. Don't let anyone sell you some with the idea that it's "close enough."

There is some "leakage" of energy from within a coax cable especially if the SWR is not exactly 1:1. If the DME or Transponder makes little clicking or buzz-burst noises in your radios or audio system, try a double-shielded coax. RG-214 is suitable replacement for RG-8, RG-223 is a double-shielded version of RG-58.

STANDING WAVE RATIOS

Coaxial cables used in 95% or more of all aircraft feedline installations is rated at 50 or perhaps 52 ohms. Looking into the end of a 50-ohm coax terminated at the far end by a 50-ohm load you will see 50-ohms. If the far end is terminated by something else, say 100 ohms load, then the impedance you see looking into your end may be anywhere from 25 to 100 ohms depending upon the length of the feedline! This impedance transformation occurs along with a phenomenon known as standing waves.

If you've ever had occasion to install a c.b. antenna on a vehicle, the instructions will recommend and outline a procedure for adjusting the antenna for minimum VSWR or simply SWR (Standing Wave Ratio). Some c.b. transceivers even have SWR instrumentation systems built into the radio! The procedure generally tells you adjust the length of the antenna to achieve an SWR as close to 1:1 as possible. When and if 1:1 is achieved, you are assured that the antenna now presents a 50-ohm load to your 50-ohm feedline.

Quite often, an exact 1:1 is not achievable, perhaps 1.5:1 is the best you can get. Or, in the case of multi-channel radios, you might achieve 1:1 on one frequency only to see the SWR figure climb on other frequencies. This is simply a manifestation of two characteristics ascribed to all antennas: feedpoint impedance and bandwidth. For example, our hypothetical antenna is exactly resonant on only one frequency so it is quite natural to see shifts in feedpoint impedance as frequency changes. Further, the antenna may never present an

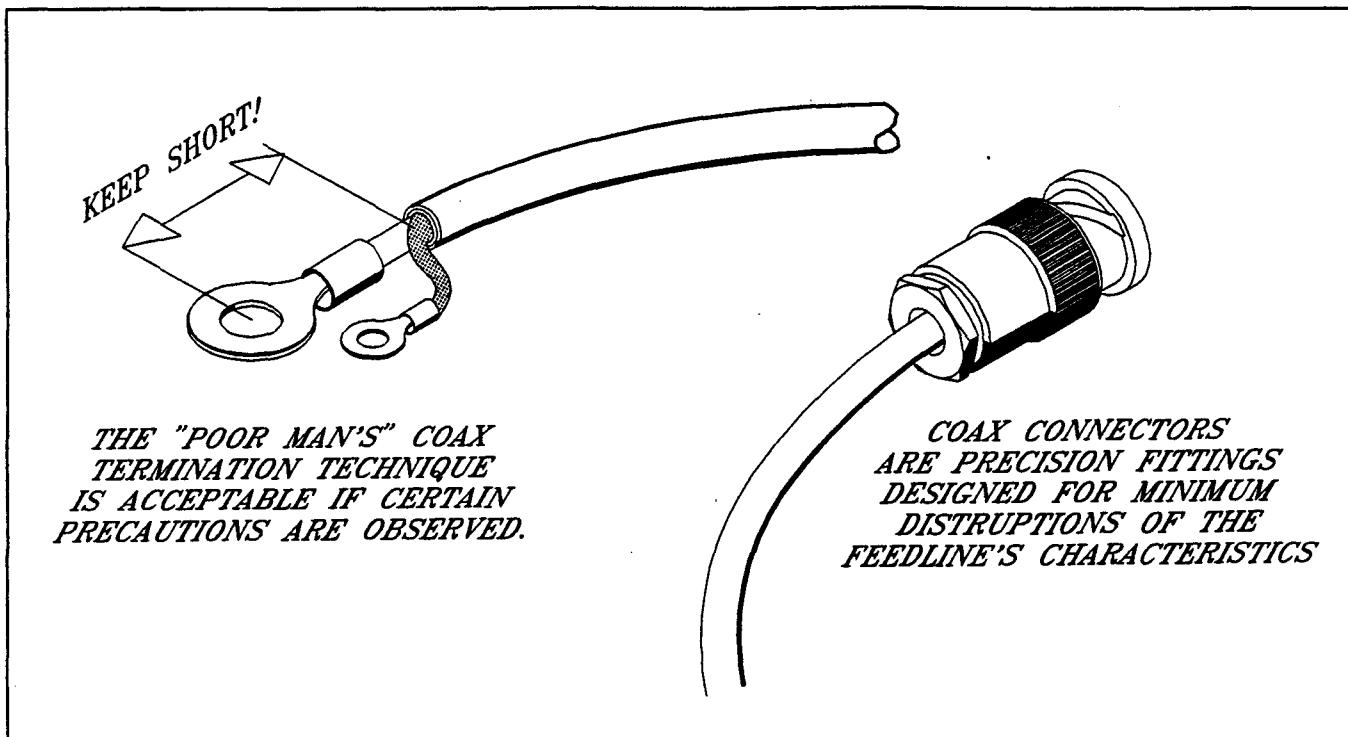


Figure 13-18. Two Styles of Coax Cable Termination.

exact 50-ohm load to the feedline even on its resonant frequency. The theoretical feedpoint impedance at the base of a 1/4-wave vertical is about 35 ohms. This means that the SWR on 50-ohm coax feeding this antenna will never be better than 1.4:1. Some commercially built antennas may have specialized matching transformers built into their bases which provide a better match over the antenna's design operating range. These antennas can be quite confusing when checked with an ohmmeter; they quite often look like a dead short! You can bet that when 120 Mhz energy arrives at the base, the antenna will look very close to a 50-ohm load . . .

MUCH ADO ABOUT LITTLE . . .

For some people, achieving 1:1 SWR on feedlines is a passion. In the real world, an SWR as high as 3:1 will make little if any perceivable difference in how your communications system performs. Some early solid state transmitters had problems with high SWR; it would cause output amplifier transistors to fail. Many of these sets had SWR instrumentation built in which shut down the amplifier in case a feedline became disconnected or an antenna was damaged. Modern communications transmitters are well protected against feedline failure. In any case, it's usually quite easy to keep antenna SWR

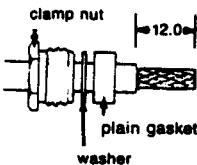
below 3:1. How bad is it? Well, if you have a run of coax which gives 1.0 Db loss at 118 Mhz when the SWR is 1:1, total losses will rise to only 1.5 Db if the SWR rises to 3:1.

ADJUSTING

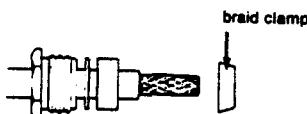
The very best way to adjust a communications antenna system is after it is installed. The radiator is cut perhaps 2" longer than you calculate. Make a temporary installation of a through-line wattmeter in the feedline between antenna and transmitter. Make SWR measurements at 120, 128 and 135 Mhz using the ship's VHF transceiver as a signal source. Observe repeated measurements as the antenna is shortened 1/4" per measurement. Stop cutting the antenna when the lowest SWR measurement occurs at or near 128 Mhz. If a signal source strong enough to operate the wattmeter in the VOR frequency ranges is available, the same technique may be used to trim the VOR receiving antenna. By adjusting antennas for the best transmitting characteristics, idealized receiving adjustments are also realized. Start with elements which are too long. Make measurements at the low, center and high ends of the frequency range of interest. Trim for lowest SWR at the center frequency and observe that it does not exceed 3:1 at the ends.

**MIL-STYLE
NON-CAPTIVE CONTACT
(B)**

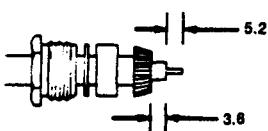
Slide clamp nut, washer and plain gasket over the cable: trim outer jacket from cable as shown, without disturbing the braid.



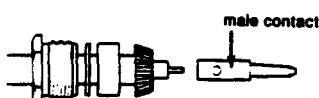
Fit braid clamp so that the internal shoulder butts to the end of the outer cable.



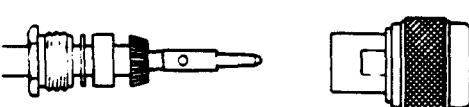
Fold back braid, avoiding crossed wires, and trim surplus braid. Trim dielectric and check that dimension of exposed center conductor is as shown.



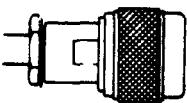
Tin center conductor and fit contact to butt against face of dielectric. Hold cable and contact tightly together and solder.



Slide plain gasket, flat washer and clamp nut to braid clamp and press sub-assembly into body as far as possible.

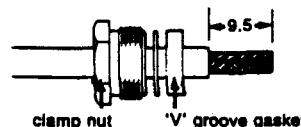


Engage and tighten clamp nut.

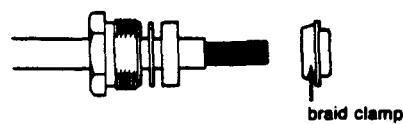


**UG V-GROOVE STYLE
CAPTIVE CONTACT
(A)**

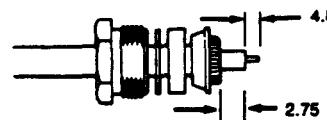
Slide clamp nut, washer and "V" groove gasket over cable, (groove of gasket to face free end of cable) Trim outer jacket from cable as shown, without nicking the braid.



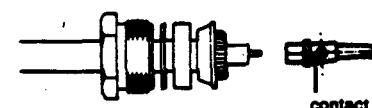
Slide braid clamp over braid so that internal shoulder butts against face of outer jacket.



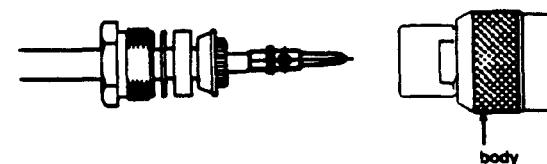
Fold braid back over braid clamp avoiding crossed wires and trim off surplus braid. Trim back dielectric and check length of center conductor.



Tin center conductor and fit contact onto center conductor, hold cable and contact tightly together and solder.



Slide 'V' groove gasket, washer and clamp nut up to braid clamp and press sub-assembly into body as far as possible.



Engage and tighten clamp nut.

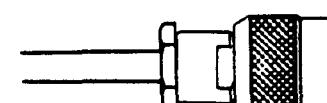
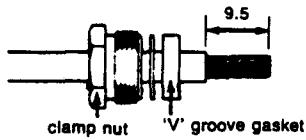


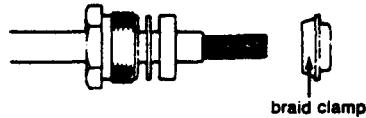
Figure 13-19. Type N and Type TNC Connector Installations.

**V GROOVE STYLE
NON-CAPTIVE CONTACT
(A)**

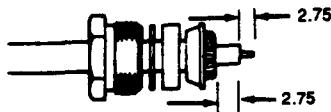
Slide clamp nut, washer and 'V' groove gasket over cable, (groove of gasket to face free end of cable) Trim outer jacket from cable as shown, without disturbing the braid.



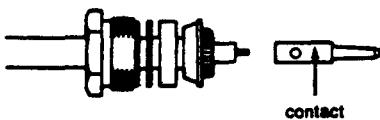
Slide braid clamp over braid so that internal shoulder butts against face of outer sheath.



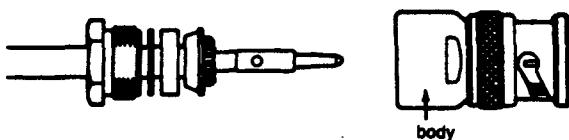
Fold braid back over braid clamp avoiding crossed wires and trim off surplus braid. Trim back dielectric and check length of center conductor.



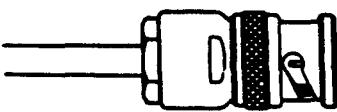
Tin center conductor and fit contact onto center conductor, hold cable and contact tightly together and solder.



Slide 'V' groove gasket, washer and clamp nut up to braid clamp and press sub-assembly into body as far as possible.

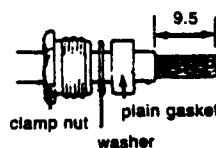


Engage and tighten clamp nut.

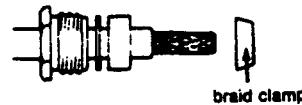


**UG-STYLE
NON-CAPTIVE CONTACT
(B)**

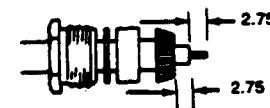
Slide clamp nut, washer and plain gasket over cable trim outer jacket from cable as shown, without disturbing the braid.



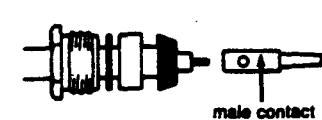
Fit braid clamp so that the internal shoulder butts to the end of the outer cable.



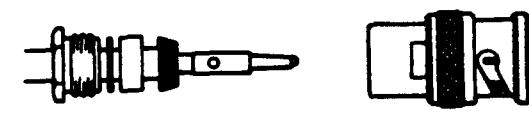
Fold back braid, avoiding crossed wires, and trim surplus braid. Trim dielectric and check that dimension of exposed center conductor.



Tin center conductor and fit contact to butt against face of dielectric. Hold cable and contact tightly together and solder.



Slide plain gasket, flat washer and clamp nut to braid clamp and press sub-assembly into body as far as possible.



Engage and tighten clamp nut.

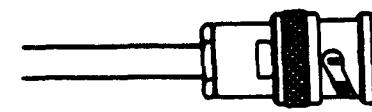


Figure 13-20. Two Types of BNC Connector Installations.

CONNECTORS

There is a do-it-yourself connection not recommended by any cable manufacturer but it performs well if precautions are observed. Figure 13-18 shows terminals crimped or soldered onto prepared coax braid and center-conductor. This works very well at marker-beacon, VHF and glide-slope frequencies but take care with DME/Transponder applications. Coax is "coaxial" only if the conductor is inside the shield. Once the center conductor is exposed, it becomes a common piece of wire. At 1000 MHz it can add considerable inductance to the system if not kept as short as possible.

Coax connectors are specially designed to join concentric cables to devices or other cables without breaking shield integrity and to minimize impedance "lumps" in the feedline system. The majority of general aviation avionics use BNC, TNC or N-series connectors. Some radios use mounting trays with captive connectors built into the back. A radio chassis will make proper connections to the airplane wiring via special connectors on the rear which mate with connectors on the tray when the radio slides home.

There are a number of vendors for coax connectors listed in Appendix-A. Catalog listings often break down connectors by several attachment styles such as clamp/crimp, crimp/crimp, clamp/solderless, clamp/soldered, etc. Quality of "solderless" connections can vary with manufacturer. Crimped joints often require expensive tools. My own favorites are connectors which clamp the shield braid and solder the center conductor pin. These take a little more skill in measuring, cutting, preparing and assembling than high volume production versions but . . . I can put one on anywhere with minimal tools and the connector is often cheaper than the high-volume part. Figures 13-19 and 13-20 illustrate installation details on a few styles of coax connectors found in airplanes. Installations shown here are some common variations on a broad theme. When ordering connectors, ask the vendor if they can provide detail assembly sheets or a manufacturers installation manual. Most vendors have or can get such data and should be willing to supply it.

BALANCED ANTENNAS AND UNBALANCED FEEDLINES

The balanced nature of dipoles and unbalanced nature of 1/4-wave verticals is somewhat obvious. Further, for best performance in driving such antennas, the feedlines should be compatible. The biggest reason for compati-

bility is for interference reduction between systems. If you had nothing but a omni receiver in your airplane and no other susceptible systems, it wouldn't matter if your antenna and/or feedline had compatibility problems. Many of you will be installing a major sampling of systems listed in Table 13-1 so let's minimize the potential for problems with some simple precautions.

At the end of this chapter, there are a number of publications I recommend for general and specific information on antennas. None of them are expensive and some can be checked out of the library. These publications will describe a number of ways to deal with feedline/antenna compatibility when going from unbalanced feedline to balanced antennas. Many of these techniques have been used from time to time on airplanes but I'd bet there's never been a real study of their effectiveness; not in Wichita at least! A few years ago, coaxies were bolted to dipoles with indifference until someone read an article and became a little embarrassed about lack of "engineering." So, in spite of the fact that no problems could be specifically traced to the evil practice, various "baluns" were fabricated and installed on VOR/LOC and glide slope antennas.

The problem with baluns (contraction of words BAL-ance/UNbalance) was that they are cut to specific wavelengths at the frequency of interest. When the frequency of interest was a range of frequencies, addition of simple wave-length cut baluns could often be demonstrated to hurt more than help. Nowadays, we can attack the problem with new technology. Toroidal ferrite cores (sometimes called "beads") can be slipped over the coax close to the joint between feedline and antenna. Normally, magnetic fields due to currents conducted on conductor and shield of a coaxial feedline will cancel each other out. No external magnetic field is generated. Any extraneous currents due to antenna mismatching cause external fields to be created outside the coaxial shield. These will concentrate in the ferrite beads and not propagate down the outside of the coax. Further, ferrite beads are not frequency selective. They perform their intended tasks over the full frequency range of the antenna. RST sells a dipole kit for roll-your-own glide slope and VOR/LOC antennas which includes the appropriate ferrite beads. Two or three beads over the coax as shown in Figure 13-13 will preclude any foreseeable difficulties. This technique applies to any situation where an unbalanced antenna is being driven by a coaxial feedline.

BIBLIOGRAPHY

New antennas for airplanes is an area that has not re-

ceived much attention from the certified side of aviation. Builders of metal airplanes who would like to hide antennas under fairings and wingtips might just have the drive to do some serious and ultimately successful antenna experiments. Plastic airplanes have special problems not addressed by any large commercial ventures. I'll be glad to work with anyone who is willing to try something different. Successes and failures need to be written up in these pages or in Hot Flashes. The successes should be shared so everyone can benefit, the failures need to be shared to keep someone from wasting their time on something that is already known not to work. If you are inclined to work further in antennas for airplanes, check into the following publications:

The Radio Amateur's Handbook, any issue. Published by the American Radio Relay League, Newington, Connecticut.

The Radio Amateur's Antenna Manual, any issue. Published by the American Radio Relay League, Newington, Connecticut.

ARRL publications are available through most bookstores and amateur radio supplies stores. Or, order direct from ARRL, Newington, CT 06111

Temperature Measurement

Pressures and temperatures play important roles in tracking performance of flight systems. In fluid dynamics, temperature and pressure are interdependent - as fuel and air are compressed in a cylinder, temperature of the mixture goes up markedly before the spark plug lights a real fire. Pressure differential across a partially closed throttle plate causes a corresponding drop in temperature; perhaps low enough to freeze any moisture present. Increased ambient temperature at the airport makes air less dense; depriving wings of lift and engines of power.

Temperature has a profound effect on many materials. The strength of aluminum alloys drop markedly at rather ordinary temperatures of 450°F. At temperatures of -60°F, some alloys that are normally quite durable become brittle and will break like glass. Oils that lubricate nicely at 200°F lose necessary qualities at 300°F. Wear rate of rings against cylinder walls goes up rapidly if head temperatures exceed 500°F. Materials physically expand as their temperatures rise - rates of expansion are a function of the material. So when different materials are used in contact with each other, their mode of attachment and quality of fit become issues affected by temperature. Temperature cycles alone may contribute as much working stress to aluminum parts as do mechanical loads. Temperature cycles may cause accelerated, sometimes mysterious failure of an otherwise lightly loaded part.

WHAT IS "TEMPERATURE?"

Temperature is easily measured and we probably use or at least hear the word several times a day. But what are we measuring and what do the numbers mean? Is a cylinder head at 415°F 4.15 times warmer than air at 100°F? We know a thermometer attached to a piece of aluminum over a burner on the stove will show an increase in temperature as burning gas heats the metal. But if a fuel/air mixture in a cylinder gets hotter just because it has been compressed, what causes the temperature rise? Yeah, I know. Some of you just want a couple of instruments on the panel to deal with a few engine parameters and get on with it. Feel free to skip on ahead folks. But if you will indulge me a few pages,

we just might change some ways you think about a machine to which you entrust your body!

Temperatures we discuss every day are stated in degrees Fahrenheit or degrees Celsius. There are other temperature measurement systems with names like Rankin and Kelvin. Every temperature measurement system must have a definition to make it understandable to any who would use the system. For example, the Celsius temperature scale is based upon the freezing and boiling points of water: water was said to freeze at 0°C and boil at 100°C. Converting these two temperatures to their Fahrenheit equivalents gives us water freezing at 32°F and boiling at 212°F. Obviously, these two systems have different offset and scale factor. The freezing point to boiling point spread in the Fahrenheit system is 180°F; in the Celsius system it is 100°C. Further, we know that "zero degrees" in either system is not as "cold" as it can get . . . both systems permit one to speak of "degrees below zero."

Indeed, we could create our own system of measurement. Let's see . . . I propose the Phramesh system where 0°P is the temperature at which 95% of all squirrels tails fracture in a 40 knot breeze; the upper calibration point will be the melting point of a Hershey bar (with almonds). Now, for scale, how about one gross of degrees? 0°P to 144°P . . . okay. In the Phramesh system, I suspect water would freeze at about 60°P and boil at 300°P. Anyone interested in instruments calibrated in °P? Unlike volts, amps and ohms that are pretty much standard with around world, temperatures, lengths and volumes can be and have been described by many users over the years with resulting differences in offset and scale. However defined, all temperature measurement systems describe the same physical phenomenon.

MEASUREMENT SYSTEMS COMPARED . . .

Figure 14-1 illustrates four commonly used temperature measurement systems. Couldn't come up with enough squirrels for calibration so we'll set the Phramesh system aside for another time. Degrees Rankin and Fahrenheit

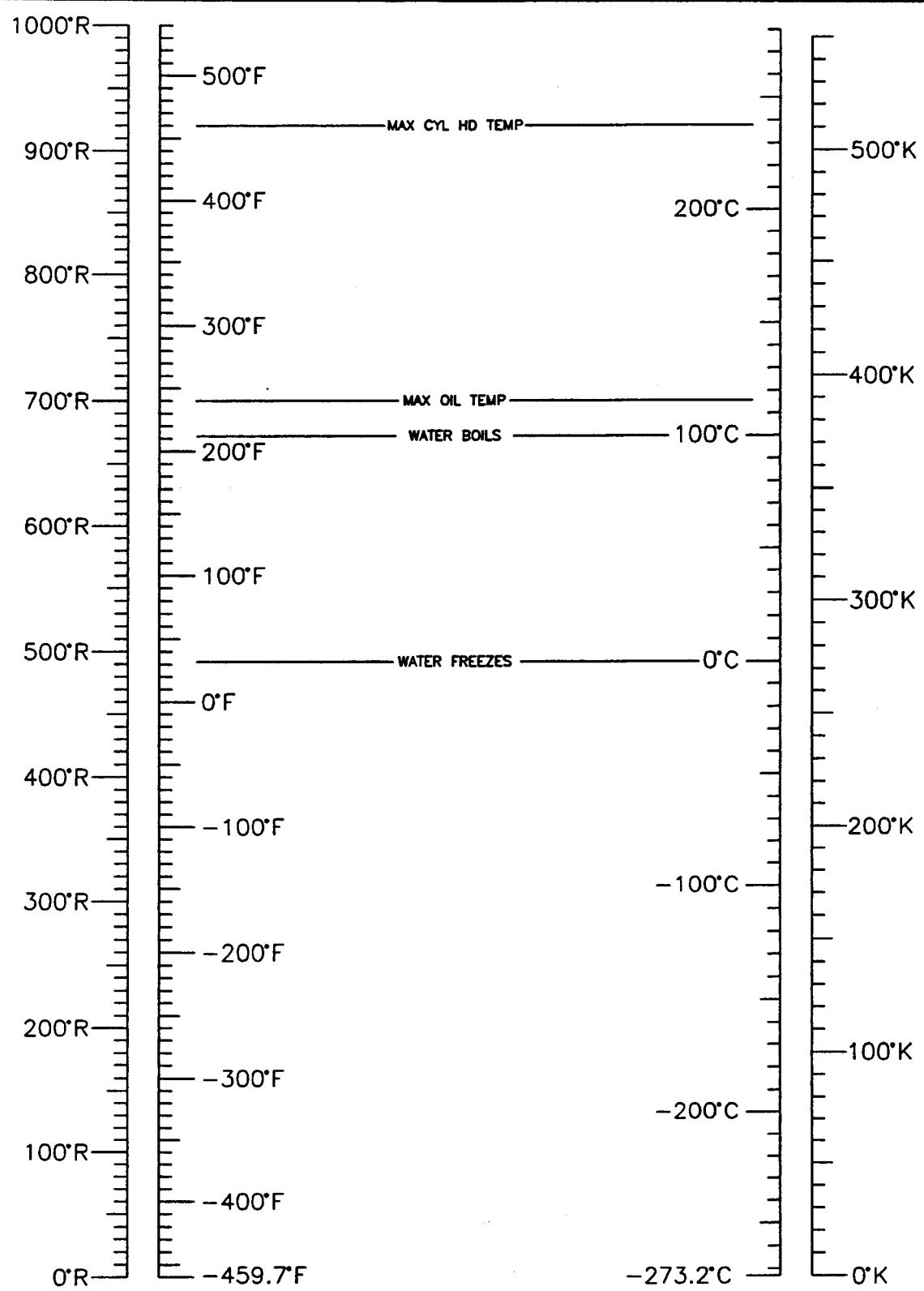


Figure 14-1. A Graphical Comparison of Four Temperature Measurement Systems.

are on the left; degrees Celsius and Kelvin are on the right. Note that $^{\circ}\text{F}$ and $^{\circ}\text{R}$ are the same size, they just start counting from a different point. They may be said to have the same scale factor but one is offset from the other by 459.7 degrees. A similar situation is illustrated on the right side. A $^{\circ}\text{C}$ and $^{\circ}\text{K}$ are also the same size; their scales are simply offset by 273.2. How cold can we go? Note that both Kelvin and Rankin systems illustrated in Figure 14-1 do not go below zero. That's because 0°K is as cold as you can go . . . absolute zero. Is there an upper bound on temperatures? Don't know. There are objects in the universe with densities so great that light and other forms of radiation cannot escape their gravitational attractions. You can bet that if an upper bound on temperatures exists, it's probably there. But let's talk about the lower bound. -459.7°F seems quite cold for a walk in the park but it's still a rather ordinary temperature in the laboratory. Scientists have achieved temperatures within a few tenths of a degree of absolute zero; the very low temperatures are where super-conductivity was first discovered. Figure 14-1 also depicts a few temperatures for things on and around airplanes.

Absolute zero is where all molecular motion ceases. Motion? Yes, in spite of our mortal perceptions of solidity or rigidity, molecules in a piece of steel or aluminum have some motion. The degree of motion describes its temperature. Adding heat energy to an object causes its molecules to become more agitated and raises its temperature. A temperature we perceive by touch would be described as warm or cold depending on its absolute temperature relative to our own; a block of aluminum at 40°F might feel rather "warm" if your skin temperature were down around 20°F ! So, for the purposes of scientific studies, most temperatures are described on absolute scales like Kelvin or Rankin. On these scales there is no "cold", just variable degrees of "warm." Recall that I asked a question earlier if an object at 415°F was 4.15 times hotter than an object at 100°F ? Referring to Figure 14-1, we may deduce: No, it is only 1.56 times hotter. Kelvin and Rankin scales are based at absolute zero. Temperatures on these scales are proportional to the absolute quantity of heat energy born by the object. To calculate the answer to my question:

$$\begin{aligned}(1) \ 415^{\circ}\text{F} &= 874.7^{\circ}\text{R} \\ (2) \ 100^{\circ}\text{F} &= 574.7^{\circ}\text{R} \\ (3) \ 874.7 / 574.7 &= 1.56.\end{aligned}$$

Of course, one may repeat the exercise with $^{\circ}\text{K}$ and get the same answer.

Now the reason for absolute zero scales becomes appar-

ent - many laws of physics are interdependent with effects of heat energy. The mathematics required to deal with these relationships are much more convenient to work with if one uses temperature systems based upon absolute zero . . . you don't need to add 459.7 or 273.2 to every temperature before its real effects can be quantified. So much for the physics lesson . . . let's get to the mechanics of temperature measurement. Indeed, some very common temperature measurement systems are purely mechanical. In spite of the very electric nature of this book, I would be remiss if mechanical temperature measurement techniques were not discussed also.

Unlike meters, feet, quarts and liters, temperature is not something that can be measured directly. Like volts and amps, temperature is described and measured by quantifying external effects that can be measured. For example, a voltmeter is really displaying the torque moment of a fixed and variable magnetic fields against a spring (see Chapter 7). In one breath we've described three or four areas where the calibration of a voltmeter can drift . . . and all of them may be affected in some undesirable way by temperature! Designers of precision voltmeters take great care to insure that temperature effects are eliminated or compensated for so that the instrument will be accurate at any temperature.

MECHANICAL THERMOMETRY

One well known temperature effect can be readily observed: most materials will expand when warmed and contract when cooled. Careful accounting must be made for this phenomenon when designing closely fitted parts that operate over wide temperature ranges. Bearing fits to shafts and piston fits to cylinder walls of engines are good examples. Design tasks become still more challenging when you discover that materials do not all expand at the same rate! For example, any good physics or mechanical engineering text will tell you that iron has an expansion coefficient of .0000066 per $^{\circ}\text{F}$ while aluminum and copper have coefficients of .00001244 and .00000900 respectively. These numbers tell us that a block of aluminum that measures $1.000000"$ at 0°F will measure $1.000124"$ at 10°F , 1.001244 at 100°F , etc. Obviously, measuring very small changes in length requires a device that is NOT itself sensitive to temperature change. Note that for 100 degrees shift in temperature, a 1-inch object made from aluminum will grow by only .0012 inch. However, consider that an aluminum piston, 4" in diameter that is raised in temperature by 200°F will grow a total of .0096. If cylinder bore expansions are not carefully considered and matched as

needed, I suspect a 0.009" inch growth of a piston would pretty well jam it in the bore!

Since most materials do expand as their temperatures increase, a thermometer could be devised by attaching a pointer to the end of a metallic rod . . . let's make it out of copper. My machinist's handbook tells me that copper has an expansion coefficient of .00000900 per °F. Here's how temperature coefficient works: Temperature coefficient of expansion is a dimensionless number that states a ratio of measurements taken at two temperatures. It's used simply as a multiplication factor. Length change due to temperature equals total length at old temperature times expansion coefficient times difference between the two temperatures in °F. Example: A copper rod having a length of 10.000 inches at 0°F will grow to 10.018 inches in length at 200°F. 10.000 times .000009 times 200 equals .018 inches expansion. Add .018 back onto original length yields 10.018 inches. Hmmmmmm . . . now all we need to do is install a pointer and scale so that the .018" long scale can be graduated with a range of 200°F. That's pretty tiny. Even with my new bifocals on, I don't think I'd be able to read anything useful on the dial. There are ways to utilize expansion coefficient to devise a thermometer, but we need two different materials.

BI-METAL THERMOMETRY

There is a simple experiment that you can do for a kid (or yourself) that illustrates the principals of bi-metal thermometry. Take a strip of aluminum and a strip of steel, each about 1/2" wide and 10 inches long. Fasten them together with a row of rivets or screws down the middle as shown in Figure 14-2. Clamp one end of the assembly in a vise with the aluminum side up. Apply heat with a torch or heat gun and observe that the free end moves down. If you allow the assembly to reassume room temperature, it will straighten out. If you pour ice water on it, a curl in the opposite direction can be observed.

This simple experiment illustrates a temperature measurement technology that has been with us for many years. The temperature sensing element in a BI-METAL thermometer or thermostat uses a special material wherein metals with different tempcos are intimately bonded to each other by welding or electroplating. Long strips are then coiled into more compact shapes. The bi-metal experiment previously described used 10-inch lengths; most bi-metal temperature sensors will be 3-6 inches total length, wound into a spiral shape. Figure 14-3

shows how the coil may be supported in the center and carry a mercury switch on the outside (peek inside the round heat-cool thermostats used in your home). Or, it may be fastened on the outside and used to rotate a shaft connected at its center (outdoor, big display thermometers do this). Almost any thermometer that displays with a pointer on a dial uses bi-metal technology temperature sensing. This would, of course, include the familiar outside air temperature indicators commonplace on lightplanes for years.

VAPOR PRESSURE THERMOMETERS

One of my favorites is another purely mechanical temperature measurement tool. The technique features a simple elegance that has to be appreciated by anyone who designs instrumentation systems. You've heard the term "vapor pressure" applied to blends of fuels being considered for use in airplanes. Virtually all liquids can be vaporized to a gas if heated beyond a certain temperature. Under ordinary atmospheric pressures, water will be totally boiled away at temperatures exceeding 100°C. However, we also know that water will evaporate into the atmosphere at temperatures considerably below 100°C. Of course, if one cools water below 0°C, it will freeze into a solid. What's going on in the region between 0°C and 100°C?

In several places throughout this book, we've mentioned the fact that various materials have different abilities to hang onto electrons whizzing about the outer shells of their atoms. We've stated further that temperature can have an effect on electron mobility. Liquids exhibit similar temperature effects. The effect can be quantified by measuring a phenomenon called vapor pressure. In Figure 14-4, I've illustrate a container with three ports. One port is connected to a vacuum pump, a second connected to a reservoir of water, the third to an absolute pressure measurement device (like an engine manifold pressure gauge or altimeter). First, with the valve leading to the water supply closed, we'll pump all the air out of the container (manifold pressure equals zero inches of mercury; altitude will be clear off scale). Now, let's close off the pump port and carefully open the water valve. We'll allow the container to fill only half full of water. Now, what happens to the pressure in the space above the liquid? Recall that no atmospheric gases previously existed in this space . . . we pumped them all out. Therefore, if anything exists in the volume above the liquid now, it must be water vapor. Suspicions are confirmed by the fact that our pressure gage no longer reads zero. Data tables in physics books predict how

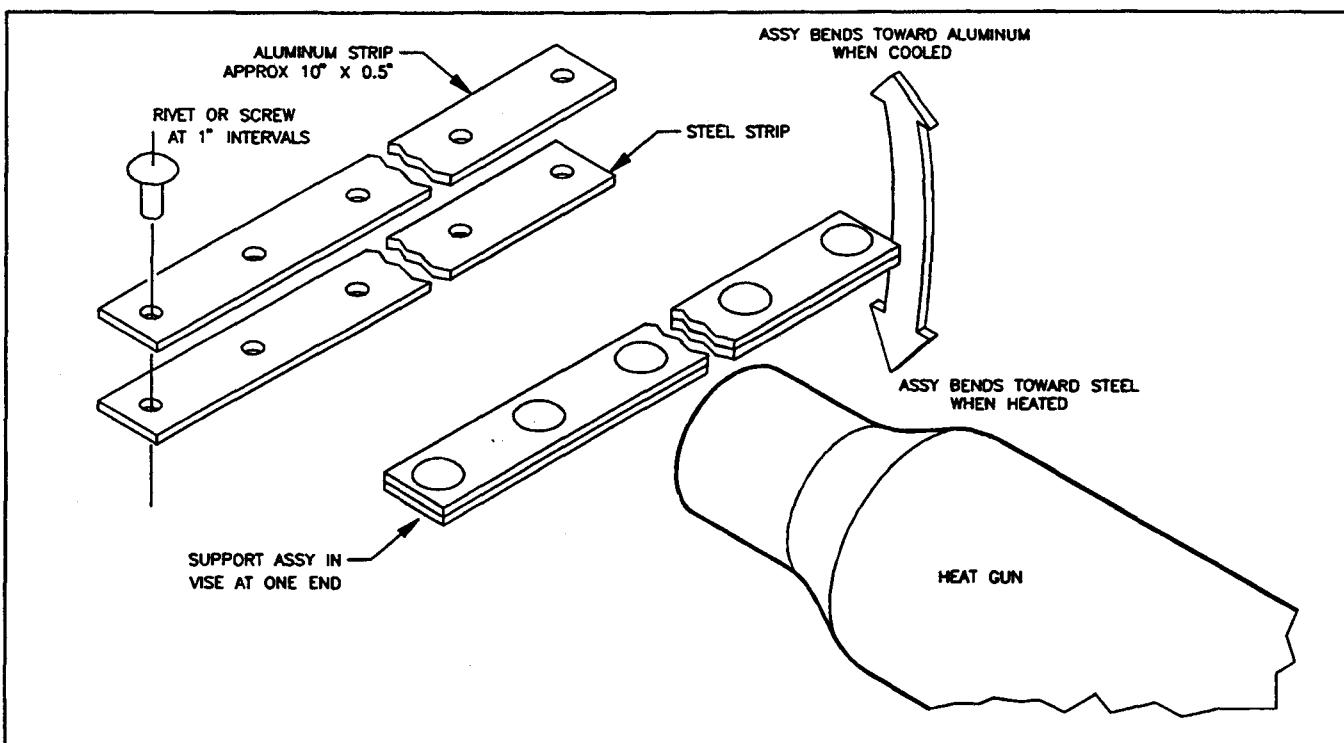


Figure 14-2. Bi-metal Thermometer Demonstration.

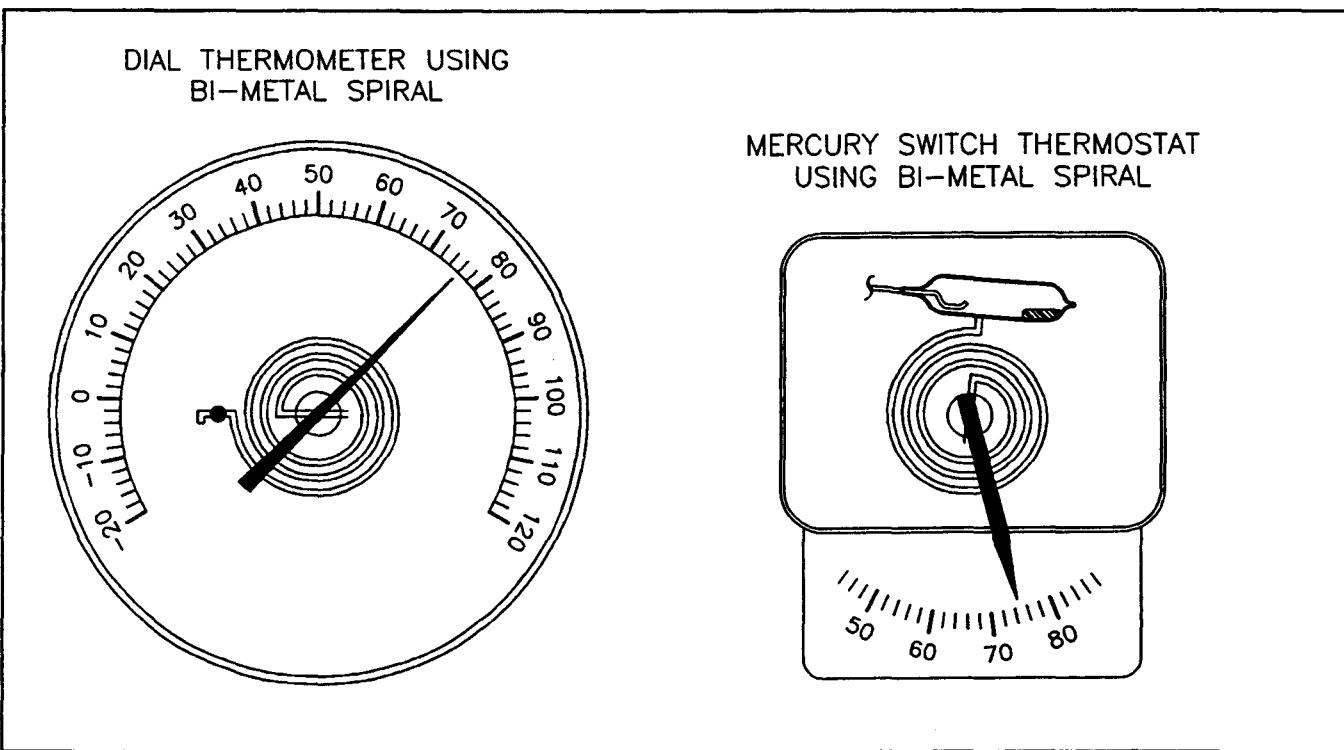


Figure 14-3. Examples of Bi-Metal Thermometers.

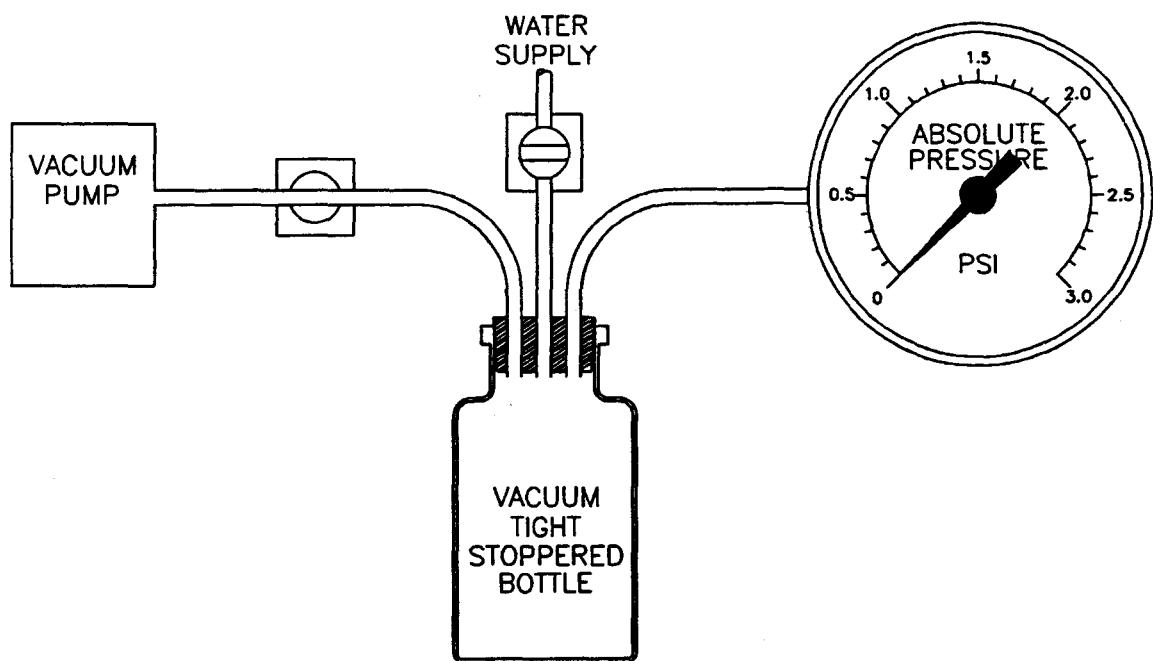


Figure 14-4. Vapor Pressure Demonstration.

how much pressure to expect depending on temperature and type of liquid. Vapor pressures for any liquid will increase with temperature. This is a practical demonstration of molecular mobility with respect to temperature. When water is introduced into a space that initially contains no other substance (absolute pressure equals zero) and allowed to fill only partly with any liquid, then molecules will begin to jump off the surface causing pressure in previously empty space to rise. As pressure continues to rise, a certain number of the liquid's molecules begin bumping into the liquid surface and becoming recaptured. As the pressure rises the rate of molecules jumping off the liquid will the equal rate of molecules being recaptured; pressure will stabilize. Pressure observed at this time will be equal to the vapor pressure for that particular liquid (in this case, water) at its present temperature.

If the water temperature is increased, the observed pressure will go up; conversely pressure will fall if the temperature is decreased. Table 14-1 illustrates vapor pressures for several common liquids. Note that while mercury does have a vapor pressure, it is small compared to other liquids. Mercury's low vapor pressure combined with a high density (13.5 times heavier than water) makes it an ideal liquid for fabrication of atmospheric barometers and pressure manometers. If we were

to repeat the vapor pressure experiment using mercury instead of water, the evacuated container would have to fill completely before a rise in pressure would be observed! Note that water's vapor pressure at 100°C is 760mm of mercury or 1.0 atmosphere

Table 14-1. Approximate Vapor Pressures of Common Materials

Temper- ature °C	Vapor Pressure in mmHg		
	Water	Mercury	Benzene
-50	tiny	tiny	.0001
0	4.5	.0001	25
50	93	.01	300
100	760	0.4	900
150	3,570		

That is what boiling is all about. When vapor pressure equals or exceeds ambient pressure, all the liquid molecules will evaporate (boil) away. Note that Benzene's v.p. exceeds atmospheric pressure at 100°C. Therefore, we should expect Benzene's boiling point to be well below 100°C. Further, the table doesn't show a tempera-

ture of 20°C but my physics handbook says water will have a v.p. of 17.5 mmHg at 20°C. That's about 0.3 Psi. Therefore, at room temperature we may expect our v.p. demonstrator gage to rise to about .3 PSI when the vacuum space is partially filled with water.

Another item of interest in the table is that water at 0°C has a vapor pressure of 4.5 mmHg. How can ice have a vapor pressure? (*Actually it does but very tiny.*) Did you know that water may exist in either liquid or ice phase at 0°C? As you suck BTU's from a quantity of liquid, its temperature will stop dropping when it reaches the freezing point. You need to remove an additional quantity of heat called "heat of fusion" from the mass of liquid just to convert it to ice. Once all the water is frozen, the temperature will begin to drop again. If this heat of fusion phenomenon didn't exist, ice wouldn't be worth a hoot for cooling a six-pack or making ice cream.

Now, let's take this principle and build a practical thermometer like that shown in Figure 14-5. Water could be used as the working liquid except for two things. First, water will readily absorb gases from the atmosphere making it depart from laboratory derived vapor pressure values. Second, it freezes at 0°C and boils at 100°C. Our water based thermometer would have to operate over a limited temperature range. Further, it would require a rather sensitive and less robust pressure gage. How about propane as a working liquid? The graph in Figure 14-6 illustrates vapor pressures for propane, a common bottle fuel. Consider a pressure gage with a measurement range from 0 to 300 psi plumbed with a capillary (very small bore) copper tube to a hollow metal bulb. Our bulb is fitted with a service port with which we first evacuate the system followed by introduction of a small amount of propane and finish with a permanent seal. Now, according to the vapor pressure graph in Figure 14-5, if our pressure gage reads 132 PSI, we know the liquid filled bulb is at 20°C; if the gage reads 257 psi, then the bulb must be at 50°C. Obviously, the final step in our manufacturing task is to replace the pressure gage dial plate with a new one calibrated in temperature instead of pressure.

The final feature of this instrument to be discussed is the tubing that connects bulb and gage. Obviously, this type of instrument will display a temperature of the hottest liquid present anywhere in the system. I recall a conversation between an uncle and the proprietor of a grocery store in Medicine Lodge, Kansas, about 1950. Large, sub-zero temperature freezers for homes were still some years away from commercial practicality. The store had

just added new walk-in freezer space behind the store. From time to time, Grandpa gave us a side of beef to butcher so my family rented a locker in this frigid room to store family foodstuffs.

The big dial thermometer on the outside wall of the freezer was giving the store owner fits. Seems it worked for awhile and then decided to display temperatures far above what existed inside the freezing room. For whatever reason, this thermometer had been built with a rather large interconnecting tube. Instructions told installers to place the sensing bulb below the indicator. Further, slope of interconnection tubing was to be downward from indicator to sensing bulb. Instructions had not been followed; working liquid migrated into the pressure gage whereupon temperature indicated was for the wall outside the freezer, not inside. A rearrangement of the installation fixed the problem. It was about 10 years later, in high school physics that I came to understand what I had witnessed!

This becomes a problem only if the temperature being monitored is below ambient temperature for the indicator. It can be prevented by building a pressure gage with a small volume and making interconnection of the sensing bulb and gage with capillary tube. For liquid to migrate from bulb to gage, an exchange of vapor space (bubbles) and liquid must take place. If the tubing is small enough, liquid and bubbles cannot pass each other going opposite directions. Therefore, the working liquid is kept in its proper place.

The vapor pressure temperature gage was very common for displaying water and oil temperatures on engines (both gas and steam) for nearly 100 years! Obviously, a higher gage pressure range and temperature scale would have to be developed to make a practical oil or water temp gage using propane as a working liquid. However, there are literally hundreds of liquids that are suitable for building vapor pressure thermometers over a range of temperatures. You won't find a simpler, more elegant method of remote temperature measurement and display. Modern trends are toward electronic sensing methods. The sense bulb, capillary tube and gage has been traded for simplicity of installation. Wires can be cut and spliced while copper capillary tubes cannot be opened or modified in length. Further, new system designs require both traditional panel displays and digital engine data monitoring. Unless you are building a very simple airplane or restoring an old one, you are not likely to encounter this form of temperature gauging system.

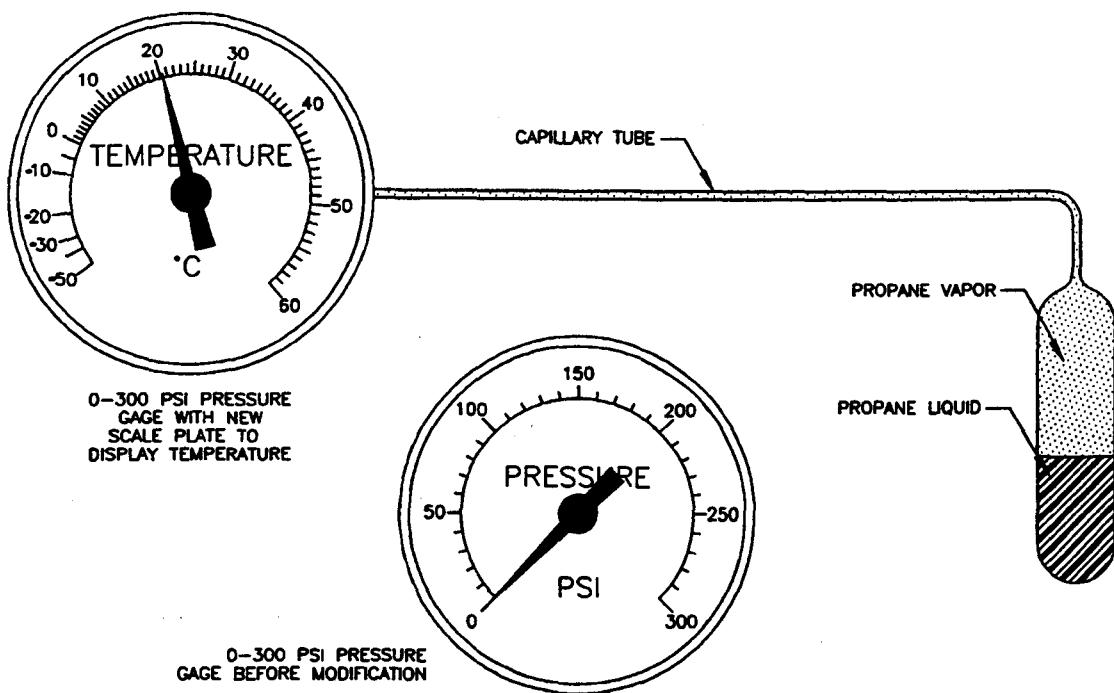


Figure 14-5. Propane Based Vapor Pressure Thermometer.

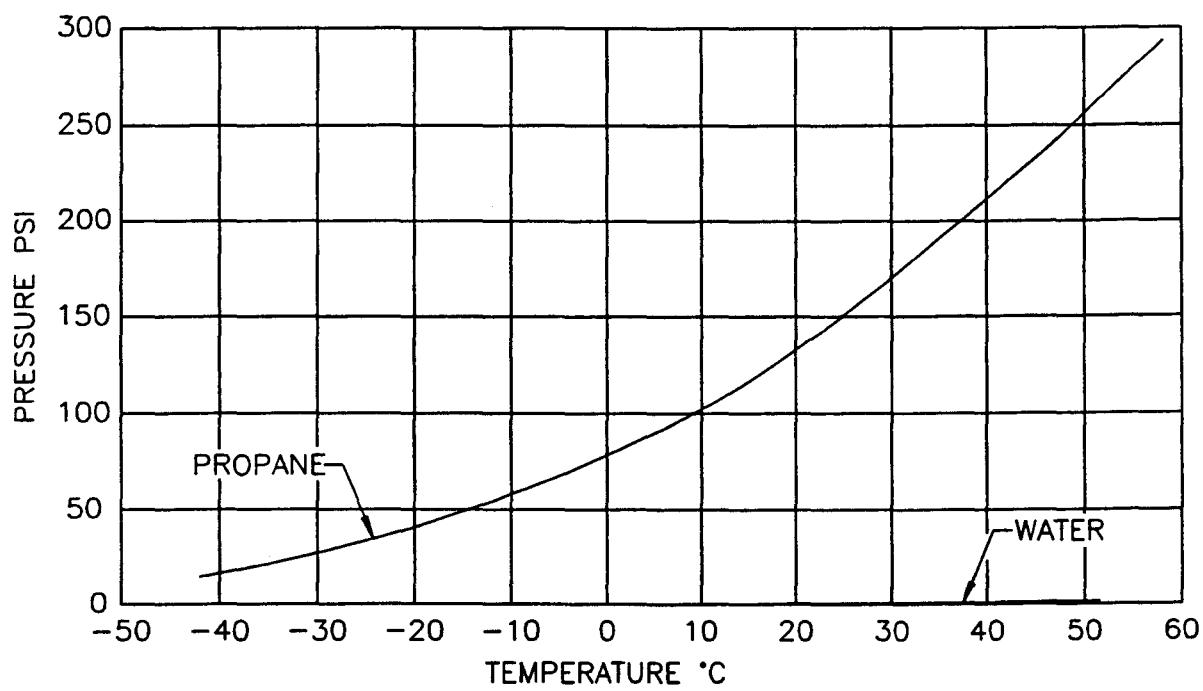


Figure 14-6. Comparison of Vapor Pressures for Water and Propane.

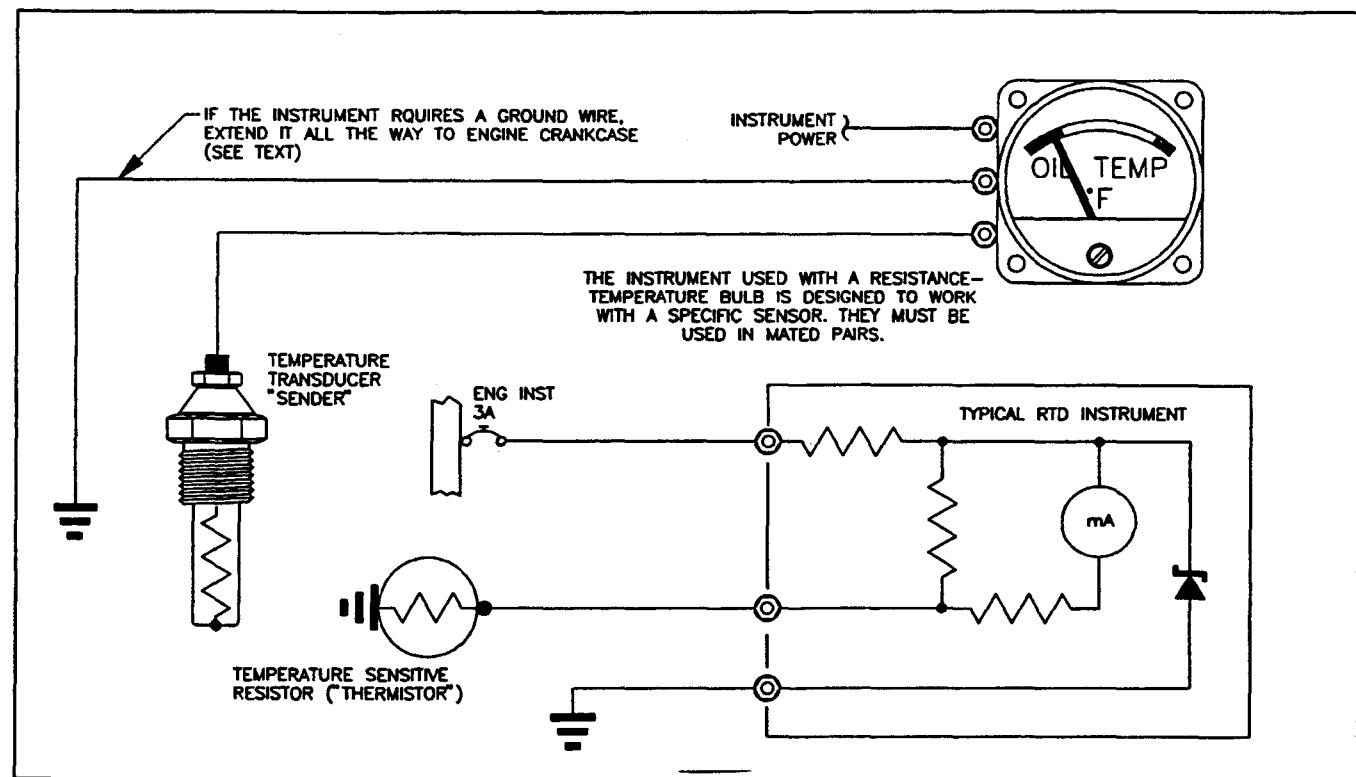


Figure 14-7. A Basic RTD Thermometer System.

ELECTRICAL TEMPERATURE MEASUREMENT SYSTEMS

The first practical motive power engine was steam driven. Development of the machines along with engineering understanding of fluid and gas dynamics went hand-and-glove with development of pressure gages and vapor pressure thermometry. The first gasoline fueled engines used magneto ignitions and had no generator or starter so vapor pressure temperature gages were technology-of-choice for measurement and display of water and/or oil temperatures. However, as soon as rechargeable batteries, generators and starter motors took hold, systems engineers had a whole new box of "tinker toys" to select from. Refer to Chapter 7 for background on basic instruments with which to display electrical phenomenon. We'll explore one of the earliest versions of an electrically driven, temperature measurement system.

RESISTANCE-TEMPERATURE DEVICES

There are a number of ways to measure and display temperature electrically. The oldest and one of the most common technologies utilizes a temperature dependent

resistor called a thermistor. These are commonly referred to as an RTD: resistance-temperature device. Thermistors are a special class of semiconductor. The room temperature value of resistance and the percent of resistance change per degree of temperature are controlled by the mix of materials used to fabricate the device.

Figure 14-7 illustrates a simple temperature gaging system utilizing an RTD (thermistor). This system is typical of electric measurement systems used in automobiles for the past 60 years or more. The gage is nothing more than a milliammeter that reads change in current through a thermistor as its temperature changes. Both accuracy and stability of this system are interdependent upon the applied voltage, hence the need for a voltage regulator between system bus and the temperature gage. In early cars, the voltage regulator was a mechanical-thermoelectric device; modern systems use integrated circuit voltage regulators. Any stand-alone RTD thermometer you encounter may have some form of voltage regulation built into the indicator.

The primary disadvantage of this system is its rather non-linear calibration characteristics. For an indicator to

be calibrated with a linear looking scale, it must be designed for equal but opposite non-linearity matching its companion transducer (sometimes called a "sender"). On the positive side, RTD thermometers are easy to install. Interconnecting wires can be any desired length and may be modified at will.

TAMING THE VICIOUS "GROUND LOOP"

This type of thermometer is commonly used for oil, cylinder head and water temperature gaging. Transducers are almost always single wire devices which ground to the engine crankcase by way of a metallic, threaded housing. This usually means the companion instrument has a ground connection. With any single wire transducer mounted on an engine, it's a good idea to extend the instrument ground to the crankcase or firewall ground bus. This is especially important on pusher airplanes where alternator ground wires have long runs.

Alternator charging currents can produce a small (tens of millivolts) drop in the alternator ground conductor. The panel mounted instrument is displaying a temperature that is represented by a voltage drop across the transducer. If the transducer grounds at the engine end of the alternator ground and the instrument grounds at the panel end, the small drop in alternator ground lead will introduce errors in the displayed temperature reading. If more than one instrument uses single wire sensors, the instrument cluster may share a single ground. It doesn't matter that the instruments are a mix of pressure and temperature indications. Tie all the instrument grounds together at the panel and run a single, 22AWG conductor from the instruments directly to the engine crankcase.

RTD INSTRUMENT SYSTEMS COME IN SETS

Unlike other transducer/indicator combinations which will be presented later, RTD transducers and their companion indicators are not mix-and-match devices. Each part number of indicator must be paired with a specific transducer. This is because RTDs come in a tremendous range of materials and technologies. Each instrument part number has been designed to compensate for any non-linear characteristics of the transducer. Further, an instrument may have internal voltage regulation to prevent errors due to bus voltage variation. The automotive industry has used RTD systems effectively for years and has produced hundreds of combinations of gage and transducer. Resist the urge to salvage any form of transducer/indicator combination from an old, certified airplane . . . getting spares for these devices has always been difficult, expensive and it's getting worse!

If you're working with a set of 2.25", individual instruments, finding modern replacement for complete gaging systems isn't difficult. But if you're committing to a custom cluster gage and a single gage or its transducer goes belly up, you may have problems getting it fixed. Thermistors are not the only form of RTD. A common form of Mil-Spec OAT sensor uses a coil of very fine platinum wire as the sensing element. As you might suspect, this critter isn't cheap! Unless you stumble across one in a surplus store somewhere, you are not likely to encounter anything other than the relatively inexpensive thermistor type transducers.

This class of electric thermometer is rapidly disappearing from all new product designs having been replaced by newer, more designer friendly products. The quality of most RTD gages used in certified airplanes hasn't really been all that impressive in terms of absolute accuracy. However, any given transducer/instrument combination is rather repeatable. That's important - you're more interested in changes from the norm as opposed to knowing exactly any given temperature. So if you've got a set of gages in place that seem to be working, leave them in until you're forced to change the technology for whatever reason.

THERMOCOUPLE TEMPERATURE MEASUREMENT

I've got a special place in my heart for simple, elegant solutions. The vapor pressure thermometer must surely find a home there along with thermocouples.

We're going to spend more time and words discussing thermocouples than any other temperature measurement method. The reason being that compared to all other measurement technologies, thermocouples are easiest to fabricate and put in place. During initial fly-off testing for your project consider the following list of temperatures to be investigated:

- Oil
- Voltage regulator
- Alternator stator winding
- Alternator diode array
- Fuel pump(s)
- Gascolator
- Vacuum pump
- Magneto housing(s)
- Cylinder heads (checks baffling)
- EGT each cylinder (checks fuel mixture distribution)
- Top radio in stack

**Dimmer heatsinks
Electro-hydraulic power pack motor**

Some of these items will be part of your permanent instrumentation. However, most airplanes have one or more equipment items that may be damaged or rendered inoperative by temperature extremes. Each item should be instrumented and investigated for worst case scenarios that may induce adverse temperatures under ordinary flight conditions. These include low-and-slow pattern work (touch and go landings), hot day best angle climb (work'n hard - minimum cooling), heat soak after shutdown, maximum electrical load, etc. The first few hours of flight on a new project are crucial; use mandated fly-off time to assure yourself that heat stress on critical components and systems are within acceptable limits.

**IT TAKES GOOD INFORMATION
TO MAKE GOOD DECISIONS**

This kind of temperature survey is routine during certification work on production airplanes; it's a simply a good idea. Technology historians have suggested that in spite of Russian ability to build bigger and stronger launch vehicles, more than one Russian rocket scientist was fearful for his future when development programs suffered from many, very big disasters. Scholars theorize that US ability to instrument prototypes and operational vehicles made analysis and correction of problems a breeze by comparison; US scientists read tens of thousands of data points on a space flight vehicle while the Russians recorded very few.

In a later chapter, we'll discuss failure mode effects analysis (FMEA) as a tool for enhancing reliability of a flight system. Comfortable outcome of an FMEA assumes that parts are going to fail because they've reached end-of-life (no matter how short). When parts fail because they are not properly installed or operated, the benefits of an FMEA are severely compromised. So when in doubt, measure it!

Thermocouples make it relatively easy to do. Thermocouple wire is sold in spools of various sizes and types of insulation. Thermocouples are easy to fabricate and attach to equipment items you wish to monitor. A single readout instrument may be switched to an array of thermocouples; surveys can be conducted with a minimum of expense and cockpit clutter from test hardware. Thermocouples are the ultimate engineering and flight test temperature research tool. I'd bet that US space flight vehicles have more thermocouples on board than any other sensor.

**THE SEEBECK EFFECT -
ELECTRONS ON THE LOOSE:**

As we've observed in our daily lives and as I've discussed here, temperature affects materials in a variety of ways. We know that all materials are made of atoms; atoms have electrons whizzing around their nucleus and atoms consist mostly of empty space. It is less commonly known that the atoms within any solid are constantly exchanging electrons to a certain degree depending on the makeup of the material *and its temperature*. Some materials are less capable of hanging onto their rambunctious electrons than others. So, if you put differing materials in contact with each other and if the materials are otherwise reasonable conductors of electricity (metal) then a voltage difference will appear between the two conductors. The material with the stronger grip on its electrons will steal a few from the other material and acquire a more negative potential (voltage) with respect to the other conductor. The amplitude of the potential (voltage) depends both on the type of metals used and upon the temperature which exists at the junction of the dissimilar metals. We've already discussed the concept of absolute zero, a place were all molecular motion stops. It's no leap of faith to understand that the voltage generated by a thermocouple goes to zero volts at 0°K. Okay! All we gotta do is hook a voltmeter to the two conductors and convert the resulting reading to temperature.

One may fabricate a thermocouple from any two, ordinary metals. This concept is illustrated in Figure 14-8 where I show an iron wire twisted together with a copper wire. There's a just a couple of very tiny problems: First, the voltage generated between the two materials is small. A typical thermocouple generates a voltage between 20 and 60 microvolts per °C. So even though we've heated the copper/iron junction very strongly with an open flame, the generated voltage is small - a few tens of millivolts. Until a few years ago, dealing with the tiny voltages was a real challenge. I was first introduced to thermocouple measurement techniques in the early '60s. Back then, tiny thermocouple voltages were measured with a cumbersome device called a millivolt potentiometer. It was housed in a box about 10 inches on a side. Voltage measurements were made by rotating a range switch and a large dial until a needle on a meter was centered. Each measurement could take 10-15 seconds. Measured voltages were recorded by hand onto a datasheet and later converted to temperature measurements by referring to charts. It was easy to make

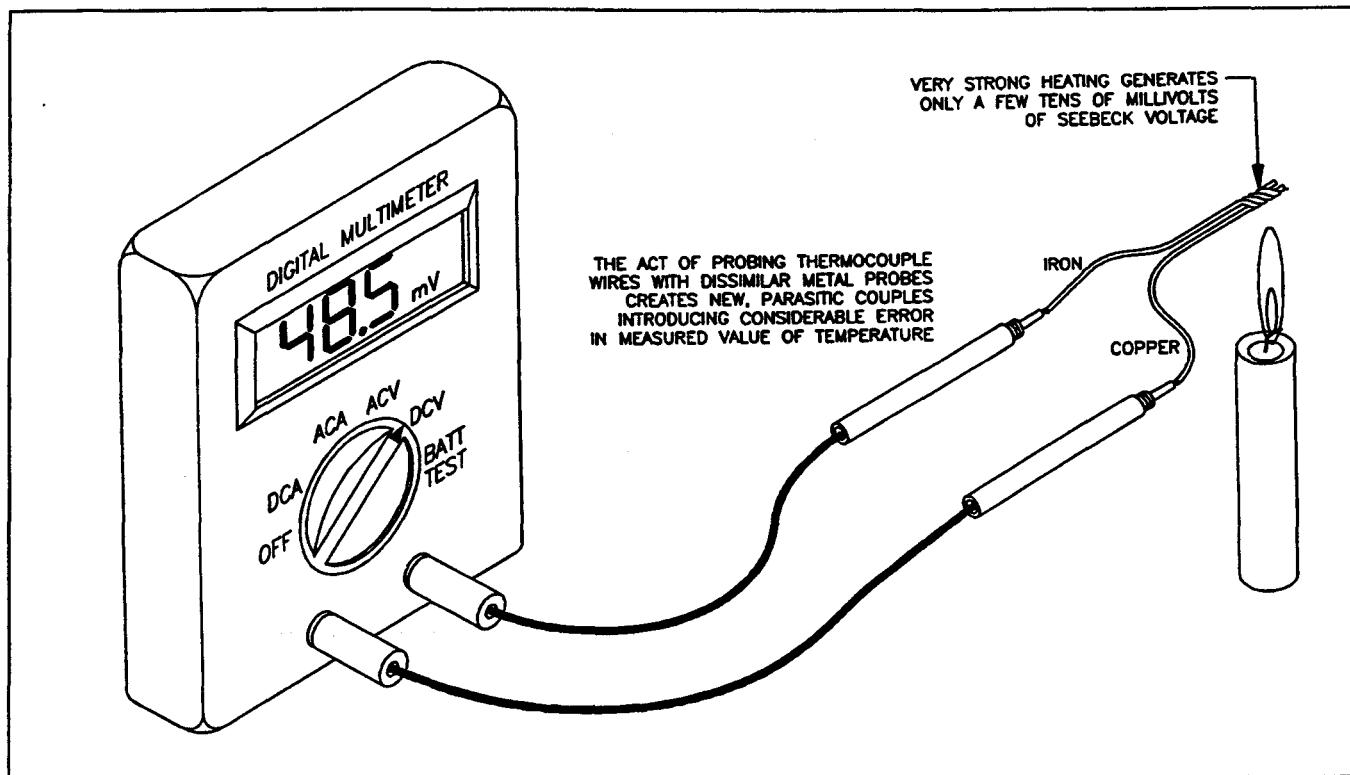


Figure 14-8. Basic Thermocouple.

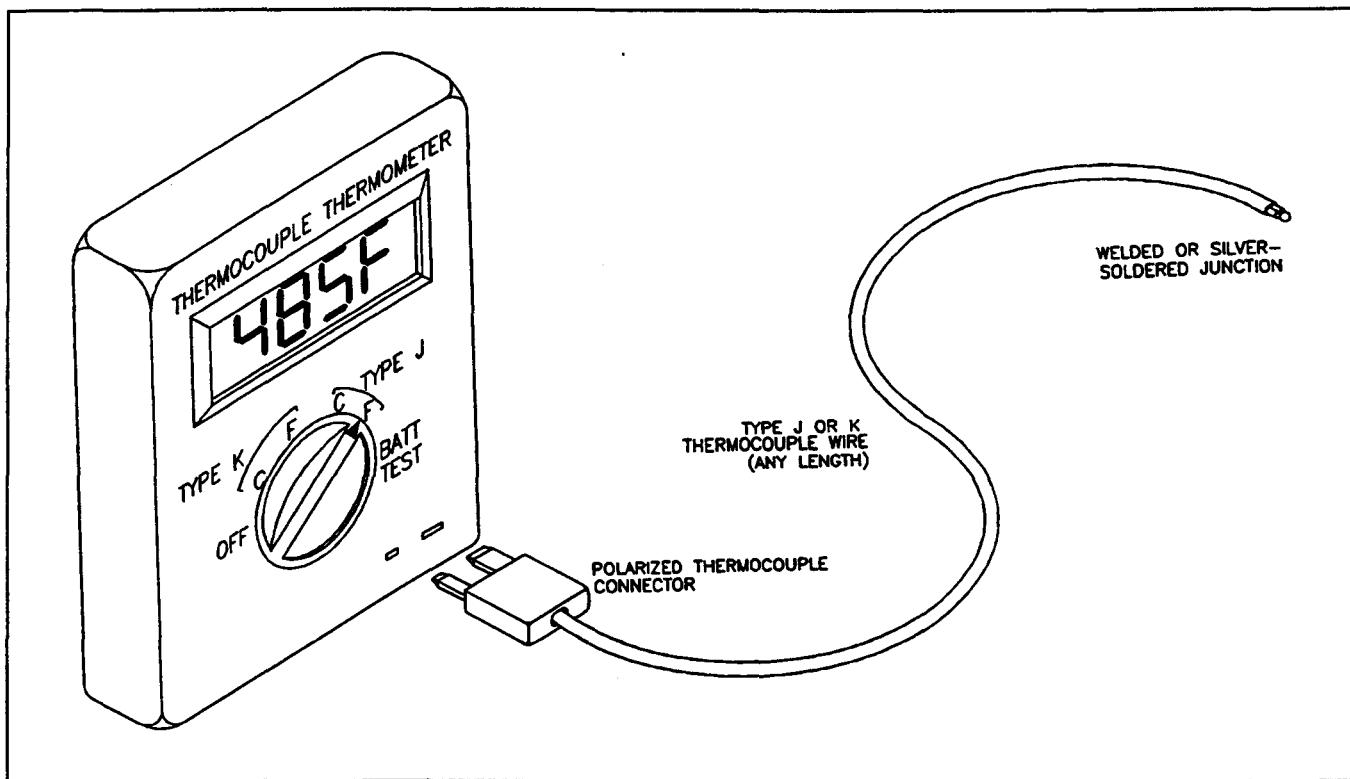


Figure 14-9. An Off-the-Shelf Digital Thermocouple Thermometer.

mistake in taking a reading especially when taking a lot of measurements in flight.

The second problem with thermocouples arises from installation logistics. Recall that any two dissimilar metals will form a thermocouple. In the illustration of Figure 14-8, I've shown plated brass probes making connection to the iron and copper thermocouple wires. These points of contact create two new, parasitic thermocouple junctions. Further, as you advance up the voltmeter lead wires, into and through the instrument's internal wiring, more parasitic thermocouples may be found; each couple contributing or detracting from the reading of interest. Fortunately, dealing with parasitic couples is easy.

Nowadays, one may purchase direct readout thermocouple thermometers for as low as \$80 (see Figure 14-9). These handy instruments have internal cold-junction or "ice-bath" compensators. They are also programmed to compensate for small non-linearities in voltage vs. temperature curves. Further, even the low cost instruments will utilize either type J or K thermocouple wire. Finally, one may choose to read either °F or °C. Some low cost, hand held instruments have two jacks to allow switching between two thermocouples. I don't recommend paying extra for a dual thermocouple device. In my experience, every time I've needed to measure more than one temperature at a time in an airplane, it was always more than two. Invariably, I have to rig a multipole thermocouple switch which I will describe later in this chapter.

Before we discuss practical applications of thermocouples let's explore their operation in more detail. Further, let's define several new terms: "type J" and "type K" wire along with "ice-bath" and "cold-junction." There are dozens of thermocouple wire types - each was developed for a specific task. The two most common thermocouple wires for aircraft instrumentation are fabricated from some pretty strange sounding stuff: iron-constantan (type J) and chromel-alumel (type K). Constantan, chromel and alumel are special alloys designed specifically for thermocouple use. Their characteristics are carefully controlled and agreed upon by international industry standards. Any spool of thermocouple wire marked type J or type K will yield consistent, predictable results according to Table 14-2. When designing a useful thermocouple one must consider Seebeck voltage (some combinations of alloys generate much higher voltages per degree than others), operating temperature (you don't want the thing to melt!) and resistance to materials in the environment to be measured (strong

acids, oxidizers, caustics, etc., may dissolve the sensor). Finally, one must select an insulation suited to the operating environment.

Type K alloys are suitable for any kind of measurement on an airplane including exhaust gas temperatures. Type J has a recommended upper limit that suggests it not be used in exhaust stacks but it is fine everywhere else. As

Table 14-2. Thermocouple Voltage (mV) versus Temperature (Reference to Ice-Bath).

Temp °C	Temp °F	Type J Wire	Type K Wire
-40	-40	-1.96	-1.50
-30	-22	-1.48	-1.14
-20	-4	-1.00	-0.77
-10	14	-0.50	-0.39
0	32	0.00	0.00
10	50	0.50	0.40
20	68	1.02	0.80
30	86	1.54	1.20
40	104	2.06	1.61
50	122	2.58	2.02
60	140	3.11	2.43
70	158	3.65	2.85
80	176	4.19	3.26
90	194	4.73	3.68
100	212	5.27	4.10
110	230	5.81	4.51
120	248	6.36	4.92
130	266	6.90	5.33
140	284	7.45	5.73
150	302	8.00	6.13
160	320	8.56	6.53
170	338	9.11	6.93
180	356	9.67	7.33
190	374	10.22	7.73
200	392	10.78	8.13
210	410	11.34	8.54
220	428	11.89	8.94
230	446	12.45	9.34
240	464	13.01	9.75
250	482	13.56	10.16
260	500	14.12	10.57
270	518	14.67	10.98
280	536	15.22	11.39
290	554	15.77	11.80
300	572	16.33	12.21

you can see from voltages in Table 14-2, Type J wire has a little more output for a given temperature than does Type K but for most purposes, either is satisfactory. The most universal insulation is a woven Fiberglas which is not very neat to work with but it has very good high temperature characteristics. My favorite is Kapton covered wire. It's smooth, strips nicely and has temperature characteristics that work everywhere except in the exhaust gas stream - no big deal; you need special, shielded probe for EGT work anyhow. Here's how you identify type J and K wires:

Table 14-3. Thermocouple Conductor Identification.

Conductor	Insulate Color	Polarity ity	Magnetic (?)
Type J Wire: Iron/Constantan			
Iron Const.	White Red	Positive Negative	Yes No
Type K Wire: Chromel/Alumel			
Chromel Alumel	Yellow Red	Positive Negative	No Yes

Spoiled thermocouple wire has a unique appearance and usually conforms to marking conventions that make it easy to identify. First, any thermocouple wires you are likely to encounter are always paired. The outer jacket may be any color. Insulation over the inner conductors usually follows industry standards: For type K wire the positive conductor is made of chromel, insulated in yellow and identifiable as non-magnetic. The negative wire is made of alumel, insulated in red and will be attracted by a magnet. In type J wire, the positive conductor is made of iron, insulated in white and magnetic. The negative conductor is constantan, insulated in red and is non-magnetic. These identifying attributes are summarized in Table 14-3.

An aforementioned consideration for working with thermocouple wire is the issue of parasitic couples - all electrical circuits are fabricated from some kind of metal (conductor). There's no way to get electrons to flow from point A to point B without bringing two pieces of metal together. So, making the transition from thermocouple wire to instruments requires special attention. One of the neat things about working with thermocouple is that parasitic couples don't have to be eliminated, they

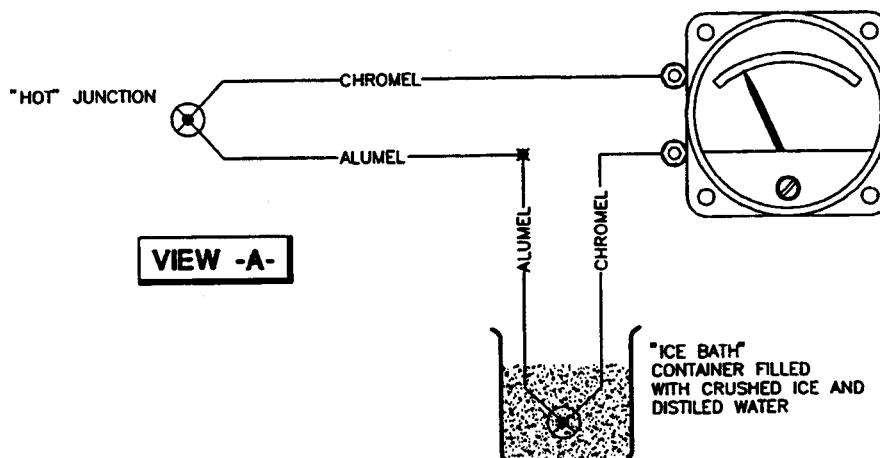
just need to be accounted for. For every parasitic couple in one side of a thermocouple lead, you need one of equal potential but opposite polarity in the other lead.

In Figure 14-10, View -A-, I show two chromel-alumel thermocouples hooked in series with their alumel wires brought together. This means that the "hot" junction generates a voltage opposite in polarity to the "cold" junction. If both couples were at the same temperature, the net voltage at the instrument is zero. Now, let's place the "cold" couple in a known temperature environment, say a bath of crushed ice and water. We know that while any ice exists, the bath is 0°C. Now the voltage measured between the two couples is proportional to temperature difference between the "hot" and "cold" junctions. Further, note that our voltmeter is now connected to two constantan wires. The two parasitic couples at the voltmeter terminals now have equal but opposite effects on the voltage of interest. In other words, irrespective of their voltage, they are opposing polarities and equal to each other - they cancel each other out. Now our instrument need be concerned only the calibrated difference voltage between hot and cold junctions. Further, the hot junction's temperature will be represented by the voltages described in Table 14-2.

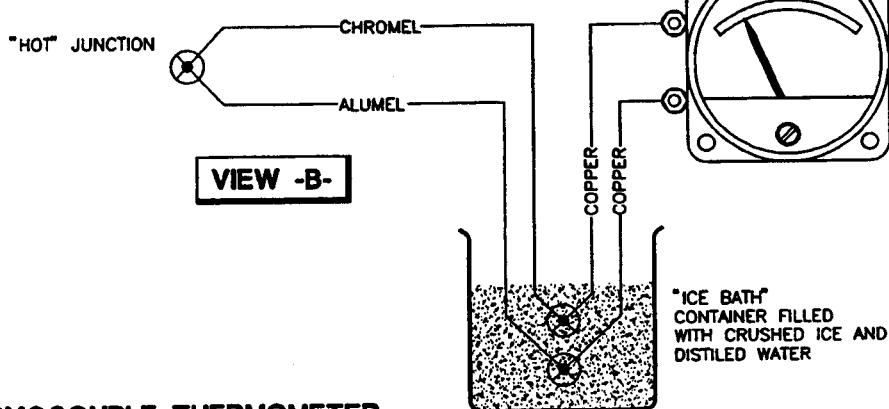
View -B- shows a two-junction ice bath. This setup is useful if you have a very long run between thermocouple and instrument - it's less expensive to do the long run in copper wire. In this case we may transition from any thermocouple wire into copper. Now we have two parasitic couples: one is chromel-copper, the other is alumel-copper. It turns out this system works fine when both transition junctions are referenced in the ice bath.

Needless-to-say, an ice bath isn't a convenient temperature reference to carry around in an airplane (*although years ago, I did it - had a special Thermos bottle with a cork that had a number of reference junction thermocouples sealed in it*). Fortunately, electronic replacements for a reference junction are possible. There are a number of instruments flying in airplanes that appear to be no more than a meter with a thermocouple attached. Common examples include exhaust gas temperature (EGT), cylinder head temperature (CHT) and a smattering of carburetor air temperature gages. If you find one of these indicators separated from its companion thermocouple you need to know that the thermocouple is matched to the instrument. The instrument contains a special, low voltage movement along with reference-junction compensation. Low voltage movements tend to draw quite a bit of current - perhaps as much as 100 milliamps! Therefore, resistance of the companion thermo-

**BASIC T/C THERMOMETER
with SINGLE-JUNCTION ICE BATH**



**BASIC T/C THERMOMETER
with TWO-JUNCTION ICE BATH**



**THERMOCOUPLE THERMOMETER
with INTERNAL ICE BATH COMPENSATION**

NON-ELECTRONIC, SELF POWERED INSTRUMENTS GENERALLY
USE SPECIAL, LOW IMPEDANCE METER MOVEMENTS AND T/C
LEADS THAT CANNOT BE ALTERED.

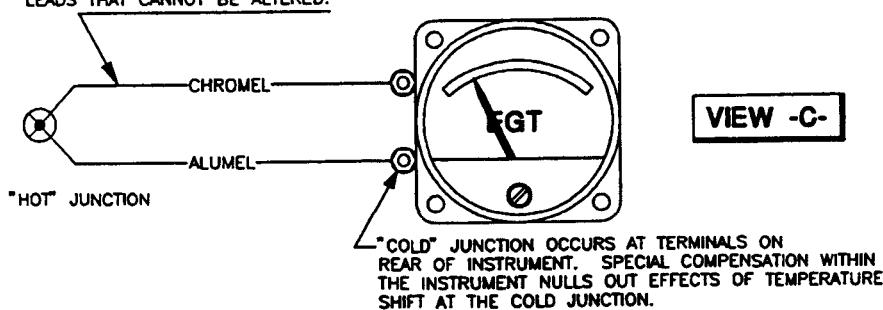


Figure 14-10. Generic T/C Thermometers and Various Reference-Junction Techniques.

couple assembly is part of the instrument's calibration. As a general rule, un-amplified instrument thermocouples cannot be shortened or extended. When Smiley Jack's Almost-Good-As-New Airplane Parts Emporium offers you such an instrument, be sure to check its calibration just be sure that the thermocouple supplied is really the one that belongs with it. Boiling water is a good calibration bath at 212°F (100°C); an ice bath is 32°F (0°C); etc. If in doubt, any instrument shop can take a quick look at it to be sure it's working properly.

Except for a few cautions, the unpowered thermocouple gage is quite attractive. It can be accurate and requires no wiring to ship's dc power. Such an instrument is illustrated in View -C-. Obviously, the reference-junction for this instrument exists right where the thermocouple wires bolt to the back of the instrument. Reference-junction compensation doesn't have to look like a 0°C ice bath. The reference-junction compensator just needs to know what the temperature is at the studs on the back of the instrument case; no problem since the compensation circuitry is right inside the case!

The basic tenets of thermocouple measurement are: (1) use two couples in series opposing so that the voltage to be measured is a function of temperature difference between the two couples and (2) design the measurement system so that all parasitic thermocouples exist in opposing pairs. With these concepts in place, we can discuss techniques for switching multiple thermocouples to a single instrument.

Let's suppose you wish to log a bunch of temperatures during your fly-off hours. Consider building your own thermocouple selector switch. Purchase a 12-position, 2-pole rotary switch from one of the catalogs listed in Appendix-A. Mount the switch on one side of an aluminum box and along with two, 13-position terminal strips. Figure 14-11 illustrates the right and wrong way to configure a thermocouple selector switch. You may use ordinary hook-up wire (22AWG aircraft wire is fine) to wire it. It is true that considerable error is introduced by each joint of non-thermocouple metal introduced in each leg of a thermocouple. The secret is that errors of equal and opposite amplitude are created in pairs - one on each side. By observing the second law of thermocouples, errors induced by our switch box cancel each other out.

Readers have called to ask what was wrong with their modern, digital display for CHT or EGT where they were attempting to switch a single instrument between multiple thermocouples. The first question is, "Are you

using a two pole selector to switch both sides of the thermocouple?" There are expensive, commercial equivalents to the thermocouple selector switch just described. If you can find a used one for a reasonable price (like 30-50 dollars), buy it and donate it to your local EAA chapter. Every new airplane should be surveyed for a variety of temperatures during flyoff hours or after some kinds of major modifications to the power plant. After that, your selector switch and thermocouple readout will sit on the shelf and gather dust. It would be better if your local chapter owned a thermocouple selector switch and indicator for loan to members. That way a few pieces equipment would suffice for many projects as needed.

CAUTION

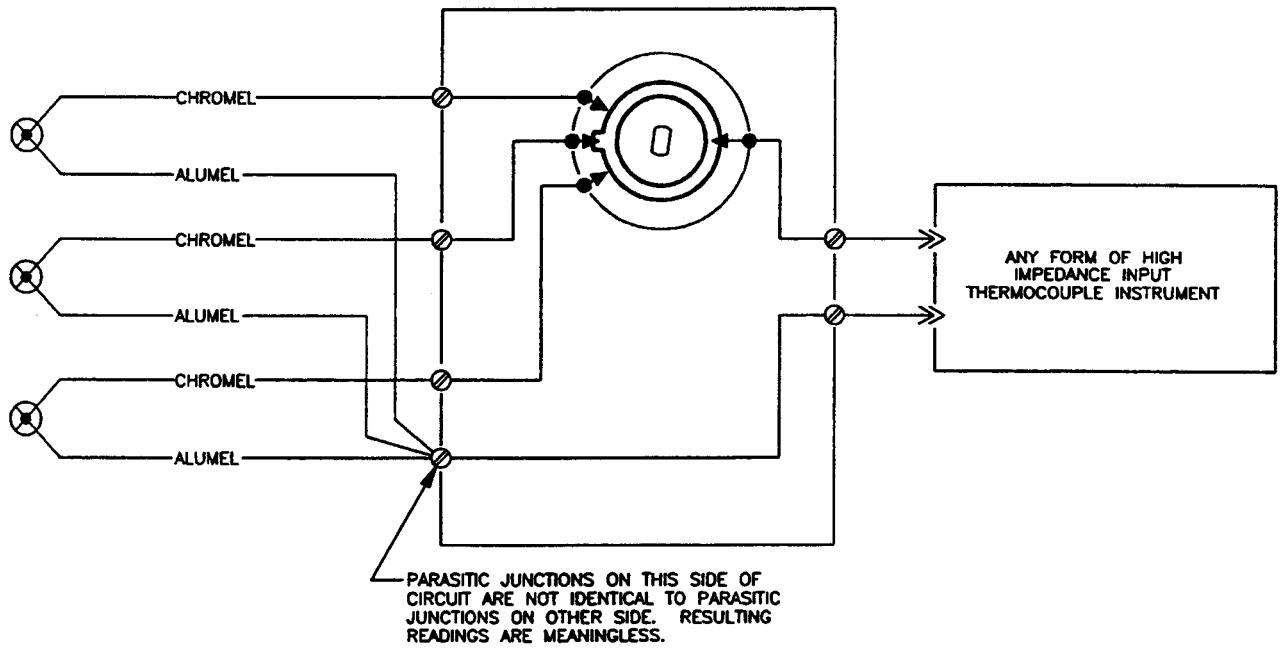
When setting up for multiple measurements with a selector switch, be certain the instrument you use is a high input impedance device that doesn't care about thermocouple resistance . . . self-powered instruments mentioned earlier are not good candidates for this task. However, any modern, digital thermocouple thermometer will be fine.

AMPLIFIED THERMOCOUPLE THERMOMETERS

While on the topic of high impedance instruments for thermocouples, I'll call your attention to Figure 14-12. In View -A- the hot-junction and reference-junction setup is similar to Figure 14-10, View -A- except: an electronic amplifier inserted between thermocouple wires and indicator. Some interesting things happen when you add an amplifier. (1) the indicator becomes a simple, much less expensive, voltmeter and (2) the current flowing in the thermocouple wires is for all practical purposes, zero. Length of thermocouple wire is no longer critical; insertion of a selector switch to manage many thermocouples is feasible. The last inconvenience to eliminate is the requirement for an ice bath . . .

A company called Analog Devices builds integrated circuits for thermocouple signal conditioning. A sample circuit is shown in Figure 14-12, View -B-. The AD594 integrated circuit is designed to provide amplification, cold junction compensation and linearity compensation for type J thermocouple wire, the AD595 is used with type K wire. The device outputs a voltage of 10 millivolts per °C of thermocouple temperature. These circuits

-VIEW A-
ONE EXAMPLE OF INCORRECT
THERMOCOUPLE LEADWIRE SWITCHING



-VIEW B-
PROPER THERMOCOUPLE SWITCHING
REQUIRES EQUAL TREATMENT TO BOTH LEADS

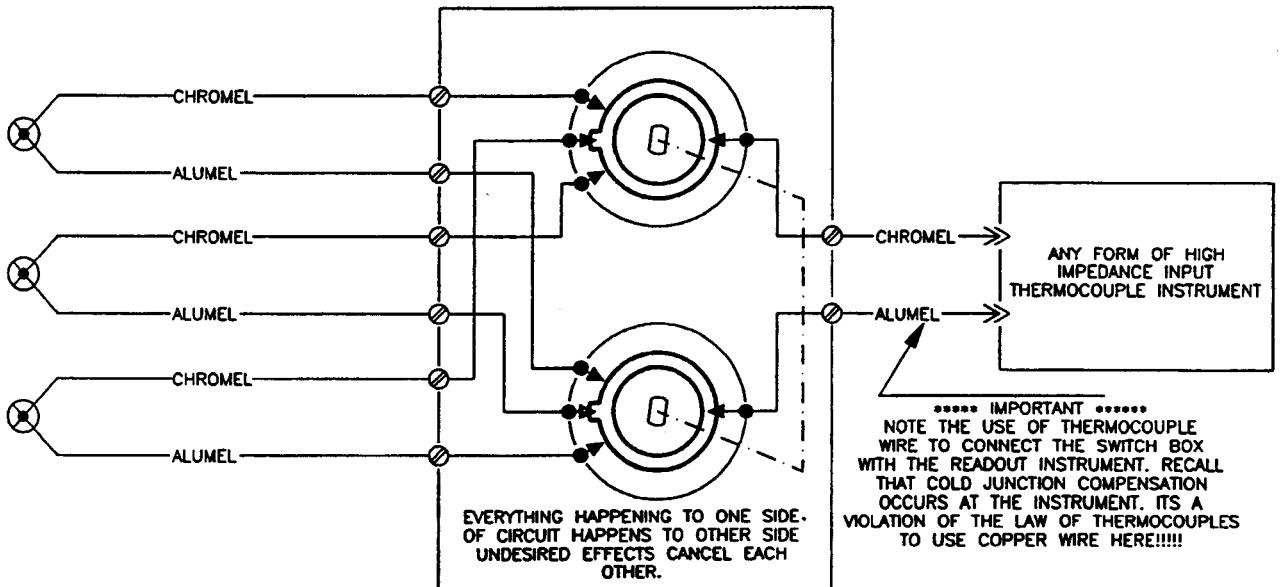
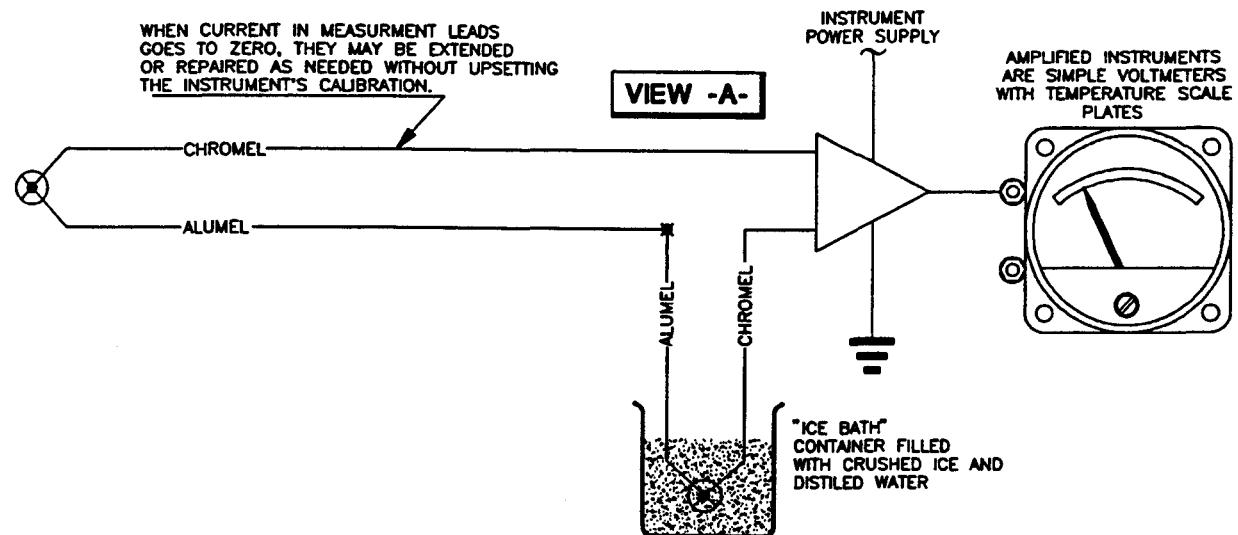


Figure 14-11. Switching Multiple Thermocouples to a Single Instrument.

GENERIC T/C INSTRUMENTATION WITH AMPLIFIER

WHEN CURRENT IN MEASUREMENT LEADS GOES TO ZERO, THEY MAY BE EXTENDED OR REPAIRED AS NEEDED WITHOUT UPSETTING THE INSTRUMENT'S CALIBRATION.



AMPLIFIED THERMOCOUPLE THERMOMETER with INTERNAL REFERENCE JUNCTION COMPENSATION.

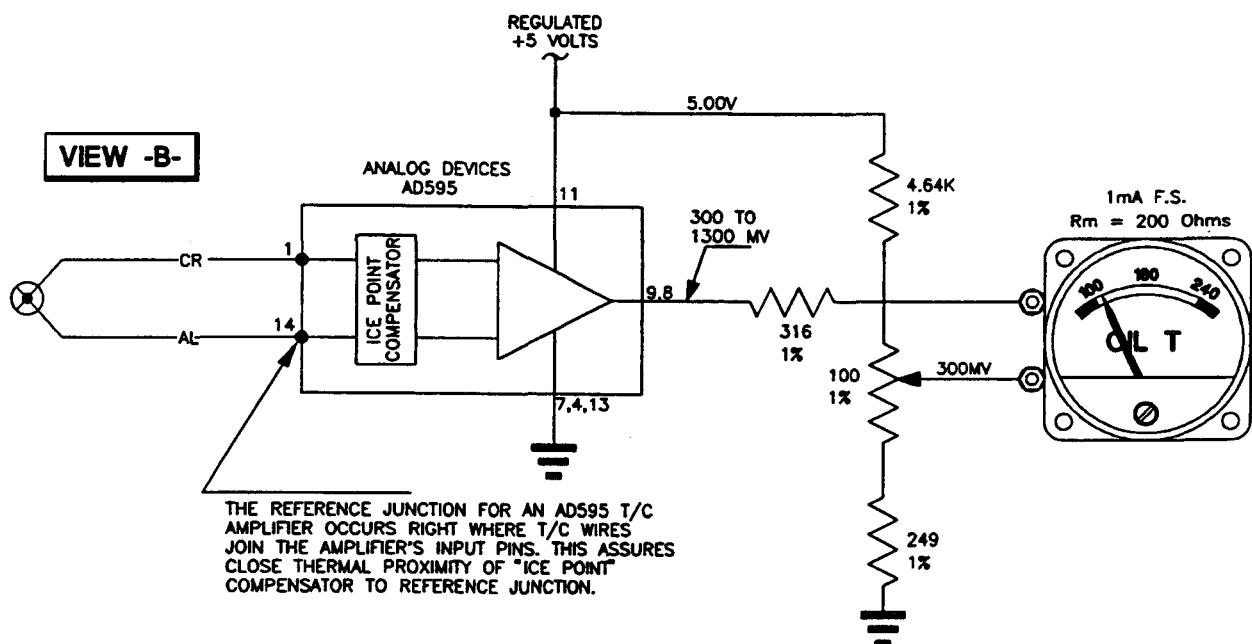


Figure 14-12. Amplified Thermocouple Thermometers.

will work in the minus temperatures if two power supplies (+5 and -5 volts) are provided. Thermocouples work best above 0°C and are quite suited for oil, EGT and CHT measurements. For these parameters, temperatures of interest are well above 0°C. Therefore, a single +5 volt supply works fine for measurements between 10°C (.10 volts) and about 300°C (3.00 volts).

For example: Let us suppose you want to display oil temperature over the range of 30 to 130 degrees C (86 to 266 degrees F). The output from the AD595 and type K wire will be 300 to 1300 millivolts over that range (10 millivolts per degree C). So, instead of designing a differential voltmeter for 10-16 volts as in Chapter 7, we're going to design for 300 to 1300 millivolts. The values shown in Figure 14-12 are appropriate for a meter having a full scale current of 1 milliampere and internal resistance of 200 ohms. Resistors for other meters can be calculated using techniques described in Chapter 7 (*OR you can simply use a digital panel meter with the decimal point set in the right place to display 10 mV°C as temperature.*)

Now, remove the meter's existing scale plate and paste a new scale on having a calibration and label as shown. A similar technique could be applied to cylinder head and exhaust gas temperature indicators. So, you see that one may consider building some instruments that are accurate, calibratable and repairable by you, the builder. I have a variety of scale plates already drawn in AutoCAD that would be easily customized to any basic meter movement. If you'd like to take a whack at building thermocouple driven temperature gages, let me know.

A final note on the AD594/AD595. If you own a decent digital or analog voltmeter you may use one of these devices to build a small adapter for measuring temperatures with thermocouples. You'll need to mentally place the decimal point for conversion of volts to degrees, e.g. 1.000 volts = 100°C; 0.550 volts = 55°C, etc.

SPLICING THERMOCOUPLE WIRES

Thermocouple wires are easily repaired, carried through connectors or extended by splicing. However, you're now aware that special techniques are required. A number of companies sell splicing devices for joining two thermocouple conductors. One may purchase butt splices that are similar in appearance to those designed for joining ordinary copper wire. If you wish to bring a thermocouple pair through a multi-conductor, bulkhead connector, crimpable terminals of the proper alloys are

available but they are not cheap . . . I've paid as much as \$25.00 per pin for chromel-alumel pins to fit MS3120 series connectors . . . that's \$100 for parts to bring one pair of wires through a connector! I try to avoid bringing a thermocouple through any kind of connector along with other wires. There's a lot of temptation on the part of builders to bring all wires penetrating a firewall through on some kind of connector. For cost, weight and time savings, I recommend fabricating firewall penetrations from ordinary grommets with sheet metal fire shields.

One may purchase small, polarized connectors with molded plastic housings. These are generally attached to the conductors with tiny set screws. I believe they are offered both for semi-permanent splicing and as mated-pair connectors that permit breaking and rejoining a splice for maintenance. These connectors are not outrageously expensive. If you would like to remove an engine without de-mounting oil, cylinder head and/or exhaust gas thermocouples, these low cost connectors should be considered. Vendors of thermocouple joining supplies may be found in Appendix-A.

Occasionally, one simply wishes to permanently join a pair of conductors when a repair or replacement of a thermocouple is done. Other times, a thermocouple wire installation task is made easier by breaking up a thermocouple wire run into two or more segments. Chromel-alumel and iron-constantan conductors may be soldered. Unfortunately, they do not alloy with ordinary tin-lead solder. I prefer silver-solder so a torch is required to achieve adequate temperatures for joining. Further, at silver-solder temperatures, you are going to smoke some insulation on the wires - a condition that does not occur with ordinary electronic soldering operations. The trick is to minimize the damage and to end up with a clean looking splice.

Figure 14-13 illustrates two methods for joining segments of thermocouple wire - solder or install a thermocouple connector. To solder as in View -A-, strip outer jacket of thermocouple pair about 4-inches on each end to be joined. Cut the conductors to be joined so that the solder joints are staggered; one joint about 1-1/2" from the first outer jacket; the second an equal distance from the other outer jacket. Strip inner insulation from each conductor about 1/2". Slip a 6-inch piece of 3/16" heat-shrink tubing over the outer jacket of one pair and 2-inch pieces of 1/8 or 3/32 inch heat shrink over each of the long conductor stubs. If you can find high-temp, Teflon heat shrink for this task, great. However, plain vanilla

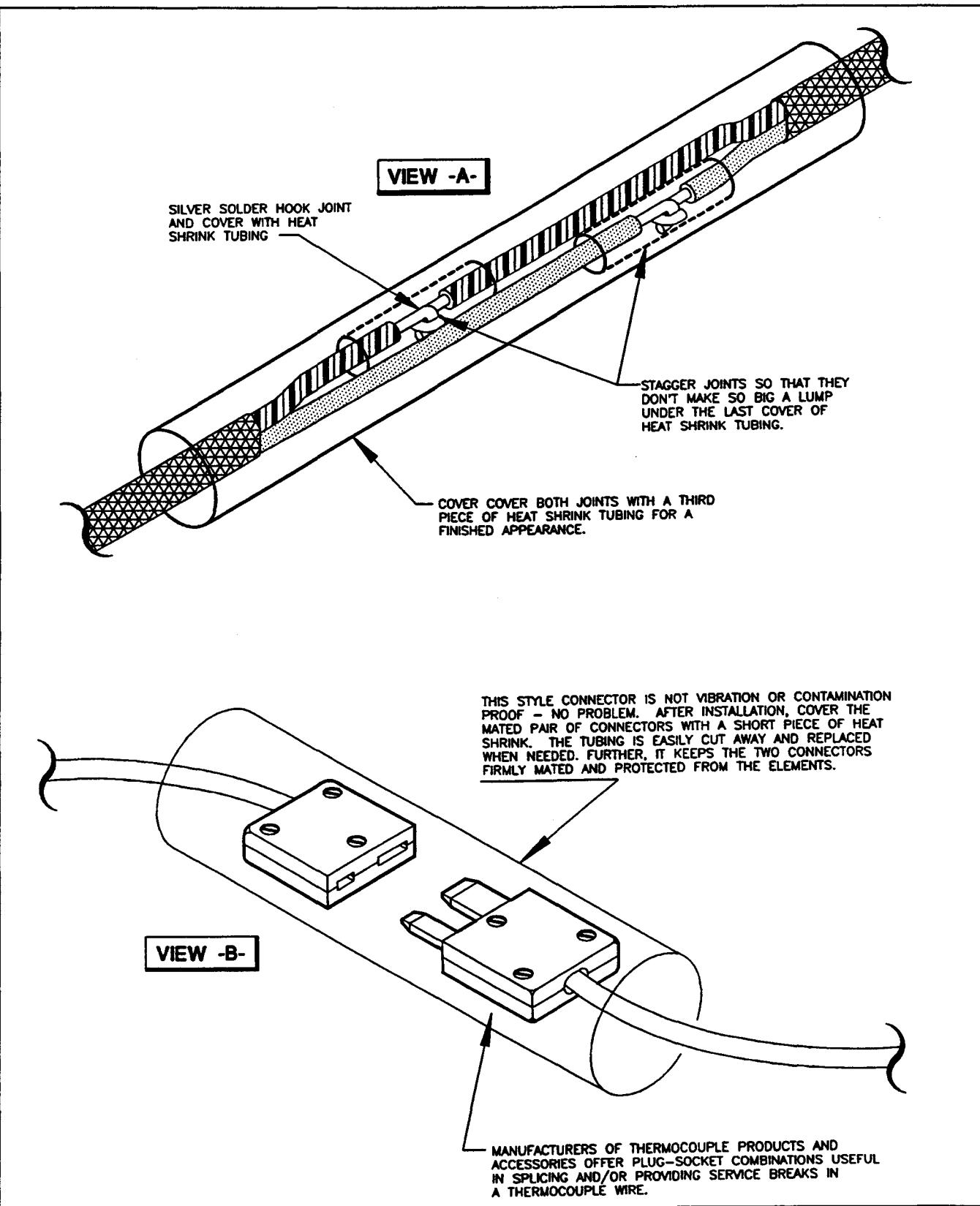


Figure 14-13. Splicing Thermocouples.

variety will do nicely too. Bend a J-hook in the very tip of the first two wires to be joined, interlock them and close the hooks with pliers.

Now, if your propane torch were to be compared with a Star Trek hand-fazer, we're going to set it for "gentle stun" mode; just enough energy to get a humming bird's attention without knocking it off its feet. One-fourth inch of dark blue, inner flame cone extending past the end of the mixing chamber is about right. Some torches I've used for this task wouldn't burn well at this setting until they've burned at a higher setting for a few minutes to warm up.

First, coat the joint of interlocked wires with silver-solder flux. Now, the task is to form a tiny joint with minimal melt-back on the insulation. Success depends on getting solder to melt at the same time the wires get up to alloying temperature. Generally, the solder heats slower than the wires so I try to bring the tip of the inner blue flame tip up to the wires about two or three seconds after putting the end of the solder into the flame tip. If you're really nimble with this process you will be on and off the joint with the torch in about 6-8 seconds. You may want to practice with a few scraps of wire before you climb into your airplane to try this. Be aware that silver solder flows at red-heat temperatures. Further, be prepared for more melt-back than you would really like to see.

In words this probably sounds more difficult than it really is. Further, there is no great sin in smoking a little more insulation than you'd like . . . we're going to cover the dirty deed with two layers of plastic! When the first solder joint has cooled, clean off any flux residue that will now look like a thin coat of glass over your finished joint. Use needle nose pliers to simply crush the fused flux - it will fall away easily. Slip heat shrink over the finished joint and shrink into place. Put another piece of small heat-shrink over the other long stub and interlock two j-hooks. *Electronic stores, like Radio Shack, sell a "third hand" soldering aid that you may find useful in fixturing your victims for this operation. In a pinch, build your own fixture by soldering two alligator clips to a 6" piece of 10AWG bare copper wire and bending it into a U-shape so that the clips can support your wires to be joined on either side of the joint.*

Solder then shrink a cover over the second joint. Finally, position and shrink the large tubing over the whole business and you're done. The judges at Oshkosh will

marvel over your clever joining of the "un-joinable" and never know how badly the insulation suffered in the process. Furthermore, instrument panel temperature gauges will read exactly what they are supposed to read: temperature at the far end of the thermocouple pair, unaffected by temperatures encountered along the way.

Figure 14-13, View -B-, shows a small, mating pair of thermocouple connectors sold by virtually every firm specializing in thermocouple products and accessories. Digital thermocouple thermometers often feature a female side of this style connector right on their front panel as shown in an earlier figure. These connectors are inexpensive . . . a few dollars per mated pair. Use these guys to break thermocouple leads when dismounting an engine without having to remove the thermocouples from the engine. Text in Figure 14-13, View -B-, suggests a means for securing these connectors from separation under vibration and protecting them from most environmental hazards.

FABRICATING & REPAIRING THERMOCOUPLES

The really neat thing about thermocouple wire is that you can make your own temperature sensors at the end of any desired length of thermocouple wire. Simply extend the wire from the instrument to a site where temperature is to be measured. Strip the insulation off the end and twist the wires together. Various laboratories I've worked in were equipped with thermocouple welders. These are nifty little machines that allow one to twist a thermocouple pair of wires together and use an electric arc to fuse them to form a neat thermocouple. The operation occurs so quickly and with so much energy concentrated at the joint that melt-back of adjacent insulation is minimized. Further, no foreign metals are introduced into the joint. Since we're not looking for laboratory grade accuracy in aircraft systems temperature measurements, the silver solder joining technique makes an excellent alternative to the purchase of a laboratory welder and uses inexpensive tools and techniques available to the amateur airplane builder. Just twist the stripped ends of the thermocouple wire together, solder with silver solder, break away flux residue and trim overall length as desired. A thermocouple joint can never be too small to function. Size of wire is purely a logistical consideration. You can buy thermocouple wire in gages (.001" diam) suitable for taking a bumble bee's temperature. On the other hand, hefty wires (18AWG for example) are available for very rough environments. Either wire is read by the same instrument!

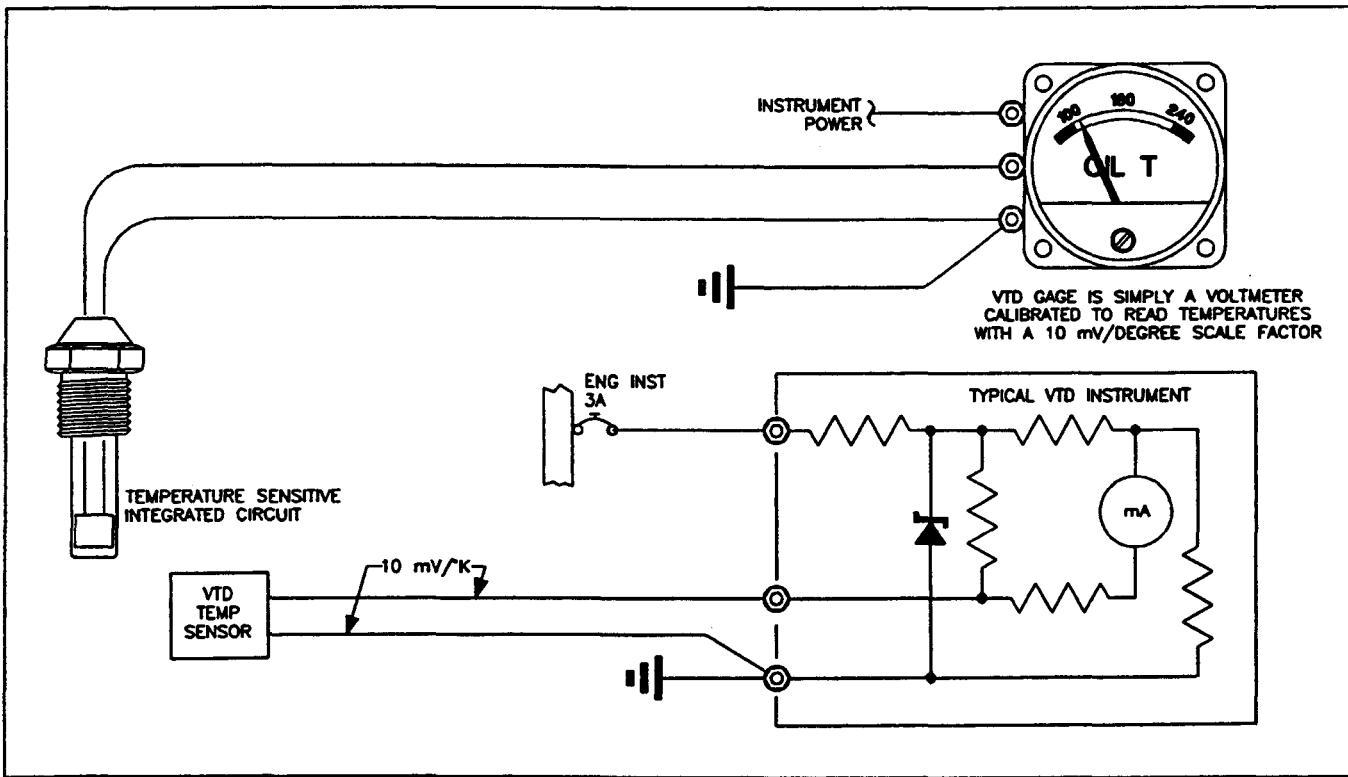


Figure 14-14. Solid State Temperature Sensor.

Insulation becomes the last consideration. Most thermocouples wires found on factory installed aircraft instruments will have a form of Fiberglas insulation on them. This insulation is resistant to most environmental stresses found on airplanes. Thermocouple wires are also commonly insulated with materials like Kapton and Kynar and Teflon. Since thermocouples are most often used to read temperatures well above ambient levels, they are purchased with heat resistant insulations. If you stumble across some thermocouple wire as a surplus item, it's probably suited to measuring about anything found on an airplane. The tough one is EGT which requires type K wire and Fiberglas insulation.

PERMANENT THERMOCOUPLE THERMOMETERS

There are at least 3 situations where you may wish to install permanent, thermocouple driven instruments on the panel. One each for oil temp, cylinder head temp (hottest one as surveyed during flyoff) and EGT (hottest one as surveyed during flyoff). As illustrated back in Chapter 7, it's not difficult to configure a meter to read any desired range of voltages. With a few more components, you can make the meter read a range of temperatures as well.

CALIBRATED ELECTRONIC TEMPERATURE SENSORS

Back in the days of germanium transistors, designing solid state circuitry to operate over wide temperature ranges was challenging. We cursed the fact that solid state devices had strong, undesirable responses to temperature. Thirty years later, clever designers of electronic components have capitalized on these phenomena to take advantage of certain temperature effects. In fact, the AD595 integrated circuit described earlier uses an internal solid state temperature sensor to develop a voltage for reference junction compensation. If resistance versus temperature devices are called RTDs, I guess we could call voltage versus temperature devices VTDs.

Several manufacturers build VTDs that look for all the world like a simple, zener diode voltage regulator. However, this "regulator" is very unstable - in fact, it drifts at a rate exactly equal to $10 \text{ mV}/^\circ\text{K}$ or $10 \text{ mV}/^\circ\text{R}$. Hmm . . . we saw that 10 millivolt figure earlier. That's become a sort of industry standard for temperature measurement devices. Everyone builds parts calibrated for measuring C-size degrees, most also make F-size parts too. Figure 14-14 shows a basic thermometer using a calibrated VTD. The indicator is nothing more

than a voltmeter with scale factor of 10mV per degree times total degrees of span and an offset equal to 10mV per degree times the lower end of scale temperature reading. The architectures for expanded scale voltmeters described in Figure 14-12 and Chapter 7 are applicable.

VTDs are calibrated devices as supplied from the factory. They are quite accurate, typically plus or minus 1.0°C or better. Their scale factor of 10 mV/°C is the same as the thermocouple amplifier shown in Figure 14-12, but they are somewhat simpler to use as illustrated in Figure 14-14. Their disadvantage is that their operating temperature ranges do not span as far as thermocouples. They are currently unable to measure exhaust gas temperatures; exhaust gases will remain an exclusive domain of thermocouples. Further, few solid state sensors are rated for temperatures experienced on cylinder heads. However, they do work well at low temperatures (below 0°C); actually better than thermocouples. Therefore, VTDs are well suited for OAT measurement. Their large inherent scale factor of 10°C overpowers parasitic thermocouples which exist in the interconnect wiring so leadwires between instrument and solid state temperature sensors require no special treatment.

BEWARE THE LURKING GROUND LOOP

Solid state temperature transducers can suffer the same installation induced inaccuracies as the single wire RTD transducer mentioned earlier. I design all VTD sensors to bring a pair of wires all the way from VTD to indicator. Any time you encounter a single conductor, engine mounted sensor (temperature or pressure), ground the instrument for that sensor to the engine via its own, dedicated ground wire.

INTEGRATED INSTRUMENTATION SYSTEMS

Several folk are offering integrated instrument systems, usually with liquid crystal displays, that present one or more temperatures all at once. Virtually all will use either thermocouples or solid state temperature sensors. Unless instructions for your integrated instrumentation system state differently, you may splice and/or extend sensor leads for companion sensors; technique depends only upon whether they are a thermocouple or solid state sensor.

OIL AND WATER TEMPERATURE PROBES

Most access to water or oil flow in an engine is through tapered, pipe-thread openings. The plumbing department of a well stocked hardware store will yield a brass

plug the proper size to fit your engine's oil or water temp sensor opening. Good thermal contact of your temperature sensor (thermistor, thermocouple or solid state) with the fluid being monitored is essential. The usual technique calls for fabricating a "thermowell." A thermowell is illustrated in Figure 14-15. Actually, about every temperature transducer (or sender) is a form of thermowell. The purposes of a thermowell are (1) to extend into a liquid far enough to measure its temperature in the main fluid flow and (2) get as much thermal isolation as possible from the surrounding environment (crankcase, etc.). The thermowell I like to build is illustrated in Figure 14-15. It is fabricated from a brass plug through which I drill a 1/4" hole. A piece of thin-wall, brass tubing is soldered into the plug. The length of the tubing is that which is judged to place the sensor into free flow of fluid inside the engine. The sensor end is squeezed shut and soldered. The sensor is then cemented or soldered into the bottom of the "well." Silicon sealant around the wire as it exits the plug is a good idea to prevent damaging the wire by pressing against the edge of the hole. Sometimes, a close wound spring is cemented into place about the wire to provide radius-relief and reduce stress on wire when tugged.

CYLINDER HEAD TEMPERATURE MEASUREMENT

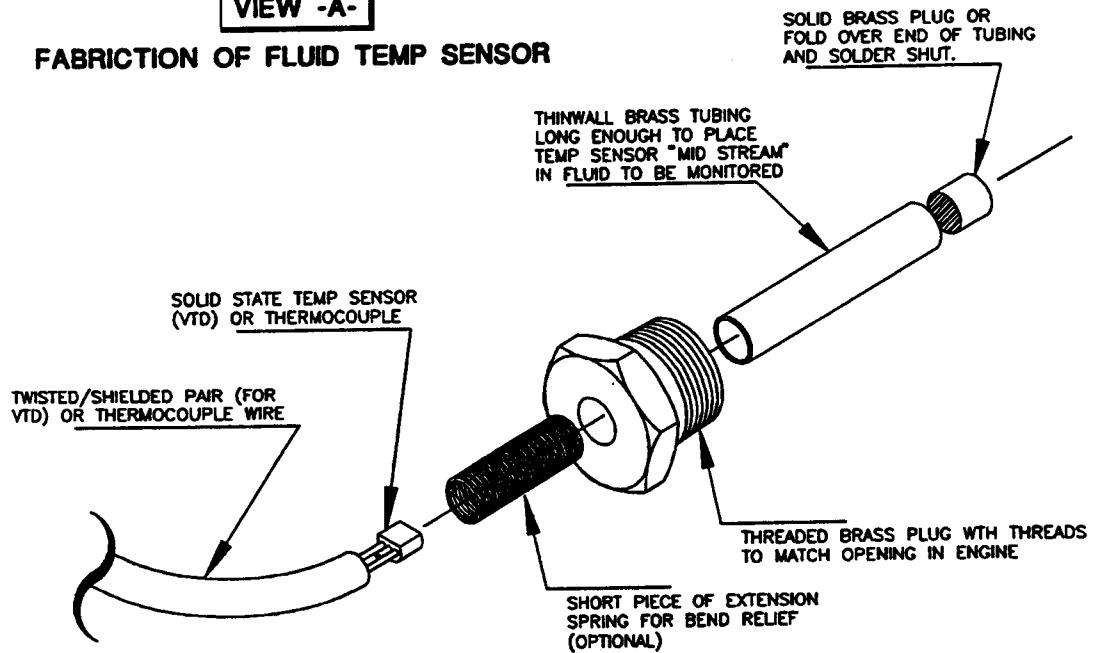
Most modern aircraft engines have thermowells built into the cylinder head. These are generally threaded for an adapter which accepts a spring loaded, bayonet-locking retainer for a thermocouple or RTD probe. I've built CHT probes using salvaged hardware purchased from an engine rebuild shop. What you need are the threaded adapter, retaining ring and the spring which is used to keep the sensor pressed against the bottom of the hole.

You can use generic hardware to build your own CHT thermocouples. Find a threaded plug that fits the thermowell on the engine. Drill through the center and chamfer the edges for wire protection. Find a stainless steel compression spring for use under the plug to hold your fabricated thermocouple against the bottom of the thermowell. Even if your CHT instrument displays one cylinder only, consider techniques outlined earlier to build a selector switch to display any desired cylinder on a single instrument.

My favorite CHT sensor is the spark plug gasket type thermocouple. Mechanics don't like these things because they break easy. I like them because they are

VIEW -A-

FABRICATION OF FLUID TEMP SENSOR



VIEW -B-

CHT THERMOCOUPLE FABRICATION

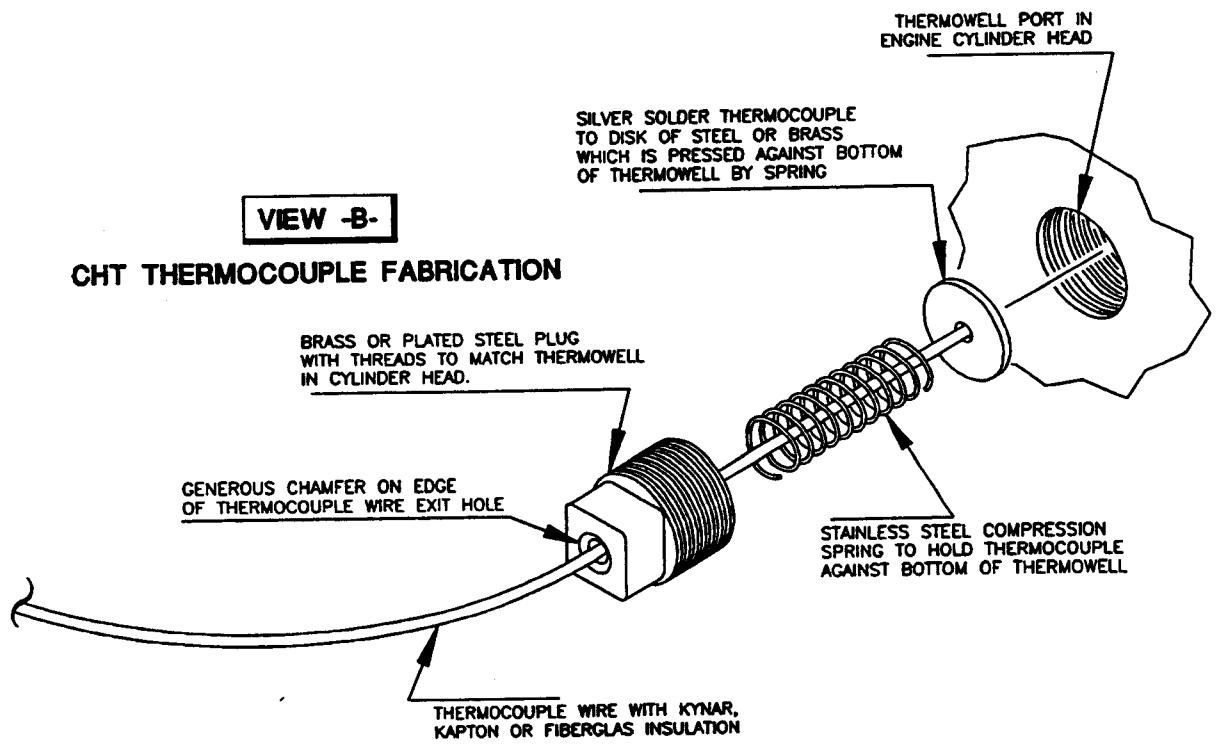


Figure 14-15. "Thermowells" for Temperature Sensing.

inexpensive and easy to repair! A number of manufacturers sell spark plug gasket probes for \$12-\$20 each. It's probably not worth the trouble to build from scratch. Recall at the beginning of this chapter I mentioned changes to materials from thermal stress? Well, copper work-hardens if you repeatedly stress it. Take a piece of copper wire and start bending it back and forth. You can sense when the worked part of the wire is getting hard, starts to crack and finally breaks in two.

Well, copper gaskets under a spark plug harden from internal stresses caused by temperature cycles. It's standard practice to put new gaskets under the plugs when removing them for cleaning or replacement. When your CHT thermocouple(s) replaces one or more plug gaskets, inexpensive replacement with each plug change is not an option. Use a propane torch to heat the washer portion of a copper CHT sensor to dull red heat and allow it to slowly cool. This single excursion to so elevated a temperature will soften the copper and make it suitable for sealing the spark plug under which it sets.

If the thermocouple wire breaks off a spark plug CHT sensor, you can repair it yourself by opening the copper wrap around the thermocouple. Fabricate a new thermocouple on the end of the old wire as previously described and wrap it back up in the old fitting. Sometimes the tab breaks off the washer. In this case, I use silver solder to tack the old (or newly fabricated) thermocouple back onto the end of the old stub. Yeah, I know, it's going to break off again. Most plug-gasket, CHT thermocouples get broken when plugs are being removed. Tie the thermocouple wire against the side of the plug for vibration support and it will last until next time you pull the plugs. If you do happen to break it during the next maintenance cycle, just think: with a little practice, you can be very quick at repairing it! I personally prefer inexpensive, easily repaired components over expensive and/or non-repairable parts.

EXHAUST GAS TEMPERATURE MEASUREMENT

Getting into an exhaust stack is a little tougher. Needless-to-say, the inside of your exhaust stack is the nastiest environment on the airplane! I've built some EGT probes but I find that they are not expensive to purchase.

Alcor (and competitors) build EGT probes for tractors and other industrial engines with type K thermocouple wire. An EGT probe needs to be fabricated from stainless steel for both thermowell and mounting clamp; temperatures are high and the gases corrosive. The "tractor" parts are identical in performance to the "aircraft" parts. Feel free to use purchased EGT thermocouples with another instrument of your choosing as long as it's designed to work with type K wire. Actually, the wire type and reference junction configuration are not terribly critical for EGT. First, an EGT gage is not calibrated for actual degrees, just degrees per some division of the scale; usually 25°/Division. Offset errors which may exist because of poor or no reference junction don't matter. An EGT gage is used to set mixture so many degrees rich or lean of peak. I suspect that most EGT gages have no, or at best, very crude reference junction compensation.

Very few of you will ever find it necessary or attractive to build temperature measurement instrumentation from scratch. However, I hope that what you have seen and read in this chapter has convinced you that you don't have to be a rocket scientist to deal effectively with installation, troubleshooting and repairing a temperature indication system on your airplane. Further, I hope that I have convinced you that when in doubt about the operating temperature of system components, you'll take the time and trouble to make a measurement to find out for sure.

At the beginning of this chapter I asked a question about temperature versus compression of gases in a cylinder. It does happen. This is the basis for operation of a diesel engine. Air is compressed so hard as to raise its temperature well above the ignition point of diesel fuel. When the fuel is injected into the cylinder, immediate ignition occurs. If gasoline is improperly brewed for the compression experienced prior to complete combustion, spontaneous combustion or detonation occurs. A diesel is designed to run under "detonation" while a gasoline engine will be destroyed by it. Temperature has more influence on the physics of flight and flight systems than any other phenomena. It will serve you well to become familiar and comfortable with its measurement and interpretation of readings.

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Pressure Measurement

This chapter is reserved for future work on pressure measurement.

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Electromagnetic Compatibility

How's that for a mouthful? The guys at Raytheon and Boeing call it "EMC" for short. Originally the chapter title made reference to "noise" but the influences we're going to discuss run much further afield; we'll talk about some interference problems that some people would not classify as "noise." I've been putting this chapter off for some time even though questions about noise and other compatibility problems have been plentiful. My reluctance was rooted in uncertainty about how to approach the subject. For some manufacturers, noise control in electrical systems and avionics is a whole separate department employing dozens of engineers. Of course, their systems integration task may be much larger than ours. None-the-less, noise and interference control are nebulous topics compared with Ohm's law or voltage regulation! So, after ten years and much discussion with many of you over the phone, I'll tackle the task.

What It Is . . .

For our purposes, electromagnetic incompatibility is any phenomenon which degrades a system's accuracy or ability to measure, display or communicate. For example: a common noise complaint is that an alternator seems to cause a loran receiver to lose lock on the transmitting chain. In this instance, the victim receiver is degraded by some energy (other than DC power) from an antagonist alternator. In another example, you might open the squelch on a communications receiver and suffer a cacophony of hiss sprinkled with crackles from the ignition system. All of this may go away when someone transmits on the monitored frequency and the voice is clearly heard. Here is a case where noise is present but its amplitude is small compared to the desired signal. Except in a simple system, it is impossible to create a noise-free environment. Therefore, discussions on noise must balance our ability to tolerate noise with our ability to limit noise. In engineering parlance, the trade-off is often expressed numerically as a "signal-to-noise ratio." For our purposes, we're not so concerned about putting numbers on noise levels; we're more likely to express our perceptions with terms like, "I can live with it" or "Good grief! That's terrible!"

When some device exhibits sensitivity to another device the antagonistic phenomenon may not be something we'd necessarily refer to as "noise." A good example comes to mind: I recently had discussions with a builder about his autopilot. It seems that every time he spoke on his VHF comm transmitter the autopilot tried to do aileron rolls! The issue was an electromagnetic compatibility problem due to poor design of an autopilot servo. A few years ago, a reader called to describe how his engine gages all wiggled when he cycled the landing light or turned the alternator on and off. This problem was traced to an improper grounding technique which induced errors into each instrument depending on the alternator's load. The problem showed up in a canard-pusher with a very long, undersized ground lead combined with engine instruments "grounded" to the battery at the front of the fuselage.

Most interference problems experienced by both amateur and professional airplane builders are INDUCED by poor systems integration techniques . . . how the equipment is installed. However, there are cases (like the aerobatic autopilot) where the design of an accessory may make it vulnerable to outside interference in otherwise perfectly ordinary situations. There's an old adage that asks, "If you haven't got time to do it right the first time, where are you going to find the time to do it over?" Of course, to "do it right the first time" presupposes that the designer/builder knows what the right way is. In both the experimental and certified worlds, compatibility problems don't show up until operation of an installed system AFTER it's built. Some interference scenarios may be mitigated by normal variability in operation, components, assembly technique and time in service. In the latter case, factories deliver product with a potential for problems that may not show up for years!

Readers of these words will likely fall into one of three categories: (1) still planning your installation and in a position to "do it right the first time," (2) you're already flying and have no problems that you are aware of (or willing to fix) or (3) some piece of equipment is beating up on another piece of equipment in some manner that cannot be tolerated. If you're in the first group, consider

what you read here as prophylactic advice for reducing your chances of future problems . . . if you're a member of the third, you will find advice for analysis of the problem and techniques for reducing if not eliminating the effects. A majority of builders occupy the second category, but some of those airplanes might be more pleasant to fly and perhaps perform better if a tolerance for "nuisance" levels of interference was not quite so high.

Irrespective of your situation, what follows is not an "eye of newt and toe of frog" potion for warding off evil spirits. Every compatibility problem has causes and solutions based on the physics of the matter. Design rules I'm going to suggest have evolved over years of collective experience within the aircraft industry.

The Nature of Electrical "Noise" . . .

Noise is the electronic version of environmental pollution. It comes in lots of forms, has many ways to propagate, and affects victims in different ways. And like environmental pollution, some level of most antagonistic phenomenon is considered "safe", or in our case studies, "acceptable." Any periodic electrical event that includes rapidly changing levels of voltage or current is going to generate a "noise." The key word here is "rapid." In the non-aviation world we can identify a number of common noise sources. Can you recall driving under a high tension power line and hearing a raucous buzz in the radio for the short time you were traversing the ground beneath the lines? If a high-tension line's insulators are in perfect condition, there is no leakage of power and no noise. If an insulator becomes damaged or filmed with dust and/or pollution, little streamers of electrical conduction may form around it, each one behaving much like a sub-miniature electrical storm. Mini-strokes of lightning form up and die 120 times per second in synchronization with the AC voltage waveform. Unlike the smooth transitions of the current in the wires, these little sparks are erratic. In addition to their fundamental periodic rate of 120 Hz, their erratic nature causes new laws of physics to apply. The most important law says that when a voltage or current waveform departs from a smooth, mathematically defined, sinusoidal waveform, harmonic energy is generated which may extend many decades higher in the electromagnetic spectrum. If we had a receiver capable of tuning in to as low as 120 Hz and we stood under the offending power line, we would detect the strongest components of the noise at 120 Hz. Tuning further up the spectrum we would find prominent signals at 240 Hz, 360 Hz, and still more harmonics until we were tuned into the AM broadcast band.

If we tune in a radio station at 1200 KHz, the 10,000th harmonic of the 120 Hz noise would set right on top of the station's center frequency. The total bandwidth assigned to a single AM radio broadcast signal is about 15 KHz. This means that with 120Hz spacing of harmonic energy packets, over 100 separate little raspy noises will blanket the RF spectrum occupied by an AM radio station! Indeed if we sat under a noisy power line and tuned over the entire broadcast band I dare say every frequency would be awash with the same noise. If we changed to FM broadcast a distinct difference would be noted. First, power line noise is amplitude modulated: FM receivers are rather immune to AM noise. Further, the energy in each successive harmonic of the original noise gets weaker as the harmonic multiplier goes up. Harmonic multipliers on the order of 10,000 are required for 120 Hz noise to be heard on the AM broadcast band. A multiplier greater than 800,000 is needed to make the pesky varmint audible at 100 MHz, and it will be a much weaker signal at this point in the spectrum. This illustrates the basic physics which raises the quality of FM broadcast transmissions. In addition to the wider bandwidth occupied by an FM signal (better audio bandwidth), the FM receiver is inherently resistant to AM noise. Further, due to the high operating frequencies, AM noise from common sources is much weaker.

So far, we've discussed noise forms which occur on or near the frequency occupied by a radio signal of interest. Interference in other forms may invade avionics components through other routes. Noises may propagate around the DC power distribution system. One very common antagonist is the ship's alternator: a 3-phase AC device having an array of diodes at the rear which converts AC into DC for purposes of powering the bus. Ideally, we'd like to build a power distribution system which has zero noise on the bus. If our source of electrical power is a battery and we have no alternator or strobe lights, we'll have as close to a zero-noise system as we can get.

Except for the disadvantage of having to replace or recharge them, batteries are probably the most "neighborly" of electrical system components. Batteries generate no noise. When you rectify AC into DC, the output from a diode array is anything but smooth, battery quality, DC power. Figure 16-1 shows some schematics common to the wall-plug power supplies we've encountered as battery eliminators for radios, recorders, video games, computers, etc. These devices contain a transformer which steps wall-socket voltages down to a neighborhood of 3 to 24 volts, depending on the device to be powered. The circuit in View -A- produces "full wave" rectification of the AC power. I've illustrated the

time versus voltage waveform of the unfiltered, rectified AC voltage. As you can see, it's pretty lumpy. However, a light bulb would illuminate and operate normally because its output qualities (light and heat) have no way to express the "roughness" or "noise" in the energy that powers it. However, if instead of light bulbs, you tried to power a pocket radio or tape recorder, you'd be lucky to hear any desired signals through an overpowering "hum."

Obviously, the wall-plug power supply must contain something besides a transformer and rectifier In most cases the extra component is a

Capacitor, the Basic Filter

Capacitors have been around since the very earliest experiments in electrical phenomena. In fact, the Leyden jar, which was discovered to have electrical storage capabilities, is probably the earliest example of a capacitor. The archaic term for capacitor is "condenser", a word widely used in the mechanic's vernacular. The "condenser" connected across the points of a magneto or automotive ignition distributor is in fact a capacitor not unlike those used in millions of electronic devices.

The capacitor is an electronic component having two "plates" consisting of many square inches of conductive foil, rolled up like a jelly-roll with an appropriate insulating medium in between. The schematic symbol for a capacitor suggests this construction. Seen in Figure 16-1, View -B-, the device is depicted as two "plates" or conductors with nothing in the middle. Quite often, one of the plates is curved. For polarity sensitive electrolytic capacitors, this will represent the negative (-) terminal.

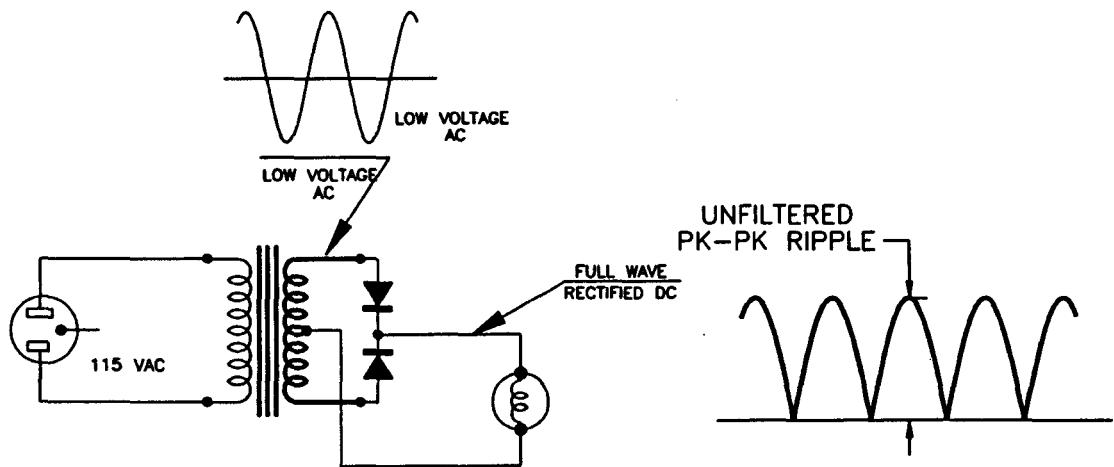
Capacitors can store electrical energy. We touched on this capability during strobe light discussions in Chapter 12. Further, many of you have heard of "capacitor-discharge" ignition systems. In addition to their service as energy storage devices, they also contribute strongly in noise filters. If you connect a capacitor across a battery, electrons will rush out onto the negative plate with every intention of jumping across the insulation to the positive plate. Insulators (very poor conductors) inhibit electron migration, therefore excess electrons pile up in the insulation on the surface of the negative plate. A law of physics says, "current flow in every part of a series circuit is the same." It follows that for every electron that left the battery's negative terminal another electron had to enter the positive terminal. If electrons cannot

jump the insulating gap, where did the electrons leaving the capacitor come from? Simple, from the insulation! It is a property of all insulators that when confined between two conductive surfaces, individual molecules of insulation will allow electrons to leave (giving the molecule a net positive charge) or take on an extra electron or two (giving the molecule a negative charge). We're all familiar with the static charge which can accumulate on our bodies when moving across a carpet in dry weather. The charge accumulates because of a difference in affinities for holding or shedding electrons by different insulators. (If you wore shoes soled with materials used to weave carpet, you could not develop a static charge, since both shoes and carpet have the same affinity for electrons).

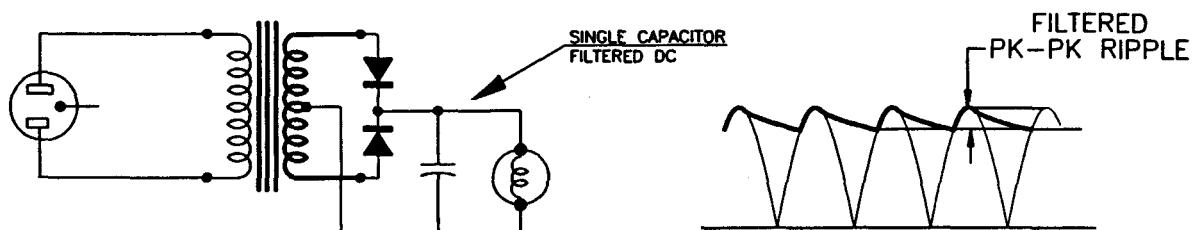
When static charges build between shoe and carpet, your body has become one plate of a capacitor with electrons piling up all over the surface of your skin, using the air as a dielectric storage medium. When your finger approaches another plate (a door handle), the insulating quality of the dielectric (air) is limited. Depending on the voltage you've acquired and at some distance from the knob, insulation breaks down; a miniature lightning stroke occurs!

The ability of any dielectric to store energy is a function of its insulating (or dielectric) material. Air has a very low capability, its dielectric constant is 1.0. Oils and plastics have constants ranging from 4 to 10, meaning they can store 4 to 10 times more energy in same volume. More exotic materials have been developed with dielectric constants of 100 or more. The catalog description or name for a capacitor usually offers a clue as to the type of dielectric used in its construction. Words like paper, Mylar, mica, polystyrene, electrolytic, oil, ceramic, and many others speak to how the capacitor is built, and will give some clue as to its physical size and suitability to the task.

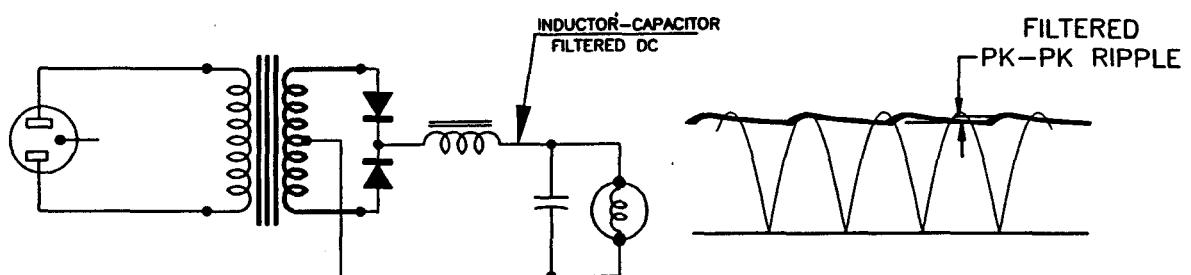
Referring to Figure 16-2, View -A- at time of switch closure, there are zero volts on the capacitor and a large current will flow limited only by internal resistance of the battery and interconnecting wires. As the charge potential approaches battery potential the current falls. After some time, charge on the capacitor equals the battery voltage. The capacitor has become fully charged and charging current falls to zero. It's a capacitor's major role in life to RESIST any changes in voltage across its terminals. So, if we place a suitably sized capacitor across the terminals of our rectifier as shown in Figure 16-1, View -B-, the capacitor charges during the peak .awoff



VIEW -A- UNFILTERED DC POWER SUPPLY

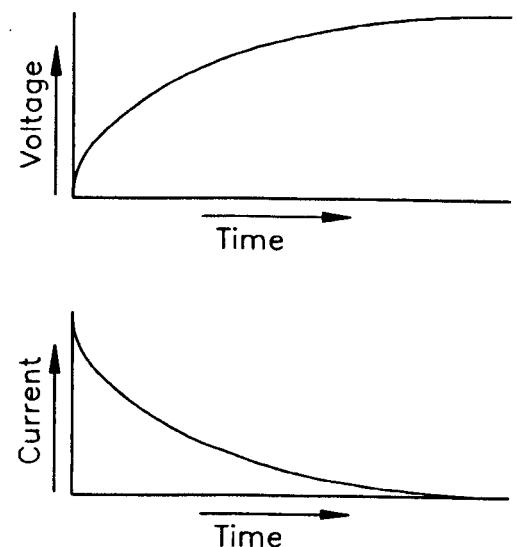
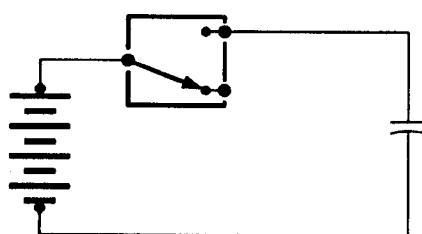


VIEW -B- SINGLE FILTER CAPACITOR

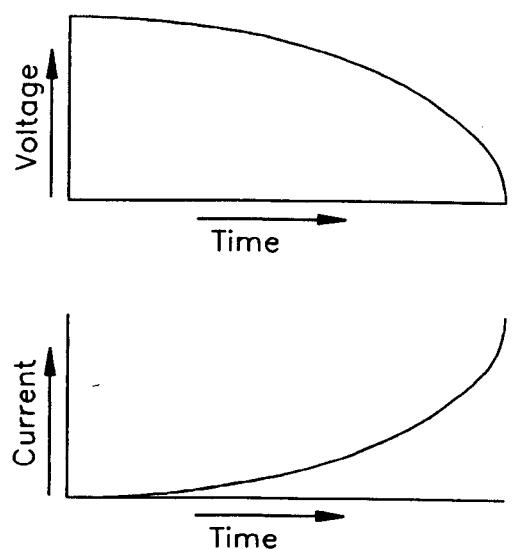
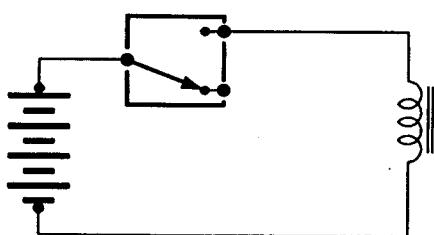


VIEW -C- CAPACITOR/INDUCTOR FILTER

Figure 16-1. Evolution of a Noise Filter.



VIEW -A- CAPACITOR DYNAMICS



VIEW -B- INDUCTOR DYNAMICS

Figure 16-2. Time Domain Characteristics of Capacitors and Inductors.

waveform cycles and provides a source of energy to "fill in" the valleys between peaks. The voltage excursions experienced by the load are now much less . . . we have "filtered" some of the "noise" from the rectifier's output energy.

INDUCTORS . . . Make Filters Work Better Yet

Unlike the capacitor whose major working component is an insulator, the inductor's most prominent feature is a conductor . . . a length of wire wound into a coil. Back in Chapter 7, we discussed magnetic fields which exist about any conductor carrying a flow of electrons. In that case, the magnetic field was used to do WORK . . . to drive a pointer upscale on an indicator. In the case of noise filters, we'll take advantage of the inductor's ability to store energy in its magnetic field.

In Figure 16-2, View -B- shows a series circuit consisting of an inductor (a coil of wire with a core of anything from air to very specialized magnetic materials), a series switch and a battery. The instant that the switch is closed, electrons begin to flow throughout the inductor and a magnetic field begins to build. The increasing magnetic field generates an opposing electromotive force (counter EMF) that tends to oppose the rising current in the inductor. Therefore, in the first few microseconds after the switch is closed, the current through the inductor climbs slowly at first, then increases in rate as the magnetic field becomes established. Compare the two curves in Views -A- and -B-. In the case for the capacitor series circuit, current is initially high and the rate of change (slope of line) for voltage across the capacitor is initially steep. As the capacitor becomes "charged" the current approaches zero and the rate of change for voltage also approaches zero. For the inductor, the current is initially zero and begins to increase in rate of rise some time after switch closure. The initial voltage impressed across the inductor is maximum at time of switch closure and decreases toward zero as the current in the circuit climbs and finally stabilizes at some value determined by inductance, circuit resistance and applied voltage. The charging curves for capacitors and inductors are exactly the same shape and are mirror images of each other. The characteristics of inductors and capacitors as depicted by their voltage/current curves suggest their ability to help us control noise in electrical and electronic systems.

In Figure 16-1, View -C- I show a capacitor and inductor used in combination along with the relative effects upon ripple voltage being delivered to the load. Note that

the resulting ripple voltage is still lower than that depicted in View -B-.

A physical analogy to the capacitor-inductor filter may be realized as follows: Suppose you have an innertube floating on a pond and you are able to move it by means of a long pole tied to the inner tube. Your task is to push and pull on the pole such that the innertube moves back and forth, say 2 feet peak-to-peak on the surface of the water once per second. Now, suppose a kid gets on board the innertube for a ride: the forces required to achieve the 2-foot shake will obviously go up. If you are force-limited, then for the same amount of effort, the innertube excursions will become damped as a result of having added mass to the equation. Capacitors are analogous to the innertube rider's mass.

Suppose the wooden pole is replaced with one made of rubber. Now what happens? For a 2-foot peak-to-peak excursion of your hand, the motion at the innertube will hardly give the kid a very exciting ride. Inductors are analogous to the pole's stretch. Added mass and loss of rigidity have sharply diminished your ability to displace the innertube. Suppose I said, "slow it down . . . you can take ten seconds to make the 2-foot, peak-to-peak requirement." Hmmmm . . . that just might be possible in spite of the changes . . . for any given set of filtering conditions, lowering the frequency of the wiggle increases its chances of getting past any given filter. The opposite is also true, "Now move the innertube over the 2-foot interval 10 times per second." Even if your end of the pole could be moved over that distance in that period of time, I dare say motions at the other end would hardly be noticed. As the frequency of interest goes up any combination of filter components become more effective.

Filters made up from combinations of capacitors and inductor-capacitor combinations attenuate the electrical antagonists ability to "wiggle" its victim. In the case for both inductors and capacitors, the faster the rise time (slope of the wiggle waveform) the more effective the attenuation of any given filter will become. This is why small filter components can strip out the effects of VHF radio frequency interference (100 MHz = very fast wiggles) and have little or no effect on audio signals (1 KHZ . . . a whole lot slower). Larger filter components can attenuate alternator whine (1 KHz) and have little effect on the 14 volt DC power which carries the noise into your audio system.

Ferrite Torroids and Beads are often suggested potential cures for noise problems. As a general rule, they

work only when the propagation path in question is CONDUCTED, only if the interfering signal is in the tens of megaHertz or higher and then only if the circuitry downstream of the ferrite is of sufficiently low impedance at the interfering frequency to let the ferrite do its job. The ferrite cores put around a wire are simply a single turn inductor with a higher inductance than if the cores were not present. Ferrite cores decrease rigidity in the conducting path, but we still need some downstream mass. Shunt capacitors are the first components to consider in any noise filtering problem with inductors to be added when still more attenuation is needed. I've found very few instances where adding ferrite cores to a wire or wire bundle made a problem go away.

Sizing filter components is a function of how much current flows in the path, strength of the interfering signal and its lowest frequency. Ninety percent of the amateur builder's noise problems will involve alternator noise, and most of those cases will be fixed by proper grounding or wire routing techniques. The remaining cases will benefit from filter assemblies and/or filter components that are readily available for automotive audio systems. For the more complicated cases, filter components will have to be sized to the task and fabricated from parts purchased from electronics suppliers. Let's talk either by e-mail or phone and we'll help you size both the task and the cure.

On the spectrum chart in Chapter 13, "Antennas and Feedlines", I show the spectral position of the common radio aids. The lowest frequency system is Loran, followed by ADF, marker beacons, VHF comm and omni nav, topped off by glideslope. GPS operates up in the multi-Gigahertz range; it would be furthest removed in spectrum from most sources of noise.

We might conclude that Loran is the most susceptible to noise. If operating frequency were the only consideration, this would be true. The manner in which a received signal carries intelligence has a lot to do with noise immunity, irrespective of operating frequency. For example, if FM transmissions were permitted on the same frequencies as AM broadcast, the FM receiver would show little irritation by the same noise source that would make an AM receiver useless. Loran uses mathematically encoded signals which are digitally processed. Digital filters easily sort the total received spectrum to separate out orderly data from noise which is random in nature. GPS is also digitally encoded. It has the further advantage of being many more decades removed in frequency from most noise sources.

Whoa! If Loran does such a whippy job of working through the noise, why is Loran degradation the biggest single noise problem experienced by homebuilders? I'll have to seek refuge in my earlier statements about signal to noise ratios. Few homebuilders are installing both Loran and ADF receivers so it's difficult to find real life examples of relative differences. If both receivers could be compared side by side in the same noise environment, we could demonstrate a Loran installation that performs well right next to an ADF rendered useless by the same noise. I don't mean to imply that the Loran would be working at maximum performance . . . signal to noise ratio indications on the Loran may show the presence of noise. The major difference is performance is due to digital signal processing which may do an entirely adequate job in spite of whatever noise exists.

Antagonists and Their Propagation Paths

Alternators are another common noise source. They are weak emitters of RF energy (harmonics of the AC voltage frequency in the stator windings created by the rectifier diodes) and don't generally become a nuisance by radiation of noise. However, as we'll discuss later, there's a strong AUDIO rate component of noise that rides on the DC output voltage that's nearly impossible to filter directly at the output. Victims pick this kind of noise up by conduction through the power input leads -or- by ground loops, a special conducted interference mode. The list goes on and we'll go over the major players in detail later on. What you need to understand at the outset is that there are no hard and fast rules about who does what to whom or how it's done. There are common scenarios but they don't account for every set of similar symptoms.

Chasing down an interference problem is like the game of Clue. You get to ask a lot of questions and use the answers to formulate the next question. We'll develop techniques and recommendations for initial installation that will certainly reduce the likelihood of interference problems but there are still no guarantees. Failure to comply with all recommendations herein does not necessarily condemn the transgressor to suffer the effects of the noise in question. For a noise to make a nuisance of itself, it must enjoy the right combination of victim, propagation mode and an operating scenario where the observer judges the noise "unacceptable."

It's impossible to predict how all of the variables will add up. I recall renting a locally based training airplane for a cross-country trip. Nobody had ever complained about magneto noise in the radios . . . most renter-pilots

talked to facilities close by and kept the squelch controls clamped down so tight that the noise wasn't annoying. Over western Texas at 8,500 feet, Flightwatch stations 50 miles away were difficult to hear through the noise. Another stress on your decisionmaking process will come in the form of free advice. Some readers have confessed to skepticism about my recommendations, "my hangar mate sez his airplane has been wired the 'other' way and it works just fine," and it probably does.

The number of potential noise sources in an airplane may surprise you. Just about everyone is familiar with the un-neighborly qualities of magnetos and alternators. But did you know that fuel tank senders have been known to emit radio noise? How about rotating beacons? Aileron and elevator hinges? Admittedly, I'm digging pretty deep into the list - these components are rarely a problem.

Sometimes, a source of interference isn't even on board the airplane enduring the problem. I recall an instance years ago where a pilot complained of poor localizer receiver performance that got worse as he approached the decision point in his approach. The problem turned out to be a spurious output from a commercial communications repeater about 1/4 mile from the runway centerline and a mile or so out. The ground based source wasn't a consideration until he discovered that approaches to other airports didn't have the problem.

FM broadcast and ground based radar stations have been known to victimize poorly designed or installed airborne equipment. So, if any broad brush statement can be made about working a noise or interference problem, it is, "Proceed with an open mind. No combination of source or propagation mode should be discounted until analysis dictates it." If the preceding gives rise to feelings of trepidation please understand that dominant noise sources and their interference propagation modes are well known. Most problems are avoided by good design and fabrication practices. In thirty-five years of hammering on airplanes, I've been involved in only a few cases where a noise problem persisted to the "hair-pulling" stage. Ultimately, all noise problems are solvable.

In summary, the chorus antagonists may include alternators, strobe light systems, motors, radio transmitters, oscillators within radio receivers, hand held transceivers, and of course, ignition systems. Less common noise sources include poor connections across moving joints such as hinges depended upon for grounding a rudder mounted navigation light. And of course, large relays and contactors have the ability to dump out little, high

voltage bursts of energy when current through the coil is dropped to de-energize the contactor. Okay, okay . . . call 'em "spikes" if you want to. I dislike the term because common perceptions consider a "spike" to be synonymous with "radio killer." Never met a spike I couldn't kill.

Potential Victims

Navigation receivers, communications receivers, audio systems, instrumentation systems, storm scopes, electronic fuel injection systems, electronic ignition systems are all potential victims. Without a modicum of protection from relatively minor excursions of bus voltage, some solid state devices can be damaged. Autopilots can get fussy when other appliances are turned on. Fortunately, protection and packaging techniques are tried and proven. I've written reams of articles and e-mail explaining performance specifications like DO-160 and Mil-Std-704 which trade off ability to limit responses to interference with ability to limit interference at the source. There's simply no excuse for a piece of modern aircraft equipment to be threatened with damage by anything the airplane can throw at it. All that leaves us is an occasional interference problem to identify, analyze and fix.

Propagation Modes

Just because potential victims are robust doesn't mean an antagonist can't be a nuisance! The noises emitted by motors, alternators and other devices may not represent a threat of damage but they can certainly exert some influence ranging from mildly annoying to outright unacceptable. The ways in which a tormentor's output gets around the airplane include:

- (1) Radiation through the air to be picked up on interconnecting cables, antennas, etc.
- (2) Conduction through power and/or control wiring. Special cases of conducted propagation include . . .
 - (a) Magnetic coupling between adjacent, parallel wires . . . and . . .
 - (b) Electrostatic coupling between adjacent, parallel wires and . . .
 - (c) Coupling through shared pathways (ground loops).

I think it's interesting that interference problems can cut both ways . . . an ignition system can render a commu-

nlications transceiver useless for listening while the transmitter in the same transceiver can scramble the brains of a poorly shielded electronic ignition system.

Problem Identification

For most pilots, identifying an interference problem is pretty easy. That whine in the headset or a nav receiver dropping a flag is ample notification that a problem exists. Some pieces of equipment, like Loran and GPS receivers have front panel displays that show signal to noise ratio or some other figure of merit with respect to signals. It's fortunate that most of the avionics we buy have been tested for their ability to withstand a certain amount of interference while making sure they don't become antagonists as well.

Common Causes and Their Cures

Alternators: It's a toss-up as to whether the alternator or magnetos are the worst antagonists but we'll take up alternators first. The alternator's noise spectrum covers the frequency ranges from audio (peak-to-peak ripple of rectified AC) with harmonics that extend to the low megaHertz range. The higher frequency components of alternator noise are generally beaten down to size with a high quality electrolytic or plastic and film capacitor. Many automotive conversions already feature a good quality capacitor connected from the alternator's b-lead to case ground. The higher frequency emissions from an alternator are a threat to ADF and Loran receivers. There's a small possibility that radio frequency interference from alternators can be heard on AM broadcast and Citizens Band radios.

Alternator interference is characterized by its unique, almost musical whine that changes pitch in response to changes in engine RPM. First you want to confirm that it is indeed alternator noise by turning off the alternator field (switch or pull breaker). If the noise goes away and the alternator is the only thing you shut off, you've pretty well confirmed it. You can tell if it's radiated noise coming in through the antenna if (1) the noise goes away when the antenna is unhooked or (2) the noise is adjustable by the radio's volume control. In the case of Loran receivers, you can try running the receiver on a separate, 12-volt lantern battery and see if signal to noise improves when the radio is powered by a "clean" source. If the noise is still there, it's getting in by way of the antenna as opposed to power leads.

Effective RF filtering for an alternator is often possible with a simple capacitor installation. Plastic and film

capacitors on the order of 4-10 microFarads may be tried. Also, computer grade electrolytics on the order of 1,000 to 20,000 microFarads have cured some problems. In either case, the capacitor needs to be mounted right on the rear of the alternator and connected with the shortest practical leads from b-terminal and case ground.

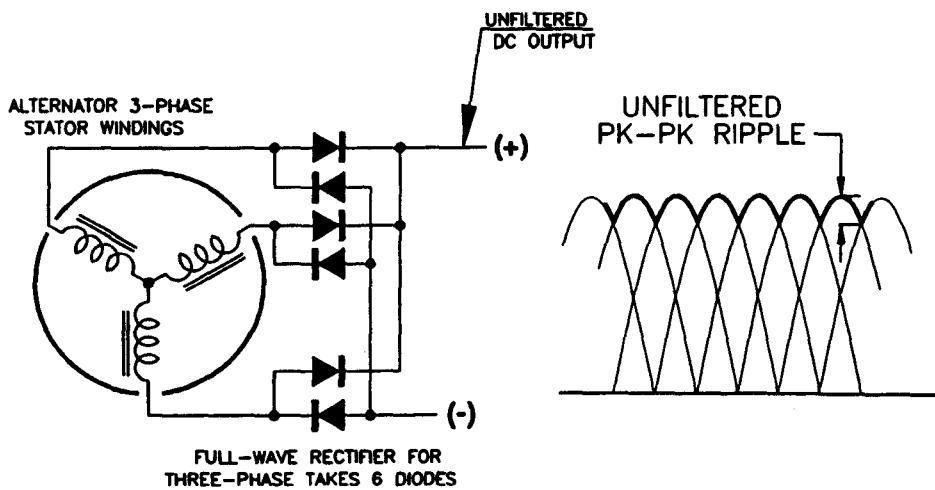
Caution

Electrolytic capacitors are polarity sensitive. They will feature (+) and/or (-) symbols or have a red dot of paint on the (+) terminal. Hooking these fellers up backwards is very messy when the case splits open and the gooey stuff comes out!

If a simple capacitor doesn't get it, some amount of series inductance is called for too. In this case, the inductor has to be rated for the alternator's output current which makes the parts get BIG in a hurry. It's worth your trouble to avoid having to resort to series inductance in the alternator b-lead . . . reserve it as a last resort.

Audio frequency interference from an alternator is quite another matter. EVERY alternator has some amount of audio rate ripple voltage on it . . . it's a pesky law-of-physics thing. An alternator is a 3-phase device where separate windings 120 electrical degrees apart are feeding energy into the system. Figure 16-3 shows how the unfiltered output from a 3 phase rectifier has only about 5% peak-to-peak ripple as opposed to 100% ripple from the single phase rectifier in Figure 16-2, View -A-. By using a 3-phase architecture, the alternator's output is already much smoother than the voltage delivered by a single phase rectifier.

If you put an oscilloscope on the output terminal of an alternator, its noise waveform will have only a very basic resemblance to the waveform in Figure 16-3. Modern automotive alternators are very compact and quite capable for their weight and size. Design compromises to achieve this performance cause the waveforms to be distorted and loaded with little bits of "trash" . . . short duration, fast moving transitions on the waveform that have HARMONIC content. Remember our discussion on harmonically related power line noise? Alternators can have it too. Our friend the capacitor can help here. If the noise from an alternator shows up where it shouldn't, a high quality capacitor from the B-terminal to ground will "smooth" those little spikes and reduce their ability to annoy.



THREE PHASE AC OUTPUTS OVERLAP EACH OTHER BY 1/3 THEIR PERIODS. THE RESULTING FULL WAVE RECTIFICATION HAS A VERY LOW PK-PK RIPPLE AMPLITUDE WITHOUT FILTERING. COMPARE THIS WITH THE UNFILTERED OUTPUT IN FIGURE 16-1.

Figure 16-3. Alternator Rectification and Ripple.

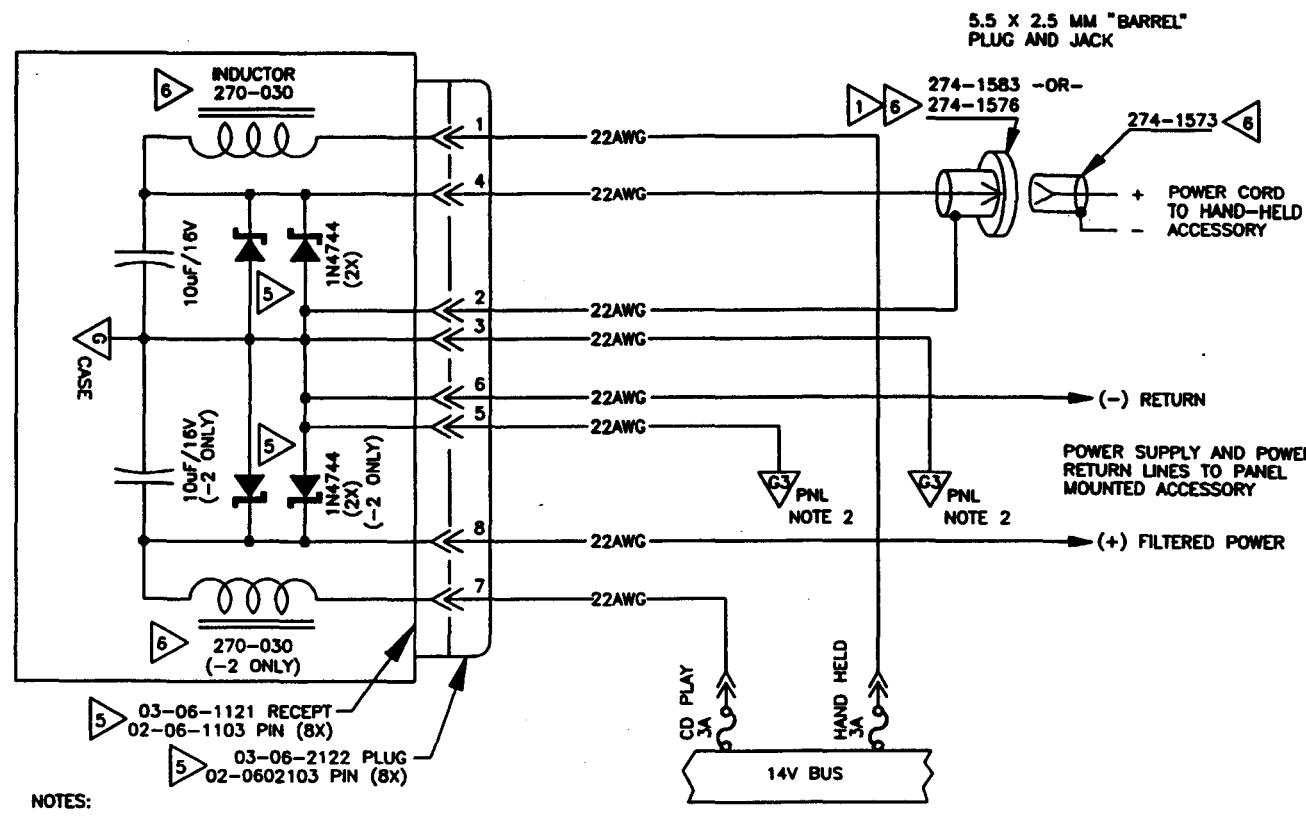
Here's where our friends Mil-Std-704 and DO-160 come to the rescue. Mil-Std-704 sez that audio rate ripple on a "properly designed bus" will not exceed 1.5 volts peak-to-peak on a 14-volt system and for the most part, a stock alternator will comply with this requirement. On the other hand, DO-160 sez that we should design airplane goodies so that noises up to and including 1.5 volts peak-to-peak are not a problem. So much for specs. If you've installed a victim that wasn't designed with DO-160 in mind, there's still hope.

Getting audio rate noises filtered off the power feed from bus to a victim appliance isn't too big a deal. Fortunately, the current requirements for most panel mounted gizmos is pretty small. Radio Shack sells a kit consisting of an inductor and capacitor that are quite effective in cleaning up the noises for devices drawing up to an ampere or so. The general rule of thumb for a single capacitor, single inductor filter is that the inductor faces the noise source and the capacitor is across the power supply leads for the victim.

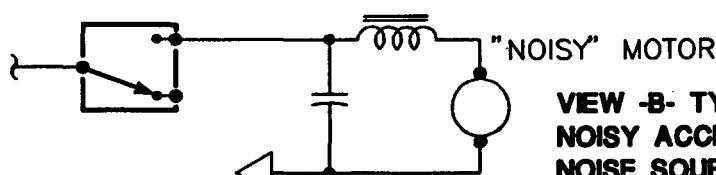
Alternator noise has a variety of common pathways into unwelcome territory. A few years ago we bought a Voyager minivan while at OSH . . . ya gotta be careful when you visit Oshkosh, there's a certain air about the event that makes us vulnerable to quick and sometimes

out-of-character decisions. On the way home I noted that the front seat speakers seemed to be putting out a bit of alternator whine . . . even when the radio was off. "Aha," sez I, "must be a ground loop . . . I'll bet the front speakers are on the bottom side of the front-rear fader stack and one side of the speaker is locally grounded at its mounting." Combine this with a grounding of the radio chassis at the console and conditions are right for the speakers to tell us what they "hear" in the way of noise flowing in the car's chassis ground.

I must confess that I didn't really take the problem as a serious issue (Dee's note: HE didn't drive it every day!) until Dee decided to get a CD player and a better sounding radio. Then the noise became more than just a nuisance. One Saturday morning, I got out the multimeter and screwdrivers and resolved to find the ground loop and break it. Turns out the speakers were NOT grounded locally to the car chassis. All grounds for the entertainment system were made at the back of the radio chassis. Hmmmm . . . after some poking around I noted a "fat" wire running across the aft side of the air-conditioning ducts. What's more, the noise could not be heard when the radio was hanging out of the panel on its harness. "Aha!!" sez I again. I finally experienced a condition that I knew was physically possible but I'd never personally run across it. I moved the "fat" wire



VIEW -A- DUAL POWER CONDITIONER USING COMMON ELECTRONICS PARTS FOR TWO "NON-QUALIFIED" ACCESSORIES LIKE HAND-HELD RADIOS OR CD PLAYER.



VIEW -B- TYPICAL FILTER INSTALLATION FOR NOISY ACCESSORY. NOTE THAT INDUCTOR FACES NOISE SOURCE WHILE CAPACITOR IS TOWARD POTENTIAL VICTIMS.

Figure 16-4. Miscellaneous Filter Applications.

up to the top of the duct so that the radio harness .awoff didn't press against it while the radio was installed. The noise went away.

This was a classic case of magnetic coupling between parallel conductors. That "fat" wire was some kind of main feedwire between the dashboard loads and the alternator. The higher the loads in the wire (lights on, a/c fan running), the stronger the magnetic field and the greater the noise. Now, it's important to note that this noise could NOT have been cleaned up with shielded wire. A shielded wire simply prevents the conductor within from acting as one plate of a capacitor . . . a shield over a wire will not prevent magnetic coupling into or out of the wire. I've built tachometers that sense spark plug current and they work just fine on shielded aircraft plug harnesses . . . you can read the magnetic field around a wire right through a shield.

The easiest way to avoid this scenario in airplanes is simple: keep fat wires away from skinny wires. Fat wires tend to be bus feeds, battery leads, alternator b-lead feeds, flap or pump motor feeds, etc. They are, by their very application, conductors of the airplane's worst noises. The skinny wires associated with instruments, radios, intercom systems, and engine gages tend to be the most vulnerable. For years in earlier chapters of this book I've preached the doctrine of "twisted pairs" in routing ground and power wires down the fuselage of a canard-pusher, get that b-lead breaker off the panel, and ground EVERYTHING behind the panel with a single ground bus. All of these things were recommended in the spirit of reducing the possibility of noise problems later on.

I mentioned the ground block . . . described in detail back in Chapter 5. Using a single ground point for everything behind the panel is the best way to avoid ground loop induced noises. Ironically, most ground loop problems present themselves in airplanes that seem to have the most favorable grounding situation . . . all metal ones. It's the assumption that hooking some piece of electrical equipment to the airframe is just as likely to work well irrespective of WHERE on the airframe it is grounded. Problems are most likely in ships with aft mounted batteries grounded locally . . . large, noisy alternator currents flow in the ship's bones on their way from crankcase to battery (-). Delicate circuitry with ground in TWO or more places along that pathway may sense and complain about the voltage difference between those two points.

Microphone and headset jacks are common victims of ground loops. A very few millivolts of noise can be easily detected either in the headphones or impressed upon your outgoing signal while speaking on the radio. In metal airplanes, use insulating washers to prevent the mounting bushings of headset and microphone jacks from making contact with the airframe. All audio system grounds should terminate at the audio system's distribution amplifier . . . usually the intercom system. Then, a single ground wire from the audio system should join all other avionics grounds at the panel equipment ground block.

In summary, alternators have strong noise components in the audio range and cause the most trouble with avionics systems. Audio frequency noise requires a larger filter than for the higher radio frequencies so it's not practical to filter anything but the weaker radio frequency components at the back of an alternator with a high quality capacitor. All other instances of alternator interference are best contained with filters in the DC, power leads to the affected device and careful attention to ground loop avoidance, and magnetic coupling due to proximity of "fat wires" to "skinny wires."

Magneton and Other Ignition Systems: Obviously, a system designed to generate little bolts of lightning inside a cylinder has the potential for creating a lot of noise. Magnetos don't generally make direct connection to other systems, so by-in-large magneto noise tends to find its way around an airplane by radiation. The strongest potential for launching noises into the ether is enjoyed by the spark plug wires. Connecting an oscilloscope to a spark plug wire would allow you to observe a fast rising, high amplitude waveform which occurs repetitively on a spark-by-spark basis: ideal waveforms for harmonic content. When the task is to control radiated emissions from a conductor carrying a noise source, total containment is the technique of choice. Given the close proximity between magnetos and plugs, keeping plug wire noise corralled inside a shielded environment is relatively easy: just ground the shield at both ends. This is a special case where the shield is always grounded at both ends.

Spark plug wires on cars are not shielded . . . why no noise? There is SOME noise but you're right, cars don't put out much radio noise from their ignition systems. In order for the plug wire to be an effective radiator of RF energy, its resistance needs to be pretty low (strands of copper are pretty good conductors). Let's look what

happens to a spark plug wire that's hanging out in the open. From a radio frequency standpoint, that piece of wire could be a fair antenna at some frequency (see Chapter 13). If you excite the wire with a little lightning strike on one end, the wire can resonate at some basic fundamental and at integer harmonics of that fundamental. Given that plug wires on aircraft engines are generally 15 to 20 inches in length, resonances in the VHF spectrum may be anticipated. Indeed, if you looked at the noise spectrum coming off of an unshielded magneto system and given that all the wires are different lengths, you would expect to observe a broad spectrum of noise in the lower to mid VHF frequencies.

Now, let us suppose the copper wires are replaced with a resistance material. The wire's ability to function as an antenna is severely curtailed. From Chapter 13 you'll note that antennas at resonance have high current nodes at some point along their length. If we're trying to develop a current through a resistive material, the material simply warms up. Energy that might have been launched toward your comm antenna is instead converted to heat. Another way of looking at resistance wire is that it lowers the "Q" (quality) of what used to be a resonant and reasonably efficient radiator. Resistance plugs figure in this effect as well. Automotive ignition designers have worked hard at this and modern gasoline ignition systems can be relatively free of radiated noise in spite of their unshielded plug harnesses.

Magnos are such sorry sources of high voltage energy that we are reluctant to waste ANY of it in resistance wiring so the brute-force technique of total containment was adopted and, for the most part, works fairly well.

If you do have ignition noise in a radio, there are some ways to deduce the propagation mode. First, turn off the mags one at a time. Does the noise go away when only one of the mags is turned off? If so, the leakage is occurring in the one system. Disconnect the p-leads from both mags right at the rear of the housings and see if the noise goes away. If so, it's getting out through the p-lead wiring. If not, then the spark plug harnesses are suspect.

Plug harnesses may be electrically tested (continuity between end of center conductor and between ends of shield braid). Unhook individual plug wires and do a continuity check between the spark plug connector shell (attaches to shield) and engine crankcase. If the noise goes away when p-leads are disconnected, check the routing of p-lead wires with respect to wires of the victim system. Does the ignition noise change in intensi-

ty as the receiver's volume control is adjusted? If so, the noise is probably radiated and coming in through the antenna system along with desired signals. If the noise is constant with respect to volume control setting, the interference is probably getting into the system via system interconnect wiring. P-leads of magnetos are routinely shielded but many builders ground the shield at both ends . . . not a big potential problem in all-metal airplanes but we generally have to go out of our way to FIND a ground behind the panel on a composite ship. Quite often, this added ground wire from panel end of p-lead shields CAUSES more noise problems than it fixes. I prefer to ground p-leads on one end only, preferably to the magneto housing (case screw or coaxial wiring connector for the p-leads). Elsewhere in this book and particularly in the power distribution diagrams (Appendix Z) I show use of p-lead shield to PROVIDE a ground for the center GND terminal of the classic key-type magneto switches. This one-end-only grounding philosophy insures that equal-opposite currents flow in the p-lead shields thereby insuring the effectiveness of the shields as noise control measures.

"Grounding" p-lead shields at both ends gives rise to the possibility of ground loop conducted noise and increased levels of radiated noise from an otherwise quiet conductor. Finally, "grounding" p-lead shields at both ends makes them vulnerable to generating a lot of smoke when you attempt to crank an engine with a failed or inadvertently disconnected crankcase-to-airframe ground braid.

Electronic Ignition systems require DC power from the ship's distribution system; there's the added risk of conducting noises into the power system. Fortunately, electronic ignition systems don't require a lot of energy and draw typically 2 amps or less on a 14-volt system. Filtering of the DC power lead as it emerges from the ignition system housing is fairly easy to accomplish. Avoid installing ignition system components on the cabin side of the firewall. A short, flexible braid jumper should complete the ground between crankcase and the forward end of the stud on a firewall ground block (see Chapter 5). This short, low impedance connection should be sufficient to keep the electronic ignition's electronics enclosure firmly "grounded" to the crankcase . . .

Many electronic ignition manufacturers suggest the use of stock automotive ignition wires and automotive plugs. This permits the user to take advantage of noise reduction techniques we've enjoyed in our cars for decades.

The catalog of minor players expands out rapidly from here. Alternator and ignition noises have the distinction of being the biggest gorillas in the forest. Further, they run ALL the time we're in flight. The catalog of antagonists is more varied from here on out. They are less energetic noise sources. Many of them are low duty cycle (flap and gear motors), and a few require special conditions to manifest themselves. So in no special order, let's explore some additional antagonist/propagation/victim combinations aboard airplanes.

DC Motors generally have brushes running on slotted commutators that carry power into windings on the armature. They arc, they spark, and they'd sure like to make better contact with the copper surface of the commutator, but it won't hold still. Most motors on light planes are intermittent duty . . . they run just a few seconds per flight. I fly a number of rental Cessnas that tear up the radio during flap extension. Too small of a nuisance for the owners to mess with. Cabin vent or avionics cooling blowers might be another matter. Standard noise reduction techniques apply here. An inductor/capacitor filter from Radio Shack was described earlier. Try a temporary installation as shown in Figure 16-4. Note the inductor faces the noise source, in this case, the motor. Make sure the motor in question does not exceed the filter's current ratings. Radio Shack and many merchants specializing in automotive audio systems have an arsenal of filters rated for various current levels. All will feature capacitors adequately rated for 14-volt operation. If you have a 28-volt airplane, be sure the filter's capacitors are rated for 30 volts or more.

Strobe Light Systems invariably contain transistorized power supplies designed to change low voltage DC into AC so that it can be rectified back to DC and used to power the zenon flash tubes (see Chapter 12, "Lighting"). This power supply is a potential noise source and may be heard in the headphone on many airplanes as a sweeping, musical note that keeps time with the firing of the strobes. In metal airplanes, the strobe power supply should be grounded to airframe right where it mounts. Of course, I'd avoid mounting it on the avonics shelf with your intercom system! In a composite airplane, run power and ground wires for the strobe system parallel to each other as far as possible before splitting them apart to attach to control switch and panel ground bus. If you're hearing the sweeping audio tone in your radios, try a filter like I described for the motors.

Strobes often radiate a "pop" into the radios . . . especially nav radios where the omni antenna is co-located at

the tip with a strobe light fixture. This interference is noticeable only while listening to the nav receiver's audio output. It generally doesn't affect the accuracy of the navigation receiver so most people don't fiddle with it. If the "pop" is finding its way into your comm radio, it may be that the comm antenna needs to be relocated. It's also possible that the shielded wire provided with most strobe installations is improperly grounded. Ground the shield only at the power supply end. On composite airplanes or metal airplanes with plastic wingtips, the shield is also connected to the strobe lamp housing. If the strobe lamp housing is mounted on a metal surface, leave the shield ground loose at the fixture end.

From here the list of potential antagonist gets pretty lightweight. Almost every device carrying an electrical current, intentional or otherwise, can become a source of interference but they're pretty weak sources. Fortunately, good wire routing and grounding practices can keep most sources from antagonizing another system.

Wiring and Installation Induced Susceptibilities

I got a call from a pilot who has been flying his composite airplane for about ten years and has put up with an interesting idiosyncrasy. Seems that when he transmits on some frequencies, other folk complain about garbled audio. Changing out the radio and other things he's tried will alter the frequencies involved but the problem is still basically there. I spoke with him at length and the following picture emerged. Like ALL composite airplanes, energy radiated from comm antenna is pretty strong IN the cockpit. Composite airplanes have a design challenge in common . . . how to develop a good ground system. This particular airplane had a ground "system" that, for lack of a better term, was pretty elaborate. Lots of branches combined with an attempt to comply with common wisdom of the time, "everything that can be grounded should be grounded to every other thing that can be grounded." This statement paints a mental image of some amazing installations. I've seen airplanes where "ground" wires ran like spider webs throughout the structure without regard to the physics of what the ground wires could be expected to do. Some builders have run little wires out into the wings to attach their aileron hinges to "system ground." Generally speaking, the ONLY possible benefit this type of ground system might offer is to make sure that no static electricity potentials can exist between the various metallic components throughout the structure. Static discharge is ANOTHER topic for another chapter. It is sufficient say here that this type of ground system at BEST creates few

problems but at its worst, can produce some pretty bizarre effects.

Getting back to our builder with the garbled audio: I observed that most microphones these days are electronic clones of the old telephone style carbon microphones of yesteryear. Microphones nowadays tend to have integrated circuits or at least a transistor or two inside. Designed and tested for the padded cockpit, all metal market, these devices are potential victims of strong fields of radio frequency energy. Here's what I think was happening:

A major "clue" in this case was the frequency sensitivity of the problem. This suggests a "resonance" phenomenon of some type. A review of Chapter 13, "Antennas and Feedlines" will remind us that when a conductor "resonates" there are points along its path where very high CURRENTS can prevail. Further, these currents are only loosely related to the transmitted POWER . . . if the impedance (resistance) of the system is quite small, relatively small levels of excitation energy can produce some significant current flows. In this case, our hero was sitting amongst one or more resonant conditions that caused interfering levels of excitation either to the microphone or to the audio input circuitry of the transceiver itself.

The offending resonator is probably part of the victimized system (VHF comm transceiver) - but not necessarily. A high quality resonating component as part of another system could be increasing general levels of energy within the cockpit. Recall that our discussion on antennas talked about passive radiators . . . pieces of an antenna that were not directly wired to the system. None-the-less, these conductors could have a lot of radio frequency current flowing in them and they may exert a strong influence on the patterns of the energy's behavior . . . this is how antennas focus or "beam" energy in a particular direction. In this case, I believe wiring associated with a somewhat spider-webbed ground system was resonating at specific frequencies and giving his audio system fits. We discussed several experiments to see if the cause and/or a cure could be deduced but at the time of this writing, the case is unsolved.

I recently received a pencil sketch from a new reader showing work already done on his canard-pusher. He depicts a "ground" system consisting of copper braid laid out in a sort of ladder pattern with the "uprights" running up both sides of the fuselage and "rungs" soldered between the uprights at various intervals along the fuse-

lage. I can absolutely guarantee this type of ground system is going to be trouble.

Some Notes on Shielded Wire

Shielding a wire with an over-braid or layer of aluminum foil breaks only one of several propagation modes for noise - the electrostatic coupling mode. The lion's share of all noises in an airplane propagate by conduction . . . riding ON the ship's standard wiring from place to place. Most of the remaining noise propagates to antennas and in some cases, exposed wiring . . . shielding adds a modicum of attenuation for radiated susceptibility via wiring. Magnetic coupling between wires is more common and shielding won't break that mode . . . that's why we try to keep "fat" wires (which tend to have strong, noisy currents) separated from the "skinny" ones (which tend to be avionics and instrumentation). Unless the manufacturer's instructions specifically call out shielded wire for the installation of their product, you're safe in leaving the wires unshielded. Only magneto p-leads and wiring between strobe fixtures and their respective power supplies are ALWAYS shielded. Beyond that, it's generally limited to a few wires in the audio and navigation systems per installation instructions.

Really Off-the-Wall Problems . . .

There's a lot of testing that goes on to improve on the probably of compatible operations when multiple systems co-exist on an airplane. We've spoken often of DO-160 and Mil-Std-704 as common benchmarks for compatibility testing.

A new problem surfaced a few months back when it was discovered that the local oscillator in some nav receivers had strong enough 10th and 11th harmonics to interfere with GPS receivers in the same stack. GPS was just a dream when the nav transceivers were built - who would have thought this would be an issue ten years later? Try as we might, we cannot predict all the possibilities.

Rules of Thumb for Cleaner Living Electrically!

General notes for wiring to reduce the possibility of wiring induced compatibility problems.

(1) keep the ground system LINEAR and simple. By linear, I'll suggest that a single conductor, rated for cranking currents, run the length of the fuselage with a maximum of two extensions for under-the-cowl and behind-the-panel grounding.

- (2) Common ground points should be provided for instrument panel hardware and under the cowl hardware. I'm going to relax my suggestions in Chapter 5 that the battery minus lead should run directly to the crankcase. This may be electrically ideal but it does generate another firewall penetration that's a hassle. So, a brass stud through the firewall may be used to carry cranking current grounds through the sheetmetal. Other than this, the grounding path recommendations in Chapter 5 are useful noise control techniques.
- (3) Avionics and audio systems should not share wire bundles with DC power distribution. However, they can and should share common grounds behind the panel. With my favorite circuit protection (fuse blocks) I'd run DC power and control around the left side of the cockpit to accommodate switch panels on the pilot's side and keep audio/avionics wiring more or less amidships. Most avionics/instrument wiring is local to black boxes on the panel . . . except for antenna coaxes and extensions of audio wiring, the stuff tends to be compacted on center to a little left of center on the panel.
- (4) Engine instrumentation is pretty immune from cable conducted interference. However, it could become part of the propagation mode for bringing under-the-cowl noises into close proximity with audio/avionics, so plan separate bundle routing for these wires away from the radios.
- (5) In metal airplanes, antennas get grounded to airframe local to their mounting locations. In composite airplanes, artificial grounds are needed for 1/4 wave antennas while 1/2 wave antennas make their own. In any case, don't add extra ground wires from these antennas to the DC power ground system. The two are entirely separate systems and do not benefit from any form of interconnections.
- (6) Avoid the "bad hair day" look in wire bundles. From a noise reduction standpoint, it's better to keep wires as close together as possible for as much length as possible. Many installations I've observed look like a tree . . . a fat wire bundle "trunk" with lots of fuzzy branches going everywhere. This installation technique is particularly vulnerable to

radiated intrusion. When planning wire routing, envision a highway that routes close by every component in the system with short breakouts from the bundle to service each piece of equipment.

- (7) Consider antenna locations with respect to their tasks. Receive antennas need to avoid proximity with noise sources, while transmit antennas should be located to minimize their coupling to potential victims. This is pretty easy in an all metal airplane: antennas on the outside are effectively shielded from stuff inside the airplane. Even graphite structures offer a high order of attenuation. The pure glass and plastic machines need careful attention to locations. Check with other builders and the editor of your type-newsletter for information on where/where-not to install antennas.

There are two ways to use the information in this chapter: (1) use as many of the recommendations as you're able or comfortable with as a prophylactic measure and/or (2) review for possible solutions to any problem that presents later. There's no way to guarantee a noise free airplane on first flight. The materials I've offered are necessarily limited to my own analysis and experience and cannot be all inclusive. Some of you are bound to discover some new combination with unacceptable effects. Identify the source and propagation mode. First, consider ways to control noise at the source . . . if the interference can be contained at the source, the possibility of multiple victims is eliminated. If the product producing the noise cannot be modified or filtered, then consider the ways to break or shield the propagation path and finally, consider ways to make the victim more tolerant or immune from the noise.

Observing the design and fabrication philosophies described here and in other chapters of this book will go a long way toward elimination of noise possibilities from the outset. But use caution before you add any extraordinary features to your noise reduction campaign. A builder called me about 7 years ago and described all the shielded wire and filters he'd added to his electrical system before he asked, "What else do I need?" "Gee, I dunno, have you got a noise problem?" "Oh no," sez he, "I've not flown the airplane yet!" I didn't have the heart to tell him that he was probably carrying 5-10 pounds too much weight and has spent hours of time installing materials and equipment that he probably didn't need.

Electrical System Reliability

Everyone with an electrically endowed aircraft wants a "reliable" electrical system. How is this accomplished? Does certification have any benefits toward electrical system reliability? Having worked in the aerospace industry for 38+ years, I can attest to industry's quest for the holy grail embodied by the world's most "reliable" electrical system. Given the efforts of industry and government for the past 50 years, how are we doing?

The following article was shamelessly purloined from the pages of AOPA Pilot Magazine for March of 1999. There was no particular reason to pick this story - it was simply the most recent one I could recall. It's one example of perhaps hundreds of similar stories appearing in aviation journals for decades. I didn't want to interrupt the flow of the story so you'll find only footnote tags [] tying points in the story to later analysis. AOPA Pilot Magazine and other journals publish "Never Again" style articles with a stated goal of, "Enhanced safety by providing a forum for pilots to learn from the experiences of others." So, read carefully and observe. Afterward, we'll talk about what this story reveals.

Sparks in the Dark

As an Air-LifeLine pilot, I thoroughly enjoy flying patients to and from places for medical care. On one such trip I took a 4-year-old patient and her father to the Cincinnati Municipal Lunken Field from my home base at the Manassas (Virginia) Regional Airport. Our return trip was to be a three-hour flight in a rented Cessna 172RG. The weather was 3,000 feet overcast at Lunken, dropping to about 1,000 feet at Manassas.

We left Lunken in the late afternoon, and it soon became dark. I adjusted the cockpit lights accordingly. As I tweaked the elevator trim wheel on one occasion, I noticed that the instrument lights got brighter for a second or two. I assumed that the brightening was caused by a loose wire's being jostled by the motion of the trim wheel. Since the cockpit light rheostats are close to the trim wheel, I ignored it.

The undercast was slowly rising to meet us, so I asked for a higher altitude. As I adjusted the rudder trim after the

climb, I again saw the lights get brighter briefly and again wrote it off to a loose wire.

During my last several trips I had been regularly updating what I called my escape route - where I would land if I had an emergency. I would open the Jeppesen book to the selected airport and tune in its ATIS. On this flight, I added a new twist to my planning - a handheld GPS. By keeping the cursor on the selected airport, I always knew its bearing and range. The airplane was also equipped with an IFR-capable GPS.

At the time of the electrical hiccups, the chosen airport was the Beneduni Airport in Clarksburg, West Virginia, which was well above minimums for ILS and GPS approaches. About 30 minutes after I first saw the lights brighten, they got bright and stayed that way. I looked down at the ammeter, which was pegged at a full charge. I turned the alternator on and off several times, hoping to clear the problem [1].

On the third cycle, a puff of smoke and a shower of sparks erupted from behind the panel. I turned toward Clarksburg, now about 20 miles away, started a descent, and called approach.

"Mayday, mayday, mayday, Lifeguard Cessna Four-Eight-Five-Seven-Victor. We have an electrical fire; we'll need a descent into Clarksburg."

The controller cleared me to 5,000 feet and asked if my ILS receiver was working. I intended to keep my transmissions to a minimum. After all, I might not be able to land at Clarksburg, and I wanted to keep the battery charged to power the ILS receiver [2]. He vectored me toward Clarksburg.

Just before we entered the clouds, another shower of sparks erupted from behind the panel, so I turned off the master switch and utilized the small flashlight hanging from a chain around my neck. I kept the airplane on a northerly heading using rudder only, because my hands were busy with the flashlight and setting up the radios for the ILS [3].

By the time I got Clarksburg set in the handheld GPS we were in the clouds, and I was wandering 30 degrees on either side of my assigned heading. Suddenly, I remembered my passenger, gave him another flashlight, and asked him to shine it on the panel. This freed up one of my hands and allowed me to use my smaller flashlight to read the approach chart. Occasionally during the descent, I turned the battery back on to get a new heading from the controller. On one occasion, the controller told me that a departing aircraft had reported the ceiling at about 1,000 feet AGL. He suggested a visual approach. I'd been planning on an ILS, but I wasn't flying too precisely, so a visual approach had some appeal.

Once I reached 2,500 feet, I again turned on the battery and called the controller. He asked repeatedly if I had ground contact beneath me, and I repeatedly told him that I did not. Four miles from the field, I conducted a prelanding checklist and was able to lower the gear with battery power.

When I broke out of the clouds I saw bright lights at 11 o'clock, where the controller and the GPS said the airport should be. I wasn't sure that it was the airport I was looking at, seeing no runway lights, rotating beacon, or approach lights. I descended slowly to 500 feet AGL without positively identifying the field. Eventually, the GPS confirmed that the airport was behind me, as did the controller. Once I surrendered the navigation task to the controller, I had allowed myself to lose situational awareness - despite having two GPS receivers. I turned to the right and saw the runway lights.

On short final, I thanked the controller for his help and made a normal landing.

There are some important lessons that I took away from this flight.

Land first, fix it later [4]. At the first sign of an electrical malfunction, I should have landed. Waiting for the smoke and sparks to make the decision for me was stupid. I had a stable situation until I started troubleshooting it. As I learned later, the voltage regulator had failed, sending too much charge to the battery-which was indicated by the pegged ammeter [5]. Coincidentally, the alternator circuit breaker did not trip to protect the rest of the electrical system [6].

Fly the airplane. While fiddling with the avionics, I allowed my heading and altitude to wander.

Navigate. Once I had allowed the controller to vector me, I essentially stopped navigating. Had I lost commu-

nications at that point, I would have spent several precious seconds flying around at night, in clouds, over mountains, while determining my position.

It pays to be prepared. I would have been more scared had I not carried two flashlights, extra batteries, and a handheld GPS receiver. It pays to play "what if" scenarios through your mind during those hours of boredom.

Get help wherever you can. The Clarksburg Approach controller made a great copilot. He took over navigation and terrain clearance, though probably more than I should have allowed him to. Your passengers can help, too; they can pump the gear, hold a flashlight, fold a chart, and more.

Martin Gomez, AOPA 830204, an engineer from Fairfax, Virginia, is a 675-hour commercial pilot.

I congratulate pilot and author Gomez for his resourcefulness and skill in bringing this event to a happy ending. Further, I appreciate his willingness to publish his experience for our benefit. Critical review like that which follows is not intended to demean the author or diminish his stature in the community of aviators. One purpose of this chapter is to demonstrate how Mr. Gomez and our fellow aviators have been trapped by circumstances which need not have happened. I will suggest design and operational philosophies that will allow us to fly for the next fifty years "never again" having to experience this kind of problem. Let's look at some data points in the article:

[1] I looked down at the ammeter, which was pegged at a full charge. I turned the alternator on and off several times, hoping to clear the problem.

This is a clear indication of either regulator failure or a shorted cell in the ship's battery. If the airplane had a voltmeter, momentarily setting the alternator field switch at OFF would confirm the diagnosis. If bus voltage falls to 12.0 volts or above, the battery is okay and the regulator is failed. If the bus voltage falls to a bit above 10 volts, then the battery is shorted. Battery shorts are very rare compared to all other battery failures so it's most likely that the regulator has failed. What happened to the ship's overvoltage protection system?

[2] After all, I might not be able to land at Clarksburg, and I wanted to keep the battery charged to power the ILS receiver. He vectored me toward Clarksburg.

Our hero's first concern after taking the alternator off line is keeping needed avionics running. Since he was in a rented airplane it's a sure bet he didn't know what the ship's battery capacity was. This lack of knowledge forced him to shut down essential systems until the final minutes of the flight.

[3] *I kept the airplane on a northerly heading using rudder only, because my hands were busy with the flashlight and setting up the radios for the ILS.*

The C-172 has overhead flood lighting that draws just under 200 milliamps. Much preferable to holding a flashlight in the teeth. None-the-less, with the master switch OFF, it was unavailable to him.

[4] *Land first, fix it later. At the first sign of an electrical malfunction, I should have landed. I Waiting for the smoke and sparks to make the decision for me was stupid. I had a stable situation until I started troubleshooting it.*

Throughout my writings and conversations with builders, I've encouraged pilots to leave their toolbox closed until safely on the ground. Unfortunately, the electrical system architecture and operating limitations built into most certified aircraft make it tempting to do in-flight diagnosis and repairs. It's distracting to an already busy pilot and may make the problem worse.

[5] *As I learned later, the voltage regulator had failed, sending too much charge to the battery- which was indicated by the pegged ammeter.*

Correct . . . but his mechanic said nothing about (or worse yet) didn't know about ADDITIONAL problems with the airplane. Where did the sparks come from? Something behind the panel was exposed and faulting to ground. What happened to the overvoltage protection? Was this built into the voltage regulator and fixed with a new regulator. OV protection might have been a separate and overlooked component, still in a FAILED condition and waiting to ignore the next regulator failure?

[6] *Coincidentally, the alternator circuit breaker did not trip to protect the rest of the electrical system.*

A very common misconception about circuit breakers. The alternator's main output breaker almost never trips in an OV condition. Alternators are current limited devices meaning that while the bus VOLTAGE is climbing, output CURRENT from the alternator is only a few percent above the alternator's rated output which should NOT open the breaker.

The alternator's field circuit breaker is expected to open during overvoltage IF the airplane is fitted with a crowbar overvoltage protection device . . . I'm reasonably certain this airplane was not so equipped.

As I suggested earlier, this article is not unlike many, many others we've all read for decades. I think you'll agree that they all end the same way. "Sure glad I did this . . . next time I'll do that . . . boy! I'll never do this again." Have you ever read an article where the author questions either the manufacturers or regulators of airplanes as to what might be done to reduce if not eliminate the probability of a reoccurrence? We're schooled as pilots and mechanics that somebody knows a lot more about airplane design and safety than we do. We're taught further that once these bastions of knowledge and public interest pronounce aviation products fit for sale to the public, the notion of making any changes for the better are overwhelmed by bureaucratic roadblocks and ignorance.

What are we really looking for when using words and phrases like "reliability" and "failure rate"? For the majority of designers, manufacturers and users in the aerospace industry, these words bring up mental images of individual components carefully designed, tested, procured, installed, maintained and used in accordance with thousands of words of documentation.

Many of the documents are specifications, regulations or rules which (if not dutifully complied with) can be the basis for punishment of individual(s) who do not faithfully follow the words irrespective of motivation. How about Mr. Gomez's C-172RG? How much of the script for his harrowing experience was written by industry and government authors?

Mr. Gomez's story has ratcheted up the worries of perhaps thousands of pilots. References [5] and [6] highlight omissions and misconceptions in the story. These can also contribute to uncertainty on the part of folks who don't do this for a living yet are obligated accept the airplane as-is-where-is. Manufacturers might have an interest in upgrading their products but regulators often make this an expensive and time consuming task. Further, when a product is so highly regulated, manufacturers tend to relax . . . after submitting their product to the will of government, it must surely represent perfection! This is the biggest reason why aviation lags decades behind virtually every other industry.

That leaves it up to our hero to do whatever he can within his limited understanding of the system to plan his own actions for the time when he may expect to encounter this problem again.

Aviation journals appreciate these stories too . . . they get a reader's attention and in some small way, publishing them may indeed improve some pilot's chances of dealing with a similar situation. This lends some validity to the publisher's stated mission of improving on aviation safety.

The very same issue of AOPA Pilot carried an advertisement from a company that takes money from pilots to prepare them for these events. A testimonial from a former student congratulated himself for having taken the training course. The pilot said something like, "Only weeks after having completed this course, my efforts were rewarded when I successfully handled total electrical system failure in my airplane." The author of these words is justifiably proud of the success he experienced by training for a very stressful airborne situation. Ignorance is a strong pacifier and fear is a still stronger motivator. A combination of fear and ignorance is useful when it comes to extracting money from people with the feel-good mission of making a pilot more confident and capable of dealing with airborne adversity.

The sad facts are that contemporary electrical systems are so untrustworthy that such training courses are valuable.

Aviation in the US deals with system inadequacy by striving for failure reduction, an increasingly expensive task as the numbers and kinds of failures become more random and rare. When system shortcomings are noted, they're more likely to be treated by add-on hardware, new regulation and/or additional pilot training rather than to fix the root problem.

The most elegant solution yet is totally unheard of in contemporary certificated aviation . . . design systems so that most failures of the nature described by Mr. Gomez don't matter. Failure tolerant design is much easier, lighter and less expensive to build than contemporary certificated designs.

For years, I've been working with amateur airplane builders who have chosen NOT to be ignorant. None-the-less, they bear heavy baggage brought with them for having read pilot's journals and listening to hangar tales of nail-biting escapes. Unlike the folk who swing wrenches on certificated aircraft, the amateur builder is encouraged to think outside the box and free to consider the value of doing something because analysis shows the action to have beneficial effect.

I wonder how Mr. Gomez might have summed up his experience if he knew that for \$15 in parts, a few hours work on the airplane and NO new training or preparation, his story would have been so ho-hum that it wasn't worth publishing?

How would you describe a reliable flight system? May I suggest this:

"System reliability is optimal when I can suffer any of the most common failures and still put the wheels on the ground, at my intended destination, without breaking a sweat."

I present forums and weekend seminars around the country on the topic of aircraft electrical systems. One of my favorite questions of an audience is to rank components of the flight system with respect to the need for absolute reliability. I get some interesting comments from the crowd but here's my personal list of reliability priorities:

I. Airframe

1. Surfaces
2. Structure
3. Flight Controls

II Pilot

1. Skills
2. Training
3. Physical Condition

III Power Plant:

1. Engine
2. Propeller
3. Fuel System
4. Controls

IV. Systems

1. Electrical

- (a) Panel Lighting
- (b) Primary Nav Radio
- (c) Transponder
- (d) Turn Coordinator
- (e) Fuel Pump/Transfer
- (f) Engine Support

2. Landing Gear

etc.

etc.

The airframe and other things that make the airplane flyable are at the top of the list. Most people are surprised when I put the pilot as number II on the list. Consider that if the airplane is hanging together, the pilot is skilled and in good physical condition, the chances of living through the

circumstances of any given flight are greatly improved. Of course, if everything lower on the list is kaput, the pilot has few options. However, assuming the engine is delivering enough power to hold altitude, only then do the options begin to include choices for WHERE you will land and HOW you're going to get there. Note that I've ranked electrical system goodies a distant fourth place.

Let us consider life's little benefits that provide the maximum reduction of sweat. I put lighting first on the list. Recall that our hero's most immediate problem upon loss of the electrical system was being able to see. I mentioned earlier that the overhead flood light in the airplane has a very small electrical energy budget . . . but given the way most certificated airplanes are wired, the flood lights are DARK any time the master switch is OFF.

Second on my list is the primary navigation radio . . . VOR, GPS, Loran . . . etc. One solid state radio receiver draws about 0.2 amperes . . . not much energy needed here either.

Third is a turn coordinator . . . generally the only electric flight instrument on the panel and it will save your buns if you are practiced in its use (remember item II. 1 - Pilot Skills?).

Forth comes the transponder. If you've got a situation placing a graceful return to earth at risk, then a 7700 squawk will go a long way toward getting airspace in front of you cleared of other aircraft with no other taxation of your time and attention than to set a few knobs.

Obviously, that list can and should be modified to accommodate your personal flight habits. If you NEVER fly at night, panel lighting isn't an item high on your list. If you NEVER get close to clouds, then perhaps you don't need to worry about the turn coordinator. Further, if your engine is electrically dependent, then perhaps fuel management, ignition and other controls would move to #1 on your list. If you share my fondest dream where vacuum systems are used only for carpet cleaning, your electrical system's architecture for reliable flight will have to accommodate the additional tasks.

Some omissions from my list brought quite a few questions from the audience . . . how about the Comm radio? Engine instruments? Autopilot? Consider this when deciding what goes on your ME²L (Minimum Electrical Equipment List): In order to keep an electrical system condition from becoming an emergency, we need to make a list of those things which are most useful in keeping you airborne with enough electrical assistance to maximize probability of comfortable termination of flight.

If we're dealing with an alternator out situation, then the goal is to run just those goodies that help us fly and navigate while minimizing loads on the battery. When you take off, there is one critical commodity on board that puts an absolute limit on time aloft . . . FUEL. Since that limit already exists, let's try not to impose any new limits on endurance. Let us see if we can design and maintain the system so that critical electrical system endurance is equal to or greater than fuel endurance.

Getting back to the Comm radio . . . how much help is the guy on the ground? Assuming you are skilled enough to use the equipment on your ME²L, do you really NEED ground based assistance? Wouldn't it be a good idea to assume that it's not going to be available? Besides, when you're busy doing your job in the cockpit and doing it right, I'll suggest that the guy on the ground can become more of a distraction than a help. Recall some of Mr. Gomez's comments about how much of his own duties he turned over to the guy on the ground and how it caused our hero to overshoot the airport and descend too low . . .

Does this mean that the Comm radio shouldn't be on the essential bus? No, but it does suggest that while you're in a minimum power consumption mode, it may serve your mission best to have the radio OFF. Tell the guy on the ground what's happening, what you're going to do and let him know that you'll be back in touch at some waypoint close to your intended destination and only after your safe arrival is assured.

Which brings up another point . . . the essential bus need not be LIMITED to the critical items on your ME²L . . . however except for devices that you want to have running under every condition, any E-bus powered device should have its own ON-OFF switch . . . most avionics do.

Autopilot? If you have one, especially a low current wing leveler, you might have it on the essential bus . . . but while you're boring holes in the sky between waypoints, you might improve your electrical power condition by hand flying the airplane except when you have to deal with maps and/or nav radios. Engine instruments? When was the last time you heard of an engine stopping because you didn't know what the oil pressure was? If you're in cruising flight and every engine instrument goes down, how does that impact the probably outcome of your flight? Engine instruments don't help keep an airplane airborne.

Many airplanes are being constructed with electronic ignition and/or electronic controlled fuel injection. These must become a part of your ME²L and essential bus planning. Planning is pretty easy and you do it like this:

Add up the current draw of all the goodies that you need to stay airborne and do a good job of navigation to a point where the airport is in sight. In the case of Mr. Gomez's airplane, the load might have looked like this:

Panel Flood 0.08 A
 Nav Radio 0.20 A
 Turn Coord 0.30 A
 Transponder 1.50 A

Hmmm . . . the transponder is the only thing that doesn't help him do his job but it draws the most power!!!! Anyhow, this list of things adds up to 2.1 amperes. Let's suppose that instead of flying in through an airport rich area of the country, he was en route from Dalhart, TX to Santa Fe, NM and had several hours of simple straight and level flight over lots of dirt, rocks and coyotes. Wouldn't it be a good idea to plan an arrival at his intended destination where there is probably assistance, tools and parts to repair an airplane? Why force a deviation into unfamiliar territory just to accommodate an under-designed electrical system?

The optimum design says that if we've just punched through a cloud layer to VFR over the top and have an alternator crap out (or sparks and smoke from behind the panel) it should be possible to fly to intended destination and make a comfortable arrival with only the battery energy on board. If you had the list of goodies running that I've show above, would you have any problem getting where you were going? In fact, you might even shut the transponder OFF on that leg from Dalhart to Santa Fe. There's not much out there!

Okay, let's leave the transponder on and crank the numbers. 2.1 amperes for 3 hours is 6.3 ampere hours. Aha! We've got a 24 a.h. battery on board, no sweat! Really? First, consider that it takes about 1.0 amps just to keep a battery contactor closed. Second, what is that battery's capacity after three years on the firewall, two episodes of leaving the master switch on and one case of exposed plates due to poor water maintenance? Just because a battery got your engine started doesn't mean that it has the capacity needed to supply your minimal electrical system needs.

I'd go so far as to suggest that half the airplanes flying today carry a FAILED battery. If the airplane suffers alternator problems ***the battery doesn't have enough energy to carry ME²L for the duration of fuel on board.***

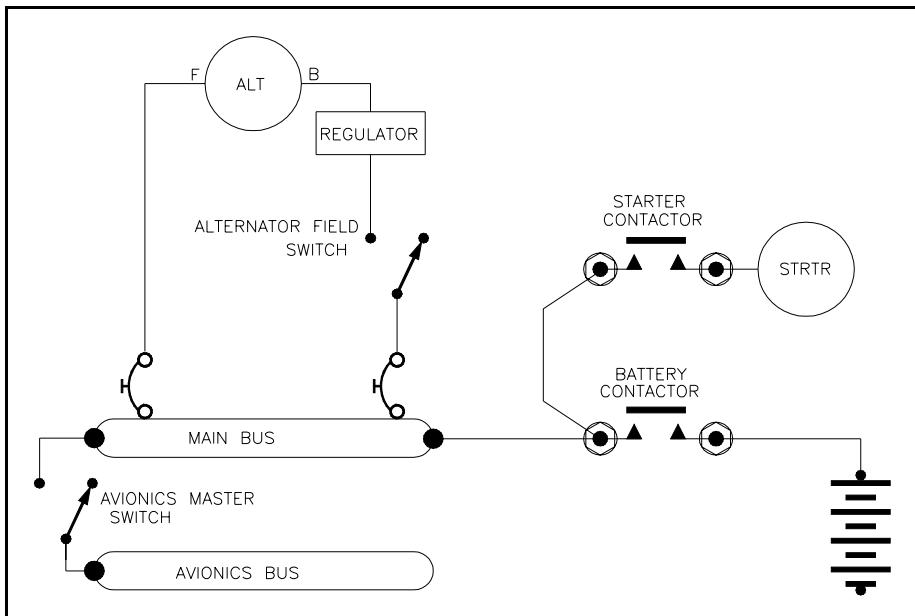


Figure 17-1. Rudimentary Single Battery, Single Alternator Power Distribution System.

Two important factors contribute to this condition. (1) There is no industry standard practice that routinely checks an aircraft battery for current capacity. Batteries get replaced when they fail to crank the engine for the second, third or perhaps even tenth time. (2) There is no industry standard practice for electrical system architecture that allows a pilot to flip a couple of switches and fly on - confident in the knowledge that necessary electrical system goodies will function all the way to intended destination.

As builders of the finest airplanes to ever fly, you have the option of rectifying these two conditions such that stories like that told by pilot Gomez will never be a part of your personal life experience. Before improvements can be proposed upon contemporary certified aircraft electrical systems, we should consider the state-of-the-art flying in the vast majority of single engine airplanes.

Figure 17-1 illustrates the factory wired configuration for pilot Gomez's Cessna 172RG. Noteworthy points to ponder include the traditional practice of routing the alternator's power output lead (often called the B-lead) directly to the main bus inside the cockpit. There was probably an avionics bus with a single power feed through an "Avionics Master" switch. This particular theme for power distribution has been standard on single engine aircraft since the mid 60's. Had pilot Gomez's airplane been wired a bit differently, the course of his experience could have been much different.

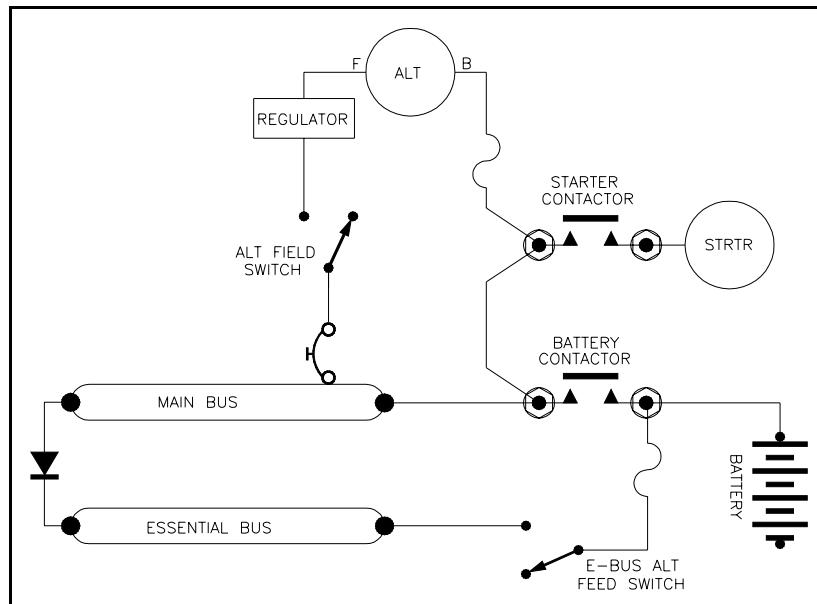


Figure 17-2. Single Battery, Single Alternator System with Dual Feed Essential Bus.

Figure 17-2 makes three important modifications over the system described above. First, the alternator B-lead is tied into the power distribution system on the firewall using an in-line fuse instead of a circuit breaker. This change provides for a much lower resistance path between the alternator (the noisiest device in the electrical system) and the battery (the best filter in the electrical system). An important feature of this change is to size the alternator's B-lead fuse such that nuisance blowing is not going to happen. Most certified airplanes with 60A alternators also have 60A breakers in their B-lead feeds. Under certain but not uncommon conditions, a 60A alternator's output can exceed its rated value and trip the breaker. Tens of thousands of certified aircraft have an alternator breaker **designed to nuisance-trip**. The B-lead breaker recommended for a 60A alternator is not less than 70A. A B-lead fuse should be 80A.

Another feature is the reconfiguration of what used to be an avionics bus into an essential bus with important new duties. Recall the list of essential goodies we developed earlier? Things like minimal panel lighting, turn coordinator, and perhaps the system's voltmeter would be fed from the essential bus.

Note that the avionics master switch has gone away. It hasn't been needed for over

20 years. Worse yet, it has been a single point of failure for every device on the avionics bus. In its place, I show a diode that provides the normal power path for essential bus equipment. Any time the main bus is hot, the essential bus is hot.

The most important feature in Figure 17-2 is the alternate power feed path between the battery and the essential bus. This power pathway supplies essential bus accessories even if the main bus has been shut down. Further, it's independent of the battery contactor. If you're in an alternator-out mode and need to conserve battery energy, then the approximately 1 Amp draw needed to keep the contactor closed is eliminated. A battery contactor draws more power than 2 navigation radios!

With a slight rearrangement of the breaker panel in pilot Gomez's airplane to (1) group our previously developed list of electro-goodies on an essential bus and (2) add a normal feed diode and (3) replace the semi-useless avionics master switch with an essential bus alternate feed switch to an always hot battery feed, his experience might have been so ho-hum that the magazine wouldn't have been interested in publishing it. Of course, it's not enough to simply add some parts and rewire a few of the airplane's appliances. The battery must be maintained in a manner that assures adequate readiness in the face of alternator failure.

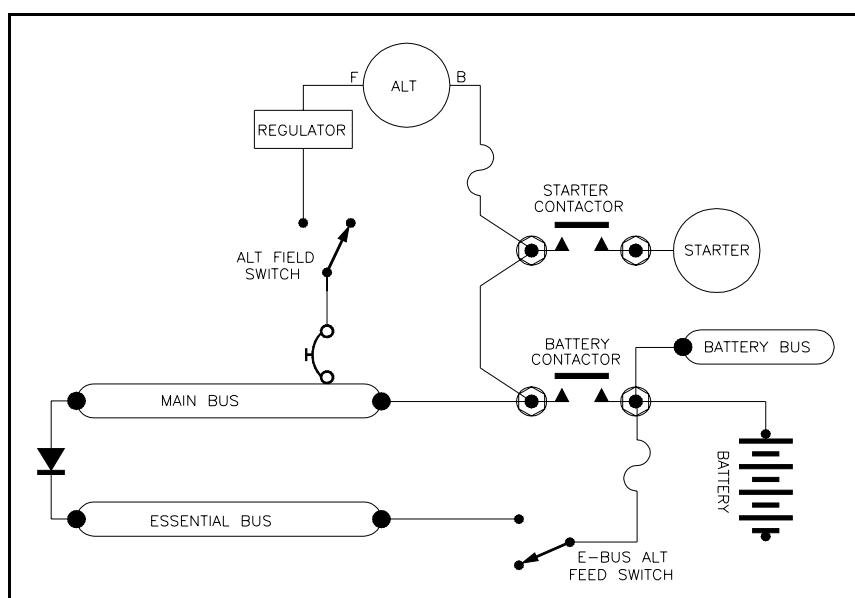


Figure 17-3. . . . Addition of an Always Hot Battery Bus.

Pilots and engineers faithful to the concept of an avionics master switch have suggested that the essential bus normal feed diode be replaced with a switch. You still have dual power paths to the E-bus and all goodies sensitive to the legendary gremlins of aircraft electrical systems can be totally isolated from the bus by opening the switch.

Several things to consider here: (1) most of the gremlins of days gone by either never existed or have been tamed by application of simple engineering solutions (2) except for gross overvoltage conditions, modern radios are by design, regulation, and corporate initiative immune from anything a normally operating aircraft electrical system will throw at it, and a very important (3) if the diode is replaced by a switch, it is incumbent upon a pilot to operate the normal and alternate feedpath switches in the proper order so that the main bus doesn't draw power through the E-bus alternate path and open its fuse or breaker. If you gotta have an avionics master, place it in series with the diode.

Another common objection to the diode is based on the fact that all diodes have a voltage drop of approximately 0.6 volts. I'll suggest this drop is not significant and here's why.

If the alternator is operating normally with a main bus voltage of 13.8 to 14.6 volts, then the essential bus sees no less than 13.2 volts. If the alternator fails and one is dependent upon battery-only operation, the E-bus voltage with the alternate feed switch closed will be 12.5 with a fully charged battery and drop to 10.5 volts at end of life. If you expect all the goodies on your E-bus to provide valuable service when operated from a battery over the range of 10.5 to 12.5 volts, why would you be concerned if the normal operating voltage is 13.2 to 14.2 volts due to diode drop?

Figure 17-3 builds on this new concept by adding an always hot battery bus. This might be a small fuse block of 6 or so fuses. The always hot bus powers things like the electric clocks, dome lights, hour meters, and a single electronic ignition backed up by a magneto. Why electronic ignition on the hot bus? I'll suggest that an electronic ignition need not behave any differently than a magneto with respect to cockpit switches. Any time an ignition switch is ON, that system is hot and ready to run an engine. By operating the electronic ignition from the battery bus, the entire electrical system can be shut down with no adverse effects on engine ignition.

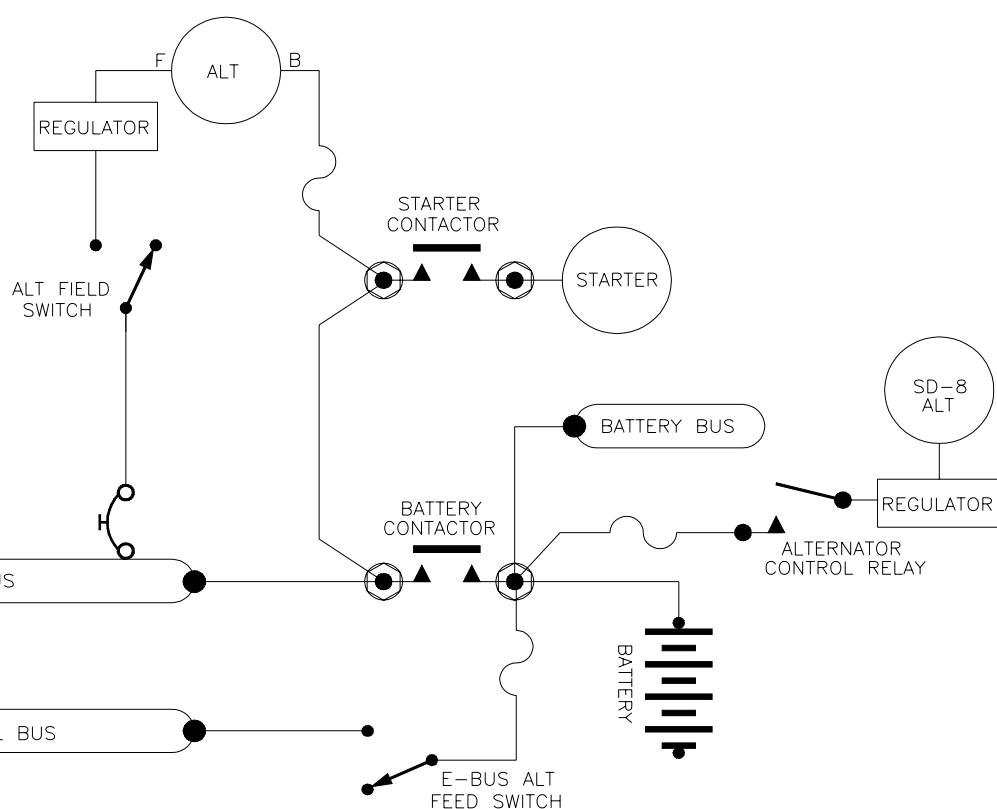


Figure 17-4. Adding the SD-8 Auxiliary Alternator

Would you like to get rid of the vacuum system with its attendant pumps, hoses, fittings, filters and regulators? How about an all electric panel? Yes, I know that electric gyros are more expensive than an attitude indicator but consider this:

B&C Specialty Products offers two sizes of alternators that will operate from a vacuum pump pad on the back of your engine. An 8A model (the SD-8) and a 20A model (the SD-20). Both of these alternators have exemplary pedigrees with failure rates less than one per 100,000 flight hours. Suppose you left the vacuum system out of your airplane and installed the SD-8 alternator in its place.

Figure 17-4 suggests a way to incorporate the SD-8 into a two alternator, single battery electrical system with an excellent reliability analysis. Recall earlier when we were adding up lights, radios and instruments to deduce the E-bus

loads? If you're considering electrically dependent ignition or fuel delivery systems, battery support of electrical loads during alternator-out operations may require an unpractically large battery. In these cases, a second alternator is the solution. The architecture described in Figure 17-4 is the easiest way to make it happen.

Note that with the battery contactor open, the E-bus alternate feed switch closed and the SD-8 alternator control relay closed, you have a rudimentary but complete electrical system that runs all of your essential electro-goodies with unlimited endurance while saving the battery until the airport is in sight.

If the main alternator is functioning, you can leave the battery master closed for normal operations. If the main alternator is down for any reason, you move the DC power master to OFF taking the alternator field off line, close the

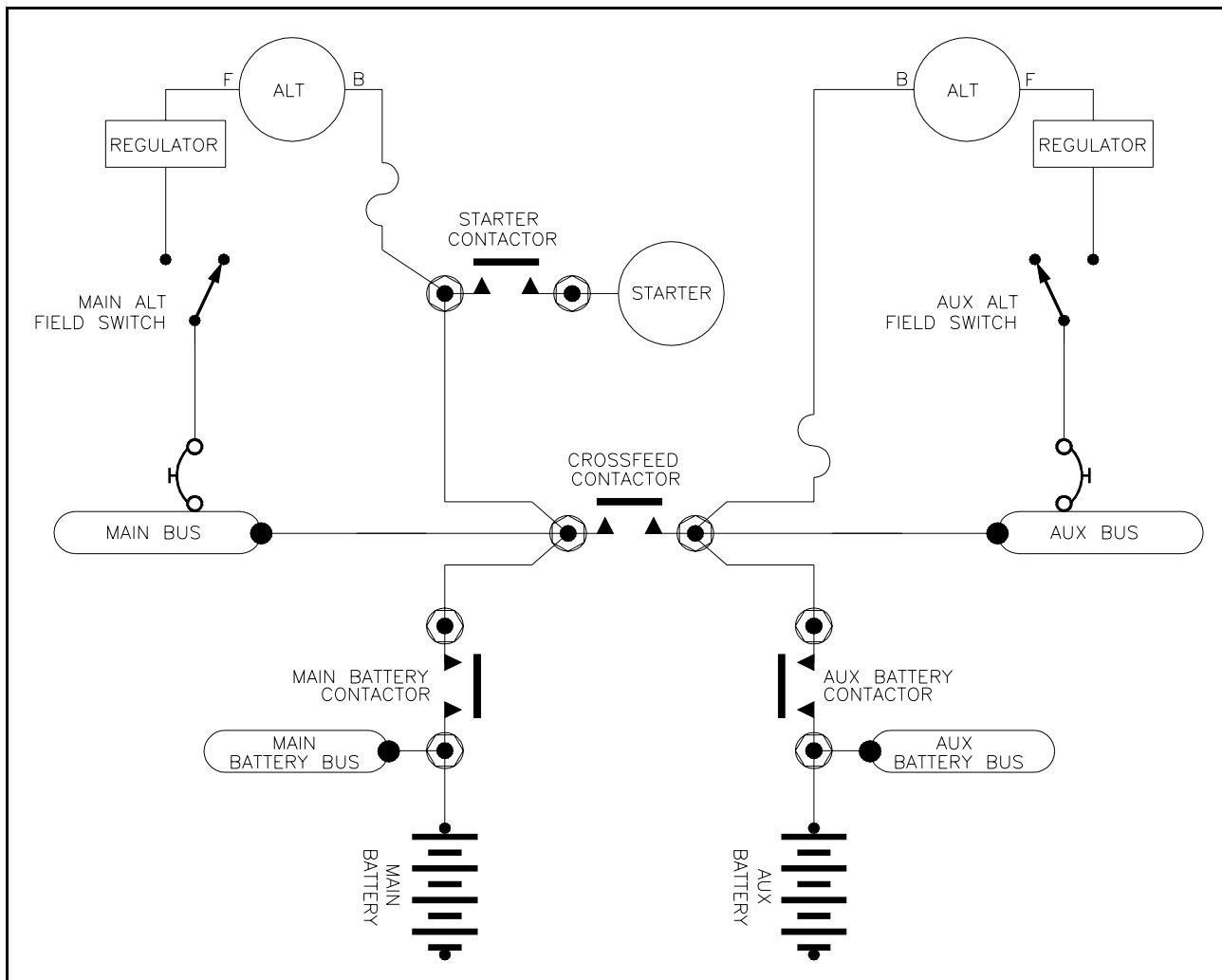


Figure 17-5. Dual Alternator, Dual Battery Electrical systems.

alternate feed path switch for the essential bus and close the aux alternator control relay to configure your electrical system in a manner that is almost identical to that used in hundreds of cross-country, VFR Vari-Ez and Long-Ez aircraft.

Without the auxiliary alternator, the battery must be depended upon for all electrical energy for comfortable continuation of flight. Once you add a second alternator, the battery is relieved of carrying en-route loads and can be saved until the approach phase where you might wish to show some lights or lower landing gear, etc.

It's still a good idea to replace the battery when its capacity drops below a few hours endurance with no alternators. However, once a second alternator is added the battery is relieved of competition with remaining fuel for flight endurance. I proposed this system architecture on a half-dozen or so internet list-servers and the response was immediate and positive.

To mitigate the expense of two electric gyros in the all-electric panel, consider the following option: install the attitude indicator first. Go ahead and punch a hole for the DG but put off buying it until later. With only two wires to hook up, it's no big deal to add it later. Consider that you get excellent heading info from Loran or GPS. Consider also one of the low cost, digital display magnetometer compasses instead of a DG. I could handle an airplane quite nicely with an attitude gyro and accurate heading and course data from electronic sources.

Dual Alternator/Dual Battery . . . the mother of all electrical systems. . . .

Every light twin I know of has a single battery fed by two engine driven power sources. Since generators will run well without a battery, the older airplanes have three, relatively independent sources of power. . . . well, probably only two good sources cause even the guys flying with two fans will flog a battery until it simply fails to crank an engine.

When you trade generators for alternators, loss of a battery contactor may well precipitate total loss of electrical power. Alternators don't run well without a battery. The dual alternator/single battery system common to US built light twins suffers a second problem. To balance loads between two alternators feeding the same bus, it's necessary to maintain voltage adjustments to within a few hundred millivolts of each other. If one regulator drifts upward in setpoint, the alternator it controls will hog all the load. If the setpoint drifts downward, the alternator it controls will shed its loads onto the other alternator. This inability to maintain

an accurate balance in no way diminished the reliability offered by redundant alternators. However, it's was disconcerting to twin engine pilots to observe large differences in alternator output. About 1982, this writer participated in the successful design of a paralleling regulator system for alternators that maintained balance between twin alternators within a few percent of total load.

If you have places on the engine(s) to drive two alternators, then why not exploit the potential for a truly redundant, extraordinarily reliable electrical system? Figure 17-5 illustrates an electrical system that light twin pilots can only wish for. This distribution architecture is equally applicable to single or twin engine airplanes. Most of my experience with this system has been on the larger, more completely equipped aircraft ranging from Glasairs up through the Lancair IVP and even a Venture or two. To date, I'm aware of two or three RV-6 aircraft slated to receive a DA/DB electrical system.

An inspection of Figure 17-5 shows two, independent battery-alternator systems with a "crossfeed" contactor. During normal operations aloft, the crossfeed contactor is open and each system functions independently. If you trace out the details of the DA/DB alternator system described in Appendix Z, you'll find that I've combined the crossfeed and starter control in a single S700-2-50 switch. Pressing the switch to a spring loaded full up position closes the crossfeed contactor and energizes the starter; both batteries assist with engine cranking duties. When the engine starts, the switch is released to spring return to its middle, crossfeed only position and then moved to the full down OFF position.

If one alternator fails, the pilot has the option of moving the crossfeed contactor switch to the middle crossfeed only position allowing the remaining alternator to power electro-goodies on both systems. The two alternators do not need to be the same size. The most common installation in amateur built airplanes uses a 40 or 60 amp main alternator and a 20 amp auxiliary alternator. Unlike most examples of certified alternators for single engine aircraft, modern products have a demonstrated failure rate of less than 1 in 100,000 flight hours. Two such alternators teamed as depicted in Figure 17-5 should live up to your highest expectations. The architecture in Figure 17-5 is being considered for the next major features update on the A-36 Bonanza currently being developed under the auspices of NASA's AGATE program.

If both batteries are recombinant gas technology, then either battery is capable of cranking the engine. The crossfeed contactor makes both batteries available for improved cranking performance.

Variations on a theme . . .

There are two important variations on a theme I'd like to discuss now. First, one may consider adding a second battery to the architecture of Figures 17-2, 17-3. One could add a second battery to Figure 17-4 but the value of doing so will be overshadowed by the second engine driven energy source.

Two batteries will co-exist nicely on the same bus contrary to many well intention but misguided warnings about the inadvisability of doing so. This is because batteries charge based on VOLTAGE applied to their terminals. It makes no difference whether you have one or a dozen batteries, a bus held to 14.2 volts by an alternator will charge every one of them. A discharged battery cannot be charged by nor present a serious drain on a charged battery. A battery needs something on the order of 13.8 volts or more to become fully charged. A battery delivers energy at 12.5 volts and below. There are no practical concerns for batteries to share a load. Consider what happens when a battery is tasked with engine cranking. If either battery in a two battery system is capable of cranking the engine, then adding a second battery can only have the beneficial effect of offsheding some of the load from the first battery . . . it matters not if they exactly share.

During alternator out conditions we expect a battery to supply ship's loads. The only reason to install two batteries is for the purpose supplying independent power sources to each half of a dual ignition system or dual fuel delivery system on an electrically dependent engine. When the alternator quits, the batteries are split off to separate task assignments . . . again, there are no practical concerns for load sharing.

Last, antiquated concerns for a battery "failure" dragging down the rest of the system are simply not founded in the physics of modern battery construction. RG battery reliability and performance supplemented with good preventative maintenance drives probability of gross battery failure to zero.

Figure 17-6 illustrates the methodology for adding a

second battery to your aircraft. Each battery has its own always-hot battery bus. The main battery bus might have taps for E-bus alternate feed, #1 electronic ignition, #1 fuel injection system, etc. The second battery's bus might carry only the redundant engine loads and accessories that benefit from an always hot feed like the engine hour meter and electric clock.

This architecture is an excellent candidate for the yearly battery rotation recommend in many of my writings. At each annual inspection of the airplane, put a new battery in the main battery location and rotate the old main battery into the auxiliary battery location. This means that the main battery with the heaviest duties under alternator out conditions is always less than a year old. The battery in the aux position is always less than two years old.

The only practical alternative to the yearly game of musical batteries is to do periodic battery capacity checks as described in the chapter on batteries. Batteries for electrically dependent airplanes should be checked (1) every 6 months, and (2) after every episode of total battery discharge. Replacement should be determined by the battery's ability to sustain essential electrical loads for duration of fuel aboard.

During alternator out operations, one shuts opens both battery contactors and closes the E-bus alternate feed switch.

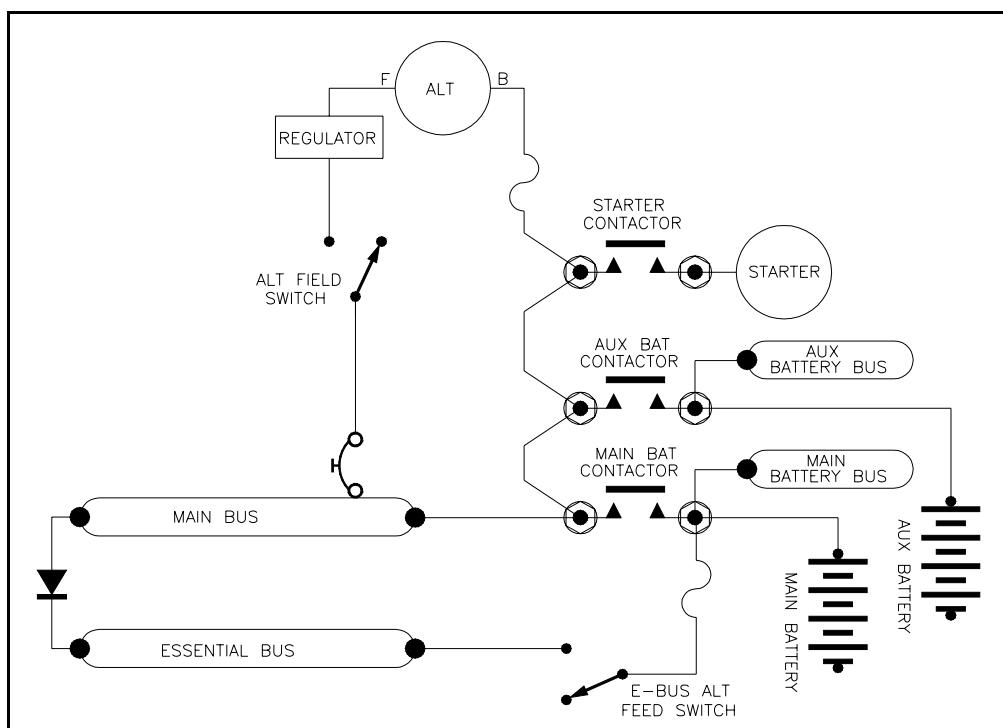


Figure 17-6. Dual Battery Installation

One might even consider shutting off the engine loads on the main battery and using only the aux battery to sustain engine operations for the remainder of the flight. Once the airport is in sight, one may close the battery contactors and use whatever energy is left to run things like landing lights.

Adding an Auxiliary Alternator with auto-switching. . .

There's yet a third way to add a second engine driven power source to an airplane as illustrated in Figure 17-7. In this instance, the auxiliary alternator is connected in parallel with the main alternator. However, the regulator setpoint for the aux alternator is approximately 1 volt below normal bus voltage.

In normal flight, both alternators are ON but the aux alternator goes to sleep because its regulator thinks that the bus voltage is too high and drives the aux alternator field voltage to zero. If the main alternator fails to support ship's loads, the bus voltage sags waking up the auxiliary alternator. B&C provides a special regulator for this application. Instead of a builtin low bus voltage warning light, the warning circuitry is configured to annunciate the aux alternator's wake-up call by illuminating an "AUX ALT LOADED" light. A hall effect sensor supplied with this regulator watches the aux alternator output load and causes the AUX ALT LOADED lamp to flash if ship's loads exceed the alternator's rated output of 20A. The pilot needs only to reduce system loads on the bus until the light stops flashing.

This system has been STC'd onto the A-36 and C-210 aircraft and is offered as a production option on the A-36 and by Mooney aircraft. I offer this system as the easiest way to add a second engine driven power source to an existing design.

Many of you are probably wondering when we'll get around to discussing hardware. After all, if you want reliability, you'll want really high quality parts . . . right? Well, there's nothing wrong with high quality parts, certainly one may expect a high dollar part built to government specifications to last longer than the automotive parts store equivalent. But

how does longevity figure into reliability? Obviously, reliability is not hurt if every part you use can be expected to last longer than you plan to keep the airplane. If parts selection was the only reliability factor, the task would be easy. But what about wires, components with complex internals like radios, terminals, nuts and screws and unanticipated damage? What about your personal understanding of the system and options for how it may be operated? Most people's notion of reliability is based on things not breaking. I've suggested in many writings that flight system reliability is driven most strongly by system architecture and the operator's knowledge of how to use it. It's much easier to plan for ways to work around occasional breakage than to depend on every the ability of every part to last for as long as we need it.

Doing the Unthinkable - Replacing Parts Before They Break!

Spam-can drivers almost never replace a part simply because it had been in service long enough. I say almost never because some parts are routinely replaced before they become unserviceable. How about tires? We've already discussed the notion of replacing a battery when its capacity falls below some optimal value. Of course oil and oil filters

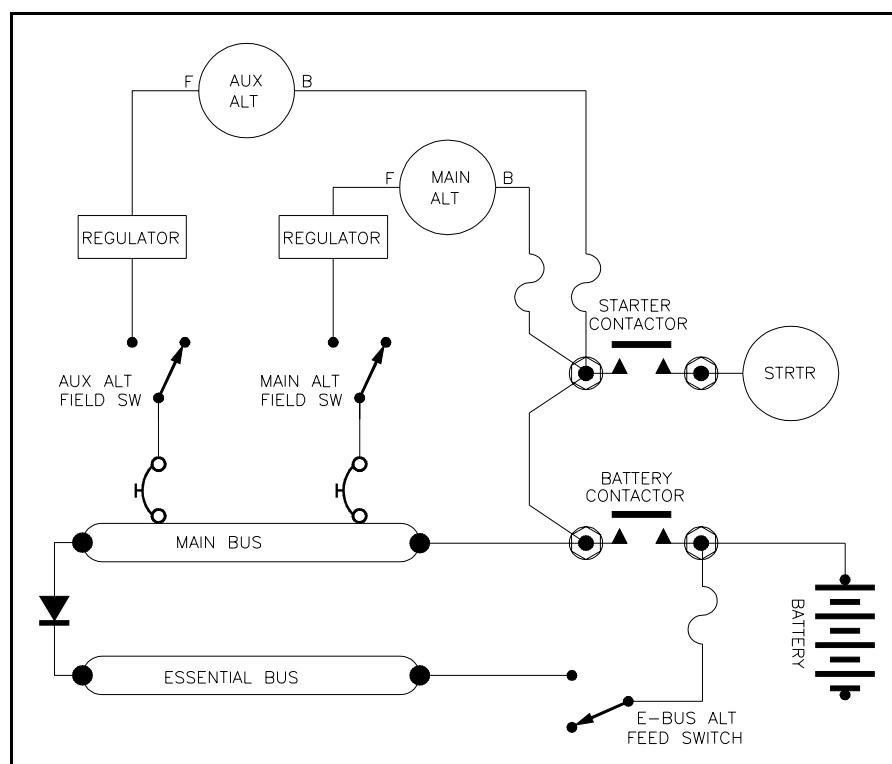


Figure 17-8 Auxiliary Alternator with Autoswitching.

get routine changes before they stop lubricating . . . how about things like switches? Perhaps a fuse block has become corroded in the Florida salt air, how about spending a \$40 and an hour's time to install a new one? If one of your switches has failed and they've been in place for 5-10 years, how about replacing ALL the switches? A horrible thing to contemplate when switches cost \$20-40 each and a high dollar mechanic has to do the job. But suppose you can sit in the pilot's seat of your RV with a nut driver and for less than \$40 and thirty minutes of work, you can have ALL new switches? How do you think this maintenance philosophy would influence the probability of in-flight failure of periodically renewed, high wear components?

Putting it all Together . . .

Now it's time to apply what we know to select an electrical system that fits your airplane and the way you intend to use it. Figure 17-1 illustrates the way 95% of all production single engine airplanes are wired. I've suggested that pilot Gomez's story would have read much differently had his airplane been wired differently. The majority of our builders will find the architecture in Figure 17-2 adequate to their needs. If pilot Gomez's airplane had received the simple modification to provide minimal lighting, primary navigation and rudimentary flight instrument power from an alternate feed to the battery, his story would have not be very exciting. Turn the essential bus alternate feed switch ON, battery/alternator master switch OFF and continue flying the airplane to a comfortable arrival. Of course, we're assuming that the FBO who rented the airplane replaces batteries in their rental fleet when their capacity drops below useful levels . . . yeah, right.

First, let's talk about Figure 17-5, the mother of all electrical systems. The only reason that you'd want to consider this architecture is if you have an electrically dependent and power hungry navigation and instrumentation system. I've had several Lancair and Glasair builders go for the whole enchilada with glass cockpit, three axis autopilot and electrically dependent systems instrumentation. I assume that pilots of these airplanes plan lots of IFR travel that might include long legs over poor landing conditions . . . like lands between LA and Wichita, or even oceans. If your sky chariot is destined for such duty, by all means, study Figure 17-5. In spite of its apparent complexity, this system doesn't have to be heavy. There are 3 pound batteries on the horizon that will crank an engine. Two of these batteries in a dual-alternator/dual-battery installation would perform quite well. Obviously, batteries this small cannot boast much capacity . . . indeed, a pair of such batteries would total only 5 ampere-hours . . . when NEW. You'd certainly want to team these products with exemplary alternators . . . which is not

difficult to do. With small batteries, a ground power jack is a necessity. You just wouldn't want to run airframe accessories without having the engine running or ground power plugged in. The point is that technology exists to replace the old Prestolite pig starters, heavy antiquated generators and alternators and flooded batteries with components having a TOTAL weight that is less than the battery we took out. All of these benefits come with levels of system reliability that will probably never be available to our spam-can driving brethren.

The architecture of Figure 17-2 lends itself to orderly upgrade to either a second battery (Figure 17-6) or an aux alternator (Figures 17-4 and 17-8). The compelling reason for upgrading to dual batteries is when both magnetos have been replaced with electronic ignition systems. If you don't plan to have a vacuum system and want dual electronic ignition, then putting an auxiliary alternator on the vacuum pump pad makes the most sense and you can stay with a single battery. B&C alternators have demonstrated fleet failure rates better than 0.5 per 100,000 flight hours . . . an 8-amp auxiliary alternator is about 5x the price of an 17 a.h. auxiliary battery but it's 1/4 the weight.

If you subscribe to our suggestion for yearly swap around of dual batteries, then the cost of an 8-amp aux alternator takes 5 years to break even with the cost of batteries and you'll carry less weight. Further, two engine driven power sources (with reputations equal to or better than B&C alternators) allow you to rationally consider running a single battery longer. I would be comfortable with battery replacement based only on load testing for cranking ability irrespective of capacity if I had two good alternators.

If you're going to have gyros, then you have to make the vacuum versus electric decision. Electric gyros are more expensive than vacuum devices. They're about the same weight. A vacuum system is about 10 pounds installed, an 8-amp aux alternator is about 5 pounds installed. A vacuum system has quite a few more parts to install and maintain. Finally, wires are easier to install and work around than hoses. As an initial cost savings to get your project air-worthy, consider punching a hole for a DG but put a cover over it and initially install the attitude gyro only. GPS gives you excellent course data. A digital compass is another excellent source of magnetic heading information. I'll suggest that the airplane can be flown quite handily with an attitude indicator and alternative sources for heading/course data.

An autopilot or even just a wing-leveler installation offers a compelling reason for going all-electric. Loss of a single alternator may force you to abandon a valuable pilot assistant

for part (if not all) of the remaining portion of the flight. A second alternator allows you to run a continuous load of 8 amps while saving the battery for heavier, end of flight duties like showing lots of lights, lowering flaps/gear, etc. 8 amps will support minimal E-bus and a light autopilot load quite nicely. Waves of the future are washing over vacuum systems and I am not sad to see them go. I'd take a single, modern alternator over TWO vacuum pumps for securing my future as a pilot any day. Adding a second alternator of any size makes it a no contest decision.

To recap the basic tenants of system reliability:

- The absolute quality of parts has little bearing on system reliability . . . even the BEST parts can break. The best parts can be rendered incapable of operation due to errors in installation or weakness in associated components. For example, what is the value of controlling your landing light with a \$100 switch when you KNOW the lamp is going to barf in 10-20 hours? There are thousands of parts on single engine airplanes that have been shaken, baked, spec'd, conformity controlled, PMA'd, STC'd, TSO'd, ad-nauseam. Does that mean the part will never break? Of course not . . . airplane parts break every day. If airplane parts never broke, FBO repair shops would be out of business . . . As experimental airplane builders and pilots we have better options for development and maintenance of a comfortable flying machine.
- Develop a considered preventative maintenance plan that rotates out aged parts. Batteries in particular need to be replaced LONG before they fail get your engine started.
- Develop simple alternatives for dealing with individual component failures. A cockpit crew on an L-1011 flew a perfectly good airplane full of folks into the Florida swamp when they became preoccupied with troubleshooting a gear-down indicator light . . . One might say the cause of that crash was failure of a lightbulb. More rational analysis suggests an inability of the crew to deal simply with a simple failure. Plan your own cockpit activities to never attempt diagnostics and/or remedies in flight.
- If there are equipment items that you depend on for comfortable completion of flight, have backups for those items. Hand held COMM, GPS and even VOR radios are readily available and less expensive than their panel mounted counterparts. Because they run on internal batteries, they are

totally independent of problems originating in the aircraft's electrical system.

- 99% of single engine airplanes are wired per Figure 17-1, I've illustrated numerous options to improve upon certified aviation's carved-in-stone shortcomings. Do some considered planning on the architecture that best fits your needs. Further, take comfort in knowing that should your needs change or you find that the first pass at a design falls short of your needs, you can FIX IT with a more useful configuration without having to seek blessings from ANYONE..

Nuckolls' first law of airplane systems design sez: "Things break"

The second: "Systems shall be designed so that when things break, no immediate hazard is created."

The third: "Things needed for comfortable termination of flight requires backup or special consideration to insure operation and availability"

The forth: "Upgrading the quality, reliability, longevity, or capability of a part shall be because you're tired of replacing it or want some new feature, not because it damned near got you killed."

I often tell my readers they're building the best airplanes to have ever flown. I explain by noting that people who work on assembly lines simply work a job. They may have special training for the task but by-in-large, if something doesn't fit exactly right, they're strongly motivated to "bend it a little" until it does. If something breaks, it's not uncommon for a group of his supervisors to conference to see how to minimize the time and costs of pushing the airplane on down the assembly line.

You folks WORRY a lot about everything. You generally don't act until you've got the necessary advice and knowledge to do it right. If you mess it up, the parts come out and you do it over. By-in-large, amateur built airplanes have the benefits of care and consideration for doing a good job that factory built ships will never enjoy.

Finally, if any of you have the pleasure of meeting pilot Gomez, congratulate him on his skills and ability to deal successfully with a situation that was stacked against him. Show him your home-built project and explain the value for having total control of your destiny. He may well have a special appreciation for the benefits. Who knows, he might even order up his own kit.



Audio Systems

If you have more than one source of audio to attach to your headphones, you'll need some manner of audio system. Many certified aircraft feature audio selector panels capable of managing audio output from a number

The audio panel illustrated in Figure 18-1 is a sort of mid-range product that might be found on a well fitted single engine or light twin aircraft. Turboprops and bizjets are more likely to have independent audio selector panels for pilot and copilot where either crew can be listening and talking on their choice of radios.

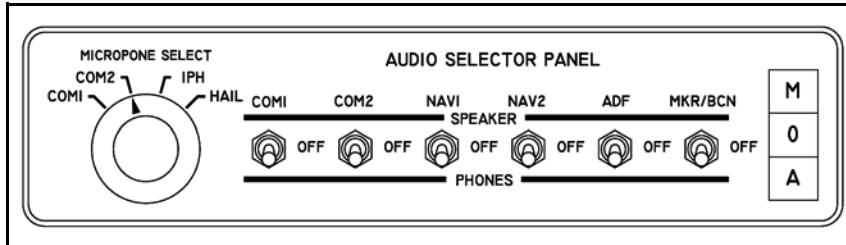


Figure 18-1. Typical Audio Selector Panel for Spam Can

of receivers and routing microphone inputs to two or more transmitters. They might also offer a marker beacon receiver and intercom features. A multi-engine aircraft might be fitted with a speaker in the nose wheelwell wired to a small public address amplifier in the audio panel. The pilot can select a "hailing" operation where it's possible to speak to persons on the flight line with sufficient volume to be heard over ambient noise. If one wished to play ATC communications or an AM radio broadcast through a speaker in the cockpit overhead, one simply moved the audio selector switch for that radio to the SPEAKER position. Aircraft manufacturers of yesteryear were loath to admit that their cabins were uncomfortably noisy . . . I wonder if current production single engine aircraft have cabin speakers?

In a more practical age, it's an easy sell to suggest that the cabin noise levels in piston engine aircraft are at best uncomfortable and worst unhealthy. Cabin occupants enjoy the experience more and land less fatigued when headsets and microphones provide ambient noise reduction and a conduit for more relaxed communication. Many commercial audio panels provide an interphone or intercom function as well.

If we're to understand audio switching philosophy, we first need to discuss the energy details of how audio systems work. In particular, we need to understand terms like "impedance" and how it is used and misused when speaking of the capabilities of system components.

It's not uncommon to see the output specification for an audio amplifier stated as "100 milliwatts into 600 ohm load."

Many individuals including folks who sell these products believe this means the output impedance of the amplifier is 600 ohms. Not so . . . and it's important to understand why. Consider your ship's battery as an energy source. In previous chapters we've discussed the importance of low internal resistance. If you want your 12 volt battery to deliver 200 amps to a starter (an effective load on the order of 0.05 ohms) then we'd be very pleased if the battery had NO internal resistance. Of course, there's no such thing as a perfect battery but it's not uncommon for a 12 volt RG battery to have an internal impedance on the order of 10-12 milliohms or less.

Borrowing from the chapter on batteries, I've shown in Figure 18-2 how the battery delivers power to the starter with reasonable efficiency. In this case, about 20% of system power is expended in the battery's internal impedance of 12.5 milliohms with 80% of it being used to drive the motor with an effective impedance of 50 milliohms. In audio system parlance, we might say that the battery's output is capable of delivering 2,000 watts

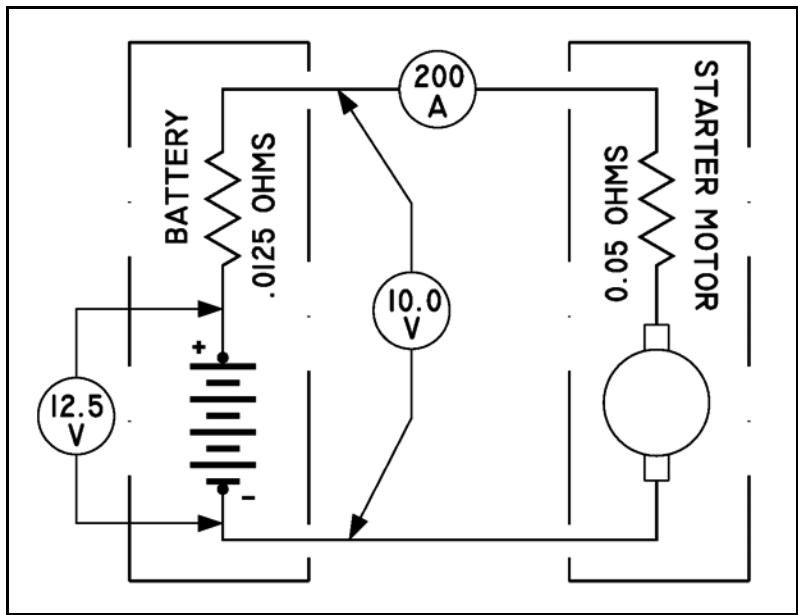


Figure 18-2. Battery Internal Impedance

into a 50 milliohm load. This does not mean that the battery's output impedance is 50 milliohms.

Suppose it WERE 50 milliohms. An internal impedance of 50 milliohms in series with the load impedance of 50 milliohms makes for a total of 100 milliohms. This

means that the MAXIMUM current the battery can deliver to the motor is reduced to 125 amps with HALF the total energy being dumped off as heat internal to the battery.

Okay, let's consider the case of an audio amplifier intended to deliver energy to a pair of headphones in Figure 18-3. The design goals for the amplifier are no different here than for the design of a battery. We'd like for the internal resistance (R) of the intercom to be as low as practical. Typically, a modern integrated circuit headphone amplifier will have an output impedance on the order of 5 ohms or less. This is an important consideration when we start to combine multiple audio sources into the headset system. The same rules apply whether the audio comes from a comm transceiver, an intercom amplifier, or a stall warning tone generator.

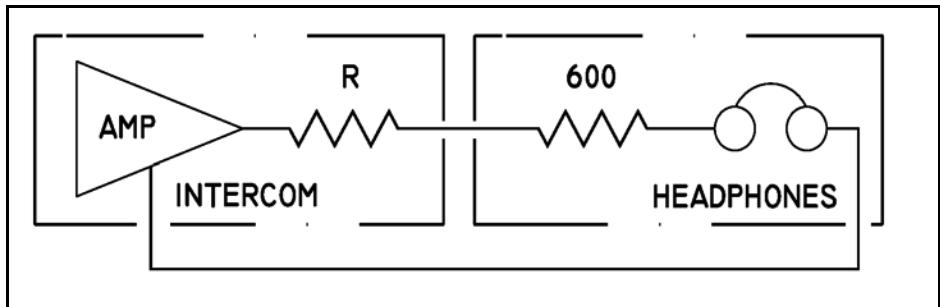


Figure 18-3. Audio Amplifier Internal Impedance

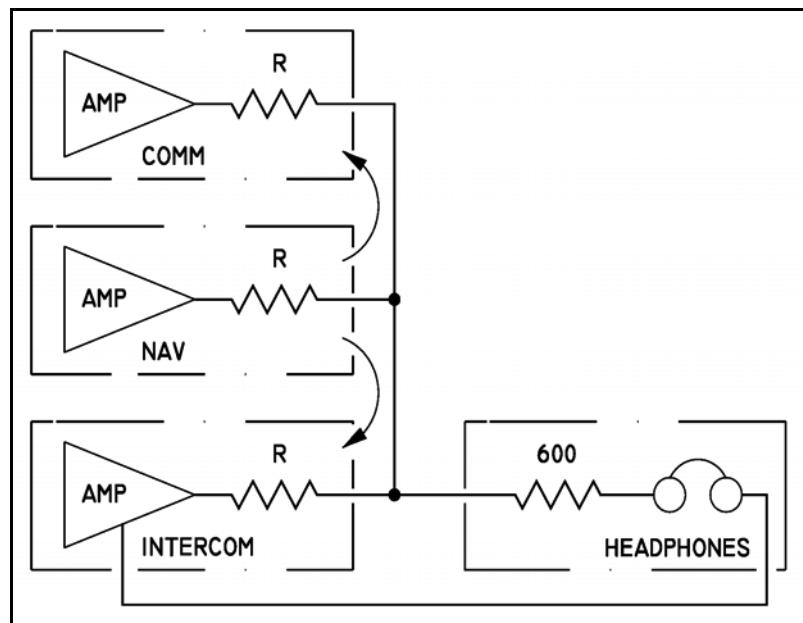


Figure 18-4. Paralleled Audio Sources

Let us consider potential problems with simple combining of audio sources to a single headset. Figure 18-4 I've hypothesized a comm transceiver, nav receiver and intercom outputs simply paralleled and connected to a headset. Let us suppose the nav receiver is trying to talk to us. Its output is indeed connected to the headset but what does the nav receiver "see" in the way of loads when looking back into the comm and intercom amplifiers? Two very low impedance values with a sum that is a small fraction of the headset load. Compared to the expected 600 ohm headset load, the amplifier sees what appears to be a nearly dead short as a load.

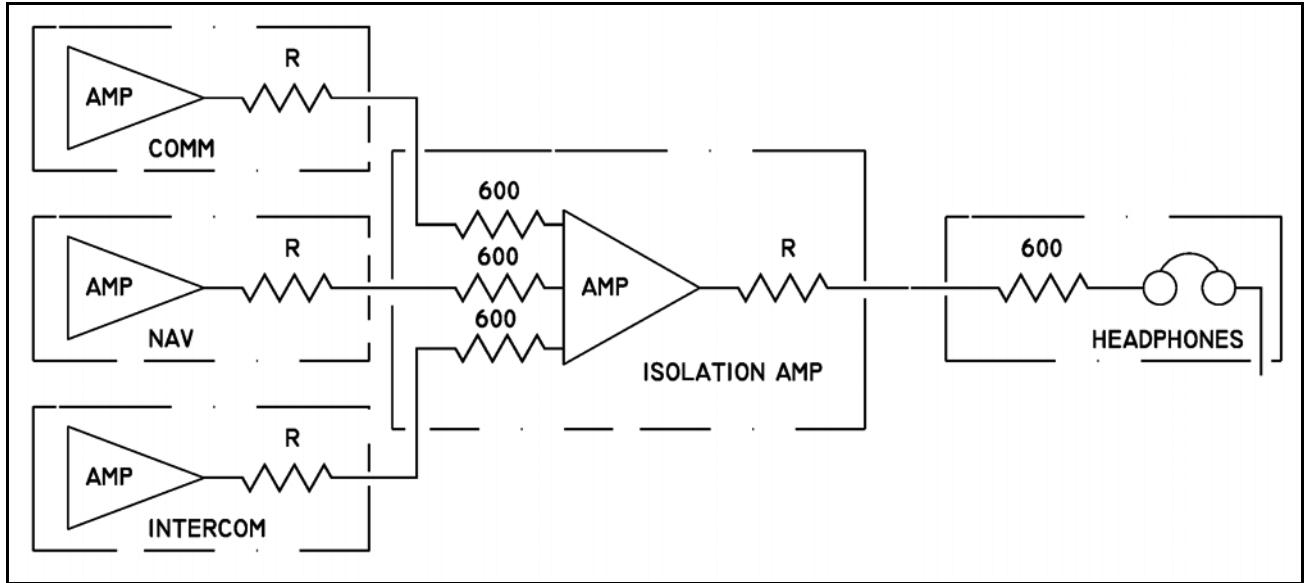


Figure 18-5. Audio Isolation Amplifier

Net result is that MOST of the audio energy is dissipated in the companion sources that are also low impedance LOADS with very little left over to tickle the headphones.

The solution is to craft a means of mixing multiple audio sources together in a manner that has each source believing that it's driving a pair of headphones. Headphones present some "load" to the source that a source can only identify in terms of its electrical characteristics. In this case, we're looking for a way to "load" each source with a reasonable impedance and do it in a way that isolates each source from the effects of loading by the low output impedance of companion sources - hence the term "isolation amplifier."

Figure 18-5 illustrates the functionality of an isolation amplifier. Multiple inputs (each having some characteristic that approximates headphones) are independently combined in a mixing amplifier which in turn drives headphones.

Stereo Audio Systems

Many pilots and their passengers enjoy listening to stereo music or radio while en route. The only difference between

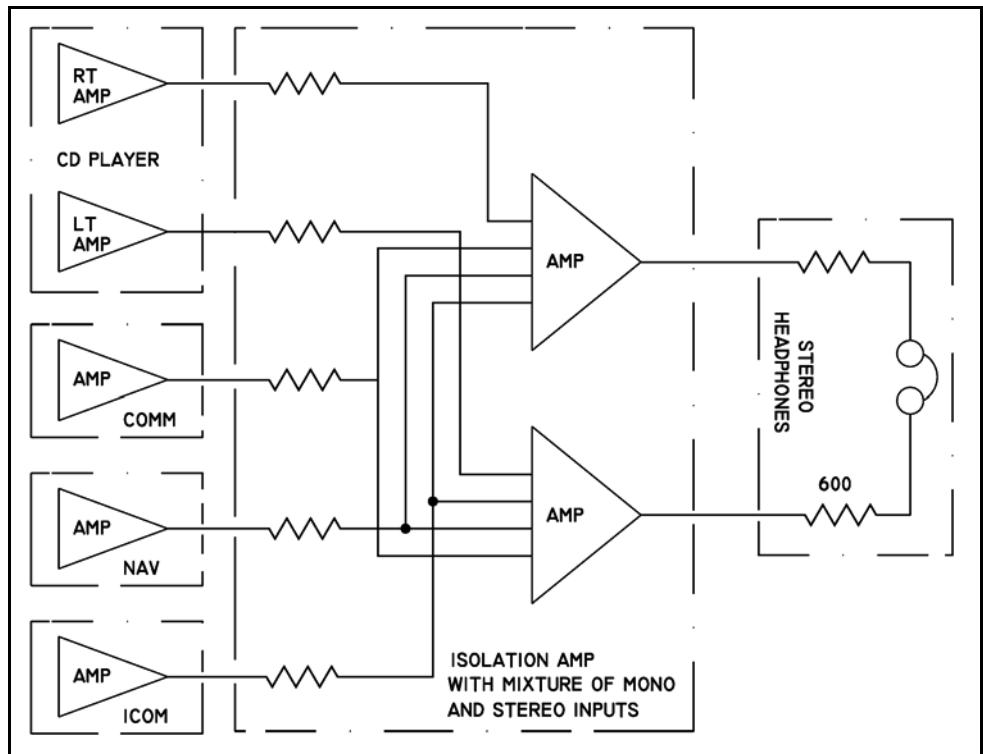


Figure 18-6. Stereo/Mono Isolation Amplifier

monophonic and stereo audio systems is that there are two channels of audio connected to right and left ear pieces of a headset. Figure 18-6 illustrates a technique for combining two monophonic isolation amplifiers in a single assembly. Stereo audio from the music source is routed to separate amplifiers while monophonic sources (avionics and warning tones) are routed to both channels simultaneously.

Note that I don't show the resistor that accounted for the output impedance of each amplifier. That doesn't mean they aren't there. I needed to simplify the drawing so it would fit nicely on the page. ALL sources of energy have an output impedance associated with them whether it's an alternator, battery, audio amplifier, microphone, etc, etc. ALL devices that load an energy source have a load or input impedance. If one is having difficulty achieving the desired behavior in any combination of components, characteristics of output and load impedance should be part of the consideration for trouble-shooting the design.

When you're installing plug-n-play hardware such as intercoms, radios, entertainment systems, etc. the manufacturer should do his reasonable best to describe a wiring scheme that produces acceptable results most of the time. However, when your game plan requires some departure from (or expansion of) the original system concept, be prepared to deal with the not-so-obvious issues like we're discussing here.

In the world of \$high\$ airplanes we call the chefs "avionics integration experts." Had a fellow working for me at Lear on the Gates-Piaggio program back about 1982. He had a wealth of experience with the input/output characteristics of most popular system accessories. He could sit down with the installation manuals of any combination of systems and produce wiring diagrams with 99% probability of successful operation first time it was turned on. A number of folks joined and left the group over my tenure at Lear . . . none of these transitions gave me heartburn. However, if my integration guy had suffered itchy feet, he would have been very difficult to replace.

It's not uncommon for a builder to post a note on a discussion group asking whether or not his particular box of goodies can be installed in his airplane. The answer is almost always a qualified "yes" but then he's disappointed that nobody can offer a turnkey description of the task. It's not a matter of lack of knowledge or skills on the part of respondents but a lack of experience with that particular combination of goodies. Just about any combination of accessories can be successfully integrated into your project but be aware that some interface issues may take some detective work where

signal characteristics combined with energy transfer (output impedance vs. load) will have to be understood and accommodated.

Audio System Controls

There's something appealing about an airplane panel covered with dials, switches and knobs. But when you consider the pilot to be an integral and critical component of the low-risk flight system . . . consider the real value of any cockpit accessory. Does it increase work load or reduce work load? Will inadvertent misplacement of the control markedly increase risk? One time I came close to dying in an airplane was after I announced my intentions to back-taxi on a runway, I pulled onto the asphalt to find myself looking down the business end of a light twin that had just landed.

They say every accident is always a series of conditions that set up the end result. It was just before sundown on a cloudy day. The twin had made a flat approach and was below the tree-line beyond the far end of the field. I didn't see any traffic in the "sky" and he wasn't running forward shining lights. I was listening to the right frequency but my radio got tuned after he announced short final. My microphone selector switch was set to the wrong transmitter so my announcement to take the runway wasn't heard by the other pilot.

I gunned it and headed for the grass, he applied power and did a touch-n-go . . . we didn't really come close enough to yell at each other but that was only a matter of random good fortune in timing.

IF he had turned on landing lights, IF I had turned to local advisory frequency a few seconds earlier, IF I had selected the right transmitter, IF . . . well, we all know how it goes. So just a word to the wise when you configure the controls for a sub-system that plays a role in setting the odds for an enjoyable day of flying. The switch set wrong or knob turned to the wrong position may be the last link forged in the chain that drags you into an accident.

Radios with audio outputs always have volume controls. Many audio sources in the form of alarm tones have screwdriver adjustments for volume so that the installer can set the warning tone level to harmonize with other sources. If you build a warning tone generator (stall warning, gear warning, canopy warning), consider inclusion of screwdriver adjustments for output levels on each tone.

Headsets often have volume controls built in. These are handy when headsets with different efficiencies are paralleled on a single isolation amplifier. If volume of all sources is optimized for one occupant of the cockpit, they may be too loud or too soft for the other.

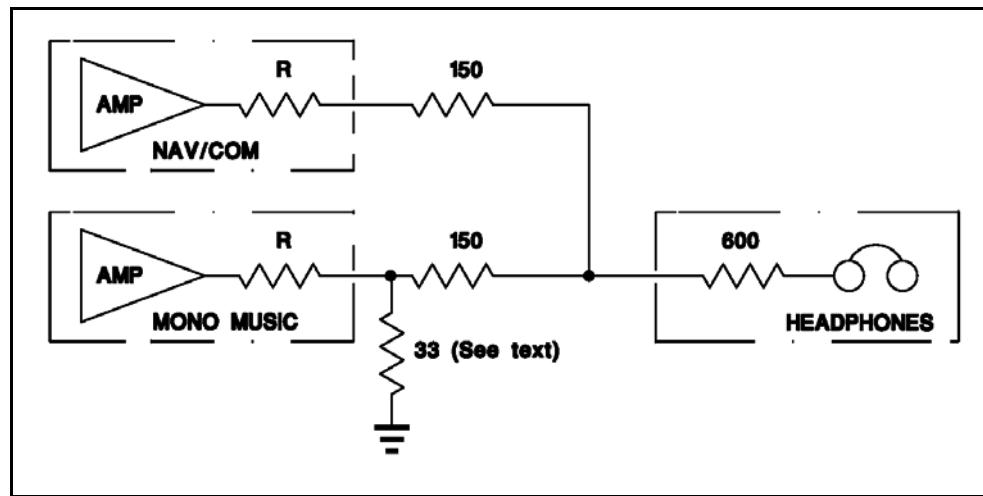


Figure 18-7. Headphone Audio for a Rudimentary Avionics System.

The very simplest audio system has no selector switches, no volume controls other than those provided on the audio source and headphones. In these cases, set up is also simple. Adjust headset controls for 2/3 of max volume. Set warning tones for a level just under comfortable listening levels for radios. After that, it's a simple matter of turning the volume up or down on the radio that you want to listen to or de-select.

This philosophy (assuming no cabin speaker and associated amplifier) makes it possible to craft an audio system without source selector switches like those shown in Figure 18-1.

Single Seat Rudimentary Avionics

Let us suppose your airplane is a single seat, day/vfr machine with a Nav/Com and a monophonic tape player. Your headphone mixing system may well be as simple as a pair of 150 ohm, 1/2-watt resistor wired as shown in Figure 18-7.

The biggest risk with this simple architecture is the potential for distorted audio from the tape player (or any other entertainment audio source) because its audio output system is designed to drive a much lower load impedance. In this case, one might have to artificially load the audio output line of the entertainment system. I show a 33

ohm resistor here (most lightweight headphones designed for portable use have an impedance in the 35 ohm range). The same condition may exist for stereo systems as well . . . you'll need a load resistor for each channel.

Two Seat Rudimentary Avionics with Intercom

Figure 18-8 climbs a little higher on the hill of audio system complexity. A two seat airplane is likely to have an intercom system.

Further, many manufacturers offer aviation intercom systems designed to drive stereo headphones and to accept stereo audio from an entertainment system.

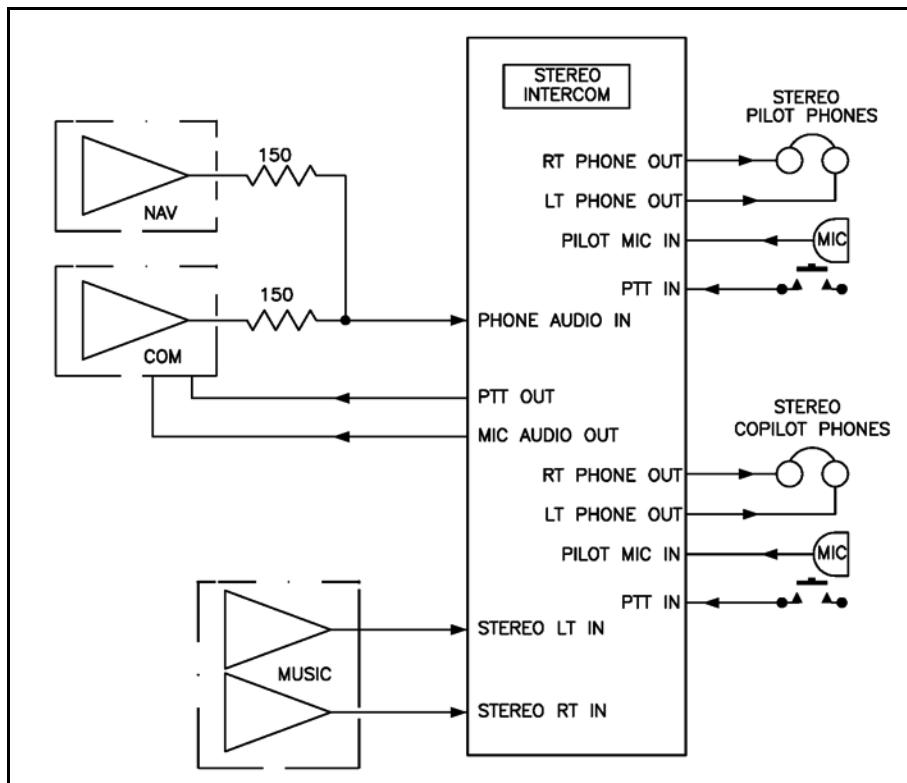


Figure 18-8. Rudimentary Avionics, Stereo Music and Intercom.

Some stereo compatible intercoms also offer a crew isolate function switch that separates the pilot audio system from the copilot system so that the passenger can continue to listen to the entertainment system while the pilot is working with pilot duties and would do best without distractions from the entertainment system. Intercom systems are universally designed to accept a single monophonic audio source from the ship's radios. If you have only two sources of aviation audio as illustrated here, then the simple resistor-mixer network suggested in Figure 18-7 may be used here as well.

Intercom System Selection

It's my recommendation that whatever intercom system you choose to fly with, make it a panel mounted system as opposed to portable. Panel mounted systems will offer a means by which the intercom may be powered from the ship's electrical system.

Further, panel mounted intercom systems will be fitted with connectors, usually D-subminiature, that are a whole lot easier to wire to your radios than fussing with cords that come with portable systems. Finally, the panel mounted system will look like it belongs in your airplane.

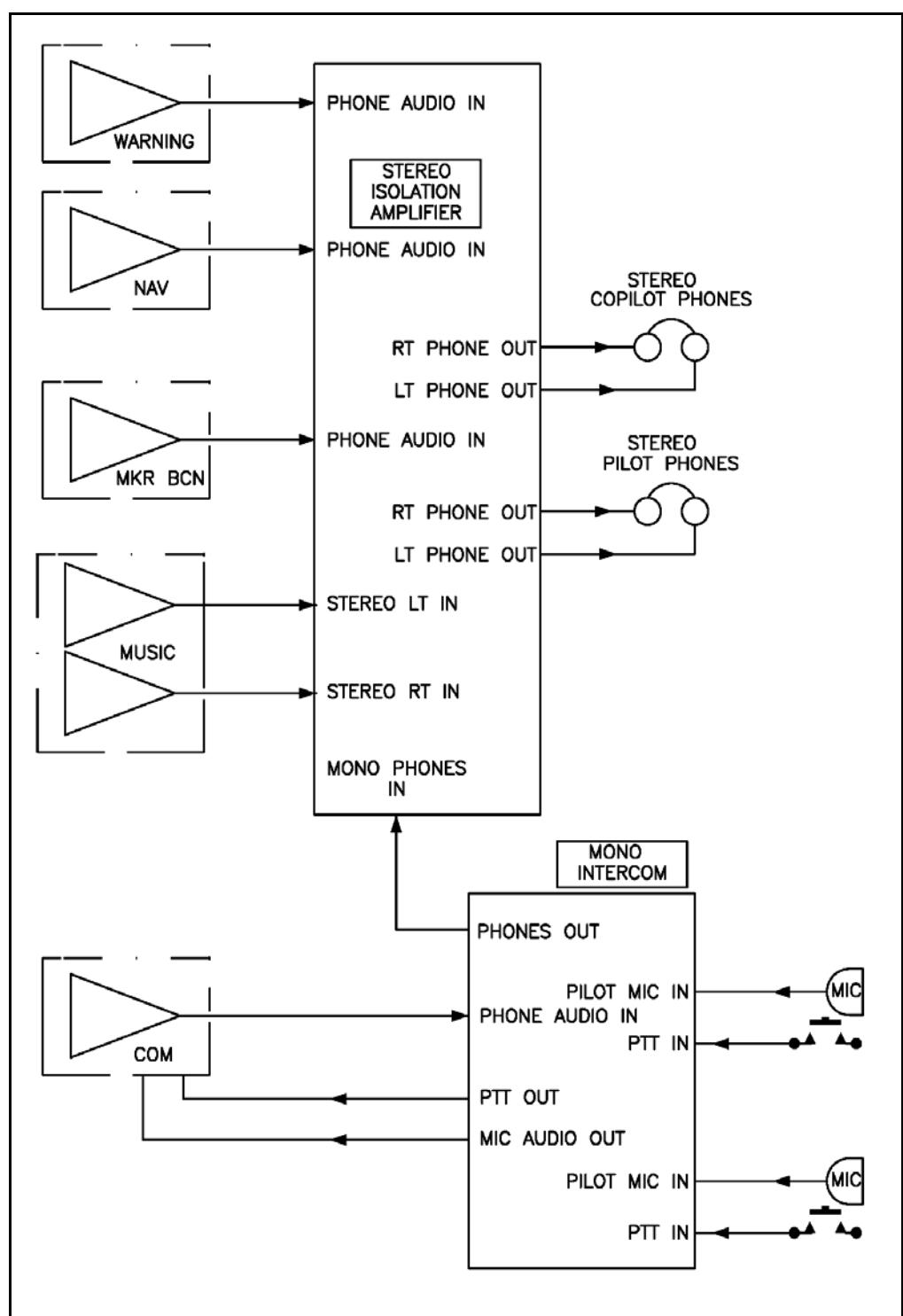


Figure 18-9. Mono Intercom, Stereo Isolation Amplifier and Multiple Avionics.

Full-Up Audio Systems

Audio selector panels typical of that illustrated in Figure 18-1 will include an audio isolation amplifier. In fact, most.

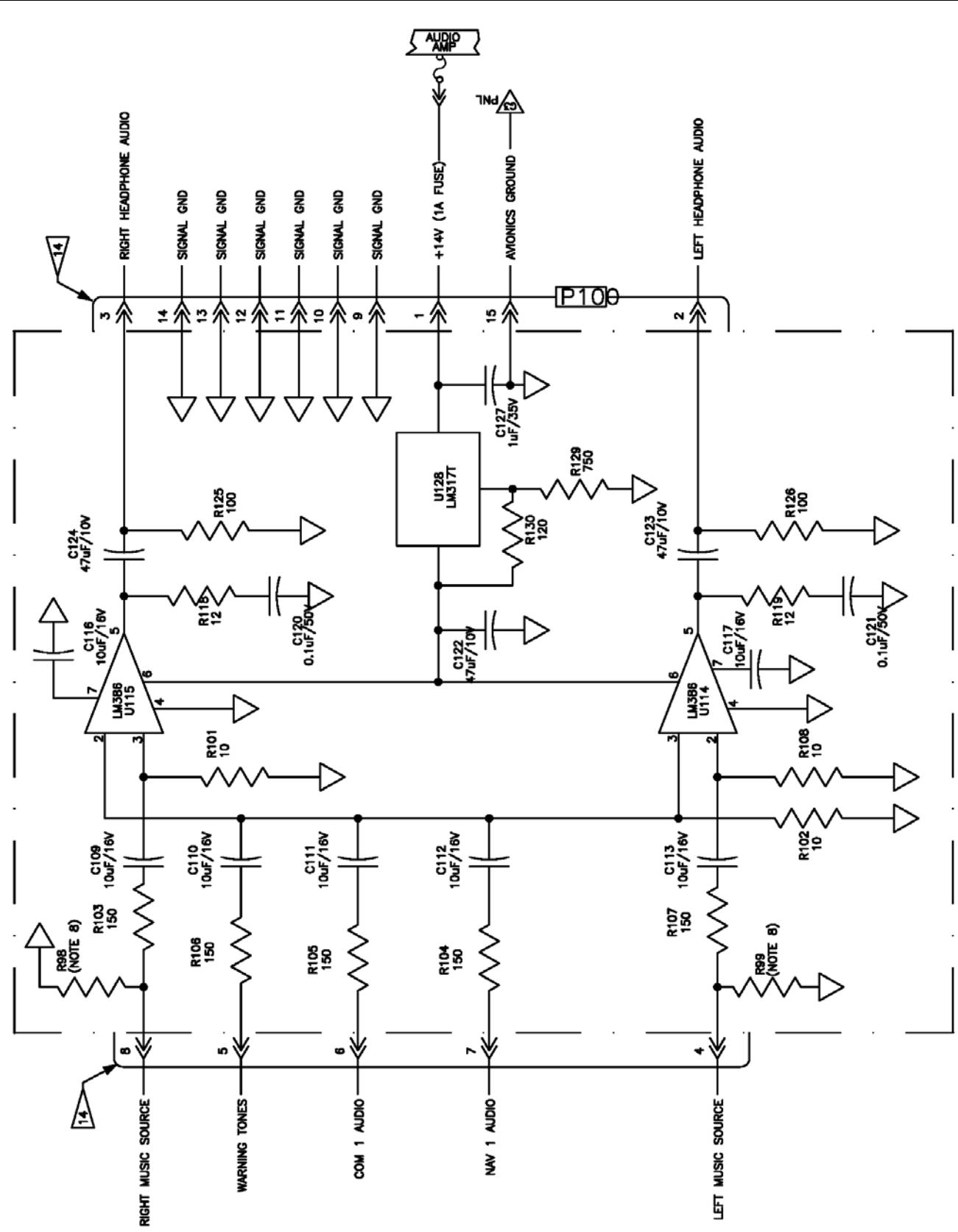


Figure 18-10. Schematic Exemplar Audio Isolation Amplifier

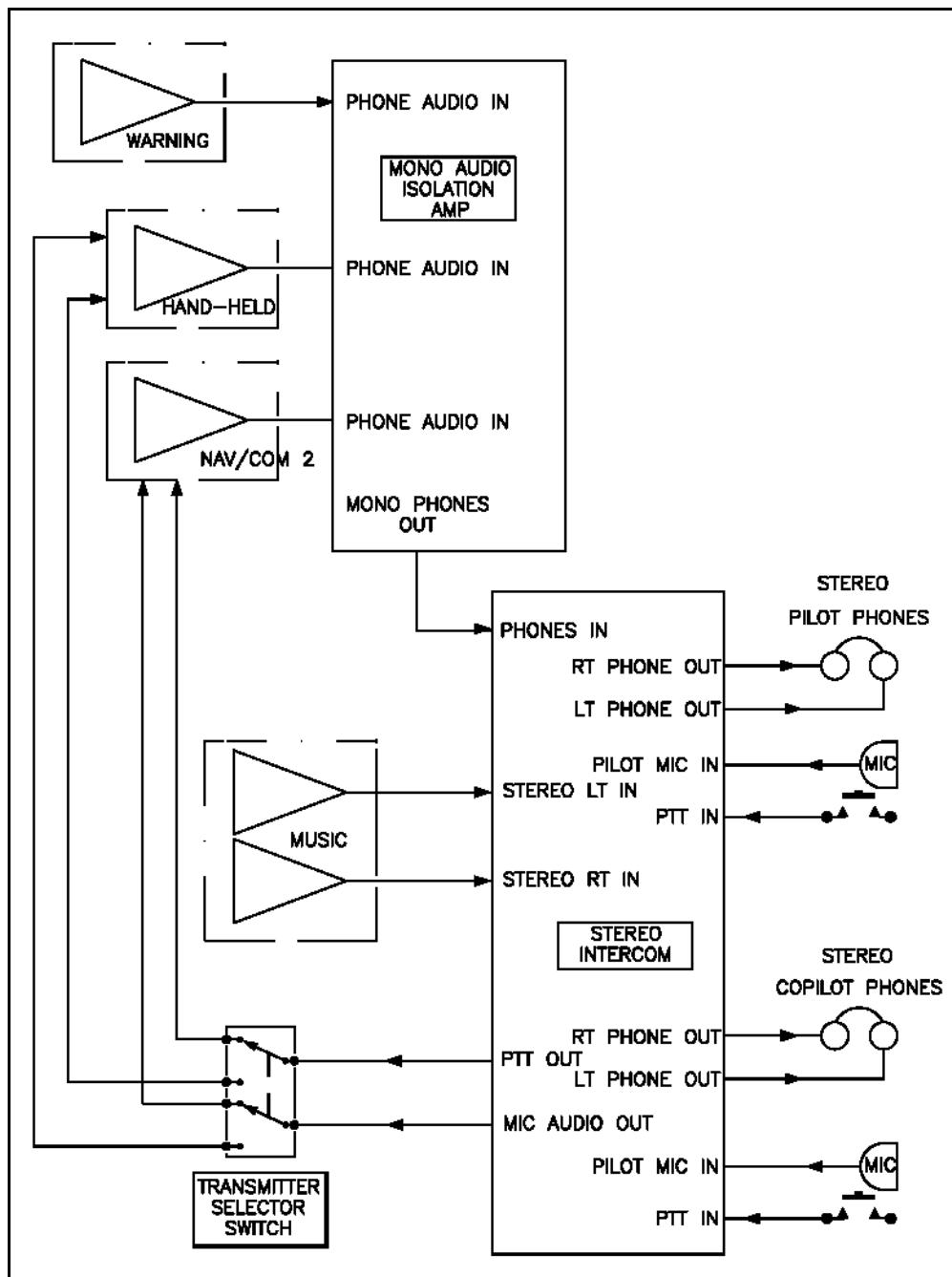


Figure 18-11.Two Transceivers, Stereo Intercom, Multiple Avionics Sources

offer TWO amplifiers. One to drive headsets and the other for cabin speaker.

Very few Owner Built and Maintained (OBAM) aircraft are fitted with cabin speakers so our first pass on a full-up audio system will feature a single audio isolation amplifier as first described in Figure 18-6. Let's take a more detailed look into use of the isolation amplifier. Figure 18-9 shows the system architecture for

incorporating a simple audio isolation amplifier that will handle a number of aircraft audio sources along with a stereo entertainment source

Do it Yourself Audio Isolation Amplifier

Figure 18-10 is a more detailed schematic of how a useful isolation amplifier can be assembled. Parts for this project are readily available from suppliers like Radio Shack and Digikey. An etched circuit board for this amplifier along with bill of materials and detailed assembly information are available from the 'Connection's website at <http://aeroelectric.com>.

Figure 18-11 illustrates another variation for audio management. This system assumes that your intercom system will accept a stereo entertainment source such that your avionics sources may be mixed together in a monophonic isolation amplifier. This figure also illustrates a simple two-pole, double throw switch for selecting which of two transmitters will get push-to-talk and

microphone audio signals. The second transmitter is shown as a hand-held but it could just as easily be a panel mounted radio. Switches and volume controls are a noteworthy exclusion from the architecture drawings. In a do-it-yourself amplifier, adjust the the 150 ohm resistors shown for each input to achieve proper balance of volume from various audio sources.

After your system is wired up and ready to test, compare

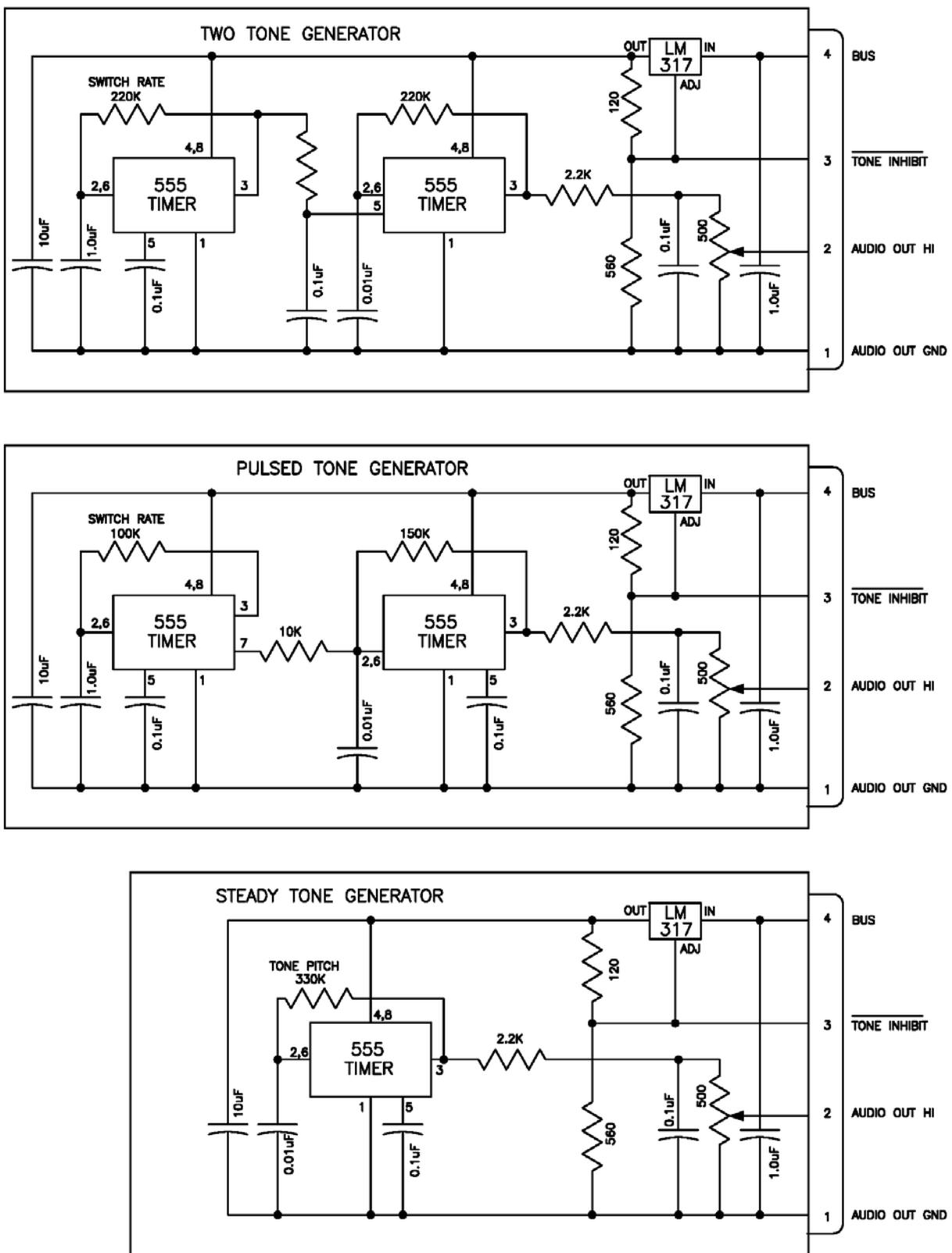


Figure 18-12. Schematics - Warning Tone Generators.

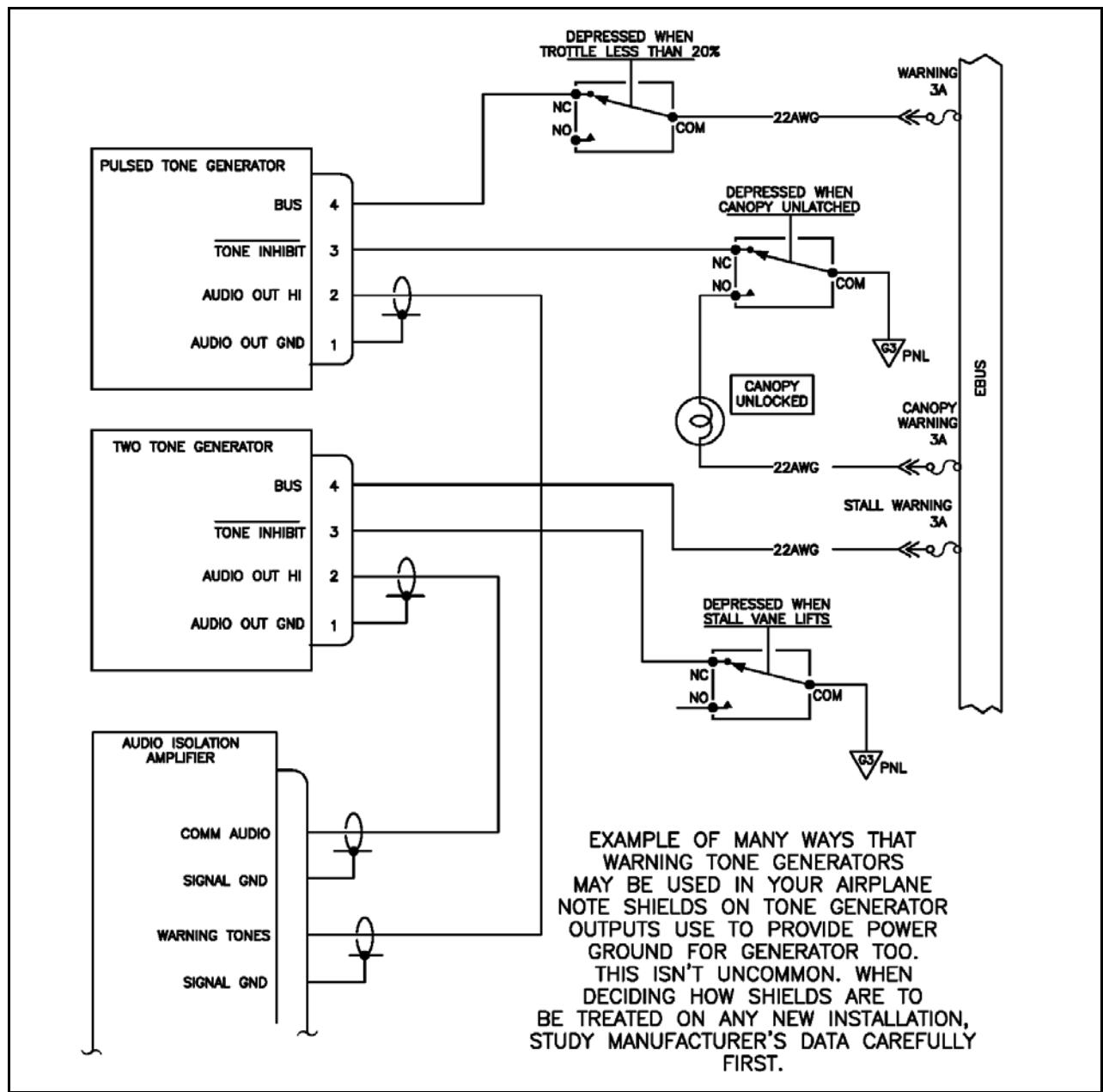


Figure 18-13. Exemplar Warning Tone System

the various audio sources for intensity. Receivers will have volume controls on the front panel. If you have a headset volume control, set it for about 2/3rd travel toward maximum. Radio receivers should be comfortable at some point between 1/4 and 3/4 travel on the front panel controls.

This leaves fixed volume sources like warning systems. Making the 150-ohm resistor larger reduces volume, making it smaller increases the volume. Make resistor adjustments in 2x or 1/2 jumps: I.e., if 150 ohms is too loud, try 300 next, if still too loud, go to 600 ohms.

Conversely, if too soft, drop to 75 ohms and then 36 ohms. Once you're in the ballpark with one of these large jumps, you may find that some value between the too loud and too soft will get it right.

Once the proper value is determined, it can be permanently soldered in place of the 150 ohm resistor that handles that particular audio source. It's a bit time consuming but the design goal is to minimize the number of "stacked" controls. For example, in several airplanes I fly, headset volume can be adjusted by the radio's panel mounted control, the audio isolation amplifier's control, the intercom's control and finally, the volume control on the

headset.

It's not a really big deal but I think it's good design to eliminate as many chances for error as possible in the interest of hearing things of interest on the radio or from your warning system.

Warning Tone Generators

Some off-the-shelf systems monitors may come fitted with alarm tone outputs. These are simply wired to one of the iso-amp inputs and adjusted for volume as needed. There may be instances where you'd like to generate your own alarm tones for things like stall, gear, or canopy warning. It's not difficult to build tone generators with distinctive characteristics so that several installed warnings are distinctly different.

Figure 18-12 illustrates three styles of tone generators easily fabricated with commonly available parts. These generators utilize the ancient but quite versatile 555 timer which is one of the oldest designs still in production. For a two-tone or pulsed tone generator, two timers are used. One to generate the tone, the other to modulate it either in pitch or in on-off rate. The last circuit is a single, unmodulated tone generator. Figure 18-13 suggests some ways that these generators might be used.

Avionics and Panel Ground System

For years, the OBAM aircraft community has taken advantage of the noise reducing qualities of a single-point ground system. This philosophy has been described in Chapter 5 on electrical system grounds.

The whole idea behind the single point ground is to avoid introduction of noise into vulnerable systems because the victim system is “grounded” in more than one place on



Figure 18-14. Manufactured D-Sub Ground Block

a conductor (usually the airframe) that is also carrying

large and noisy loads like pitot heat, landing lights, battery recharge currents, etc.

The forest-of-ground-tabs technique described in Chapter 5 is entirely suitable and convenient for most equipment in the electrical system. However, while it is electrically



Figure 18-15. DIY D-Sub Ground Block, Rear View

correct to wire all the panel mounted equipment to the same ground block, the total number of wires can be significant.

Further, given that there are a number of small signal systems vulnerable to noise concentrated on the panel, it makes sense to create a separate and co-located ground system for these potential victims. Given that panel mounted equipment items draw relatively small amounts of current, the ground bus can be fabricated using very compact hardware compared to the forest-of-ground-tabs.



Figure 18-16. DIY D-Sub Ground Block, Wiring Side

This seems to be one of many applications for the D-subminiature series connectors.

Figure 18-14 shows a permanently mated pair of 37-pin D-sub connectors mounted to an etched circuit board where all the pins are bussed together. This device offers a compact means by which instrument panel equipment grounds can be brought to a single location.

Builders can easily fabricate their own D-sub panel ground by soldering a pair of reasonably fat wires 14-16AWG to all of the solder-cups on the back of a female D-sub connector. The male connector shell should be mated to the

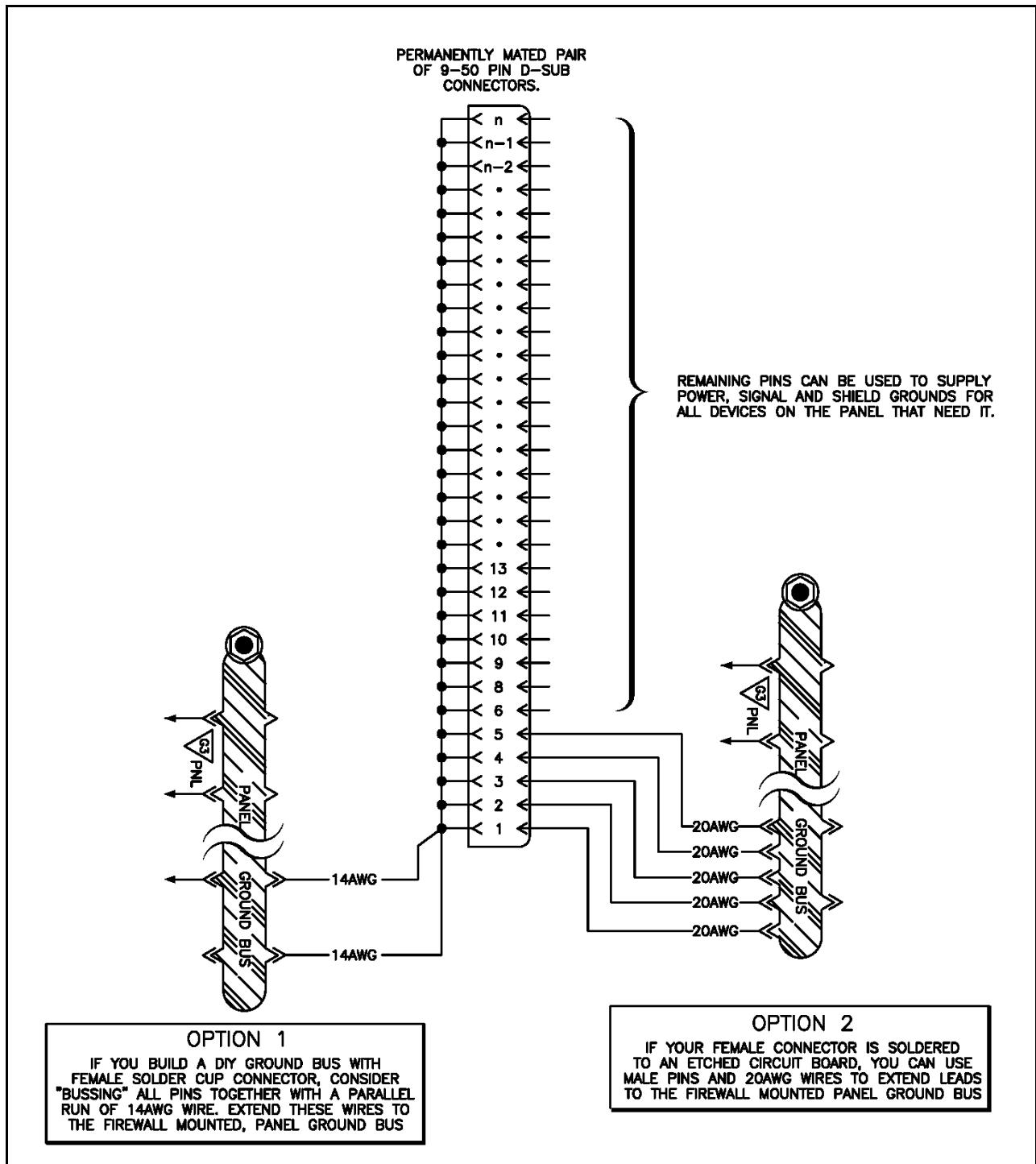


Figure 18-17. Electrical Architecture Options for an Avionics Ground Bus

female connector in a manner that will make sure the mated connectors stay stuck together. I use a spot of super-glue on the threads of the mating screws.

Once the connectors are mounted on the panel assembly, ground wires from various accessories can be easily

terminated in a male D-sub pin and installed in the ground block.

When installing your ground block, keep in mind that you need access to remove pins using the D-sub insertion/removal tool . . . so leave sufficient clearance for

this operation. Some radios call for multiple grounds and will show them on the installation wiring diagrams. If you've picked a nice fat D-sub connector from which your avionics ground block is fabricated, you'll have plenty of ground pins to accommodate the needs of every system.

Except in cases for very simple panels, I'd install a 37-pin avionics ground as a minimum . . . and a 50 pin wouldn't be out of line. That's the really nice feature of this technology, you can have plenty of spare ground pins for very little expenditure of real-estate on the panel.

An array of five 20AWG or two 14AWG wires can be used to extend the avionics ground to the firewall ground block. See figure 18-17 for a schematic of this architecture

Some Notes on Shielded Wires

There are few materials materials used on aircraft that are so poorly understood and often mis-applied as shielded wire. As we mentioned in the chapter on noise, shielding a wire breaks a very specific coupling mode - electrostatic. Electrostatic coupling occurs because of the capacitive nature of two wires running in close proximity (in the same bundle) but separated from each other by virtue of their insulations which forms the dielectric of a capacitor. The value of this inter-wiring capacitance is measured in picofarads per foot. A picofarad is a 10^{-12} one million-millionth of a Farad . . . a very small capacitance indeed. The only kinds of signals that couple significantly across this tiny capacitance are characterized by very fast rise times (square waves or very spiked waves) and high voltage. It stands to reason that magneto p-leads with their approximately 300 volt signal across the open mag-switch and very trashy waveform would have some risk of coupling to other wires in a wire-bundle. Hence the practice which always suggests the shielding of magneto p-leads.

Are there other signals conducted on wires in the airplane which present a similar risk? Well, maybe the strobe wires running from power supply to lamp fixtures on tips of wings and tail.

How about potential victims? Well, the audio input wires to and audio isolation amplifier are somewhat vulnerable due to the very sensitive nature of the human ear. If you were to tie your intercom system wires into the same bundle as p-leads and assuming poor shielding practice of the p-leads, it's almost a certainty that you'll hear every plug firing in turn on your headsets. However,

given the unique nature of avionics and strobe or magneto systems, it's both unlikely and poor practice to bundle these strong potential antagonists together with potential victims like audio wiring. The bottom line is that once the strobe and p-lead wires ARE shielded, the likelihood of any problems arising due to LACK of shielding is small.

I'll suggest that on small aircraft (no long bundles running 10, 20 40 feet through fuselage) one could substitute shielded wires with twisted pairs, trios and quads of unshielded wire for the whole suite of avionics components with no ill effects. I'll suggest further that there is greater risk that shielding improperly terminated at both ends is 100x more likely to be the root cause of a noise problem (due to ground loop) than if the wire had never been shielded in the first place (electrostatic coupling to some high noise wiring).

I've used shielded single-strand for simple tasks like hooking up the LED indicator on my Low Voltage Warning light kit. It's a natural for wiring to the back of a leaded LED. Polarity of the connections is preserved without use of colors or marked wire . . . center conductor is (+) and shield is (-). In this case, shielding is entirely unnecessary but the wire was attractive simply because of the mechanics of fabrication and installation.

Therefore, when installing a new piece of equipment where the use of shielded wire is indicated, follow the instructions. There are no hard and fast rules whether one or both ends the shield have connections and schematics that come with instructions are your best guide.

Summary

The audio system installation along with an avionics/panel ground bock are the central hub for much of what's on your panel. Very simple systems can mix two audio sources directly to the headphone circuit with a pair of resistors. However, if you anticipate multiple audio sources such as receivers, intercom, entertainment and warning tones, some form of audio isolation amplifier will be necessary.

If you have more than one transmitter, a transmitter selector switch for the microphone and push-to-talk will be needed. Finally, try to reduce the numbers of series volume controls and/or selector switches to a minimum. The fewer the controls, the less likely you are to miss some important information over the radio because some control wasn't set where it should be

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Appendix Z

Power Distribution Diagrams and Options

What's New . . .

Revision 12A incorporates all the interim revisions to the Z-figures published to date. It reinstates drawing Z-24 with enhancements and adds drawing Z-33. Figure Z-10/8 was added to suggest a combination of features in Z13/8 and Z-14 to support accessories that don't tolerate battery voltage sagging during the starter inrush interval. Unlike Z-14, this variation adds only the weight of a small support battery that's not used for engine cranking. Revision 12A also adds a patch to SD-8 alternators to make them "self-exciting". See Z-25 and Note 25.

How to use these drawings

The drawings offered in this chapter are intended to convey suggestions for electrical system architecture and should not be used to select use of circuit breakers versus fuses, sizes of breakers or fuses, sizes of wire or even to decide what accessories will receive their power from which bus.

The architecture drawings depict a variety of power distribution philosophies from which the builder may select a scheme that adequately addresses the way the airplane is to be used. The various architectures speak to design goals for meeting operating features and overall flight system reliability as discussed in Chapter 17. Further, many accessories such as progressive transfer switches, combined boost-pump and primer circuits, etc. can be intermixed between various architectures. When crafting a plan be cautious about making changes to the *architecture* or *operational* features of the Z-figure upon which your project is based. These drawings have evolved over the 20+ years that the 'Connection has been supporting the owner built and maintained (OBAM) aircraft industry. Features shown are thoughtfully crafted. Changes should not be implemented without thinking through the potential for unintended consequences to the reliability or serviceability of your finished system.

If you find that a drawing depicted herein falls short of your needs or expectations, join us on the AeroElectric-List which can be accessed at matronics.com/subscribe. This is an e-mail based forum where you can post your concerns and take advantage of the collective experience of hundreds of builders like yourself who have similar questions.

Study the diagrams and pick one that most closely matches your mission, budget and features. Then craft a document that lists each bus on a separate page, the items to be powered from that bus and the steady state current that each item draws based on the operational situation for the airplane.

About the "missing" Appendices A, C and K. In some places throughout this book you'll find references to a list of vendors from which you can order catalogs. I generated that list about 15 years ago when we began to develop the AeroElectric Connection . . . at that time, the shelves above my desk held a hundred pounds of catalogs and I thought it might be a good idea if all of you had access to the same parts data that I did. I published a list of the most useful catalogs above my desk in **Appendix A**. After a time, I began to receive calls from readers asking, "Okay, I got all the catalogs, I see about 10,000 switches in there . . . which ones do I order?"

Hmmm . . . it seems I didn't help much. I just made the list of choices longer and harder! A few revisions later, the out of date list was deleted. Today, it's even less appropriate - most of those catalogs have disappeared off my own shelves. The suppliers I work with have Internet sites and we interact with them almost totally by computer.

Appendix C was a brief catalog of products and services. This feature has expanded greatly and moved to our website at <http://aeroelectric.com> and/or the B&C Specialty Products website at <http://bandc.biz>

Appendix K used to have a couple of construction articles.

A survey of our readers showed that very, very few people found the information useful. Soooo . . . instead of printing the data in thousands of books, we converted them to articles for publication and/or downloading from our website at <http://www.aeroelectric.com>

The power distribution diagrams in this chapter are not intended to be recipes for wiring an airplane. There's very little cookbook data with respect to recommended parts. These drawings illustrate concepts for system architectures developed with and for our builders over the past 15 years. Features from these drawings may be mixed and matched to suit individual builder needs.

Early in the evolution of our mission, we attempted to offer custom wire book services for builders. The service was popular and it didn't take long before we had a backlog of 50-60 airplanes to wire . . . no way we could dig our way out from the mountain of work. When we discontinued the wire book services, the hard drive on my computer held many pages of drawings. We've decided to make a selection of those drawing available to individuals who have AutoCAD or any other CAD program that will import AutoCAD .dwg files. You may download several drawing packages from our website at <http://www.aeroelectric.com>.

Keep an eye on the Page per Systems drawing section at:

<http://aeroelectric.com/PPS>

In sub-directories under this heading you'll find a growing collection of single-page drawings in both .pdf and .dwg format. If you have access to AutoCAD or a computer aided drafting program that will open, edit, print and save AutoCAD files, feel free to download the drawings for use as you see fit. The Adobe .pdf files are readily downloadable printable. I've left the page number box on these drawings empty so that you can assemble any of these pages into your own project's wirebook. The drawing package on the website INCLUDES the architecture drawings in this appendix.

A Short Discussion on the “Endurance” Bus

For a number of years the ENDURANCE bus was called the ESSENTIAL bus . . . bad choice. Words like “emergency”, “critical”, and “essential” conjure up tense images of things going badly in the airplane. I've had a lot of queries from builders asking about running flaps, fuel pumps, and lighting systems from the e-bus. The purpose of an e-bus with two feeds was to provide reliable power for the minimum equipment necessary for comfortable continuation for the en route phase of flight using only the battery for power.

Unless you're planning TWO alternators (Z-12, Z-13 or Z-14) then the purpose of the e-bus is to provide a minimum power consumption mode of operation in a battery-only

condition such that comfortable arrival is assured after you have a clearance to land. Then, you can re-close the battery master and run any accessories you like on whatever remains of the battery's energy. If the battery goes flat then, it doesn't matter.

What endurance do you want from the battery? If your design goal is to permit only fuel aboard to dictate endurance, then your battery capacity needs to be matched to your e-bus loads such that a fully charged battery will carry the e-bus for time equal to or exceeding fuel duration.

If your personal endurance value is less, then you can increase the e-bus loads accordingly. Know further that a battery's useful capacity goes DOWN as load increases. An 18 AH battery may well have received that rating based on a 20 hour discharge rate . . . or about 0.9 amps! If your proposed e-bus loads are, say 3 amps, it is not reasonable to expect 6 hours of performance from the 18 AH battery . . . it WILL be less, probably more like 12-15 AH

Consider further that you'll want to periodically test the battery so as to KNOW its capacity or simply replace it every year. The choice is yours. The goal is to KNOW how long your battery will carry an e-bus load so that you can depend upon it. Most single engine airplanes flying right now have “failed” batteries aboard . . . they cranked the engine but do not carry enough energy for really useful battery-only endurance. Worse yet, the pilots of those airplanes don't have a clue as to what the battery's capabilities are.

As you craft your dream project, keep in mind that the e-bus and your battery maintenance philosophy can provide system reliability that few single engine airplane drivers enjoy. But you MUST understand how it works, what it's for and how to maintain it.

Individual Drawing Descriptions

The pages of wiring diagrams contain some pretty small print and graphics. Consider up-sizing pages of interest to you on a copy machine. Kinko's and office supply stores will often be able to enlarge these pages by approximately 130% to place them on 11x17" sheets of paper to enhance readability. Figure Z-14 is printed in two pages with overlapping features so that you can make copies of both pages and then splice them together with clear tape to make a larger, more readable drawing.

Figures Z-1 thru Z-9 Not Used.

Figure Z-10/8. All Electric Airplane on a Budget with a Brownout Battery.

The hardware in Figure Z13/8 is fitted with a second but small battery that is not used during engine cranking. The small battery is intended to support devices that do not tolerate sagging bus voltage during engine cranking. Wobbly accessories are powered from the e-bus. Before cranking the engine, the E-Bus Alternate Feed switch is CLOSED. A Brownout battery disconnect relay is energized to isolate a small battery in support of the E-Bus while the starter is energized.

Figure Z-11 Generic Light Aircraft Electrical System depicts a single-battery, single-alternator architecture useful on about 90% of the airplanes being built. This figure features the B&C alternator control system (regulator, OV protection and LV warning in a single product). The classic acres-of-breakers has been replaced with two fuse blocks that offer exemplary circuit protection and save many hours and dollars of fabrication effort on a breaker panel. Toggle switches for magneto and starter control are illustrated as well. This architecture plays well with any number of battery, starter and alternator brands.

Figure Z-12. Single Battery, Dual Alternator shows the architecture for a two alternator/single battery configuration not unlike that which B&C has certified onto many type certificated aircraft. If your builder's budget can stand a little taller while considering the all electric panel option, this diagram is a nice step up from the budget system shown in Figure Z-11. This system is a popular option on production Bonanzas. The major difference in the Figure 12 drawing and systems being installed on the certificated aircraft is addition of the Endurance Bus with normal and alternate feed paths.

The SD-20 alternator from B&C is capable of running a full up electrical system . . . including pitot heat if you're not running lights (and you don't want to run lights when IFR in clouds anyhow). The two alternator one battery setup with an endurance Bus is a very attractive configuration for field approval onto certified ships. Further, it's not a bad option for OBAM aircraft.

Figure Z-13 The all Electric Airplane on a Budget was conceived during a conversation with a builder who really wanted to put the SD-20 alternator in his all electric airplane project but just didn't have the dollars. I was trying to figure out an architecture that would allow the SD-8 alternator to supply engine driven power without having to keep the battery contactor closed.

Z-13/8 is a two layer electrical system. When the battery contactor is open and the main alternator off line (DC POWER MASTER - OFF), one can close the AUX ALT switch and use the SD-8 to support the battery and whatever loads are presented by closing the Endurance BUS ALT FEED switch. In this condition, you have a system not unlike that which supplies electrical needs for a whole lot of

little airplanes. LongEz and VariEz projects were B&C's customers about 25 years ago and the SD-8 was B&C's only product!

If the battery contactor is functional -AND- the main alternator is okay too, then closing the DC POWER MASTER switch gets the second layer of electrical system up and running to support everything on the main as well as the endurance bus in the classical DC power distribution scheme. I published this diagram in the summer of 1999 on our website with a short article entitled, "*All Electric Panel on a Budget*" The response from the field was amazing. Orders for the B&C SD-8 alternator increased dramatically and a whole lot of builders were looking forward to NOT fighting a vacuum pump, filters, regulators and spaghetti bowl of hoses behind their instrument panels.

If I were building an airplane today, my ship would be fitted with Figure Z-13/8 electrical system with an 18 AH battery and dual Emagair ignition systems. I can deduce no other configuration that delivers more value.

Figure Z-14 Dual Battery, Dual Alternator, Split Bus is the Mother of all Electrical Systems. *Note that this drawing was too complex to put on a single page and still have readable details. Make copies of the two pages (blow them up if the machine has that capability) and tape them together to make a nice big drawing. You'll have to trim one page at the overlap to get the wires to line up across the sheets.*

Here I show how to configure two independent electrical systems so they share system loads according to their generating capacity. However, they'll support some loads on the other system should one alternator fail.

A crossfeed contactor is wired to connect both batteries together for cranking. *In normal operations, the crossfeed contactor is left open and the two systems operate independently of each other.* Should one alternator fail, the crossfeed contactor may be used for the failed system to borrow power from the working system. The two systems need not have the same capacity . . . I've illustrated a 60 and a 20 amp system common to Lancairs and Glasairs with total-electric panels. This same configuration would work nicely with a twin engine aircraft like the Defiant. In this case, you might have a pair of 40 or 60 amp alternators.

Keep in mind that having two electrical systems with crossfeed capability doesn't mean that all electrical equipment can be operated at all times. If your alternators are 60 and 20 amps as shown, then failure of the 60 amp machine means that you need to reduce total system loads below 20 amps for endurance. This system has greater potential for pilot workload in times when it's least welcomed; such as inside the final approach fix. The risk of this happening is small and if it does happen, there's no

advantage or need to respond to the failure until after landing. Simply close the crossfeed switch and allow the batteries to make up the difference between alternator capacity and system loads.

The vast majority of general aviation aircraft including twins and light jets do not have the reliability offered by this configuration. If you're building a high performance but electrically dependent aircraft, consider the extra effort and expense of installing this kind of electrical system.

Caution

Z-14 is appropriate to perhaps 1% of all OBAM aircraft being built. Before you launch off to install this system in your airplane, join us on the AeroElectric-List and let's talk about it. Recall that less than 1% of all incidents that bend airplanes and break people have electrical system failures as causation. It's exceedingly easy to achieve system reliability on the order of 10x all single engine airplanes flying . . . and many of those aircraft spend time in IMC conditions without having a bad day in the cockpit. Figure Z-13 is an excellent example of simple, light weight, low cost reliability.

Figure Z-15 Grounding Systems illustrates three strategies for dealing with the special nature of ground systems in tractor, canard pusher and seaplane type aircraft.

Most tractor engine aircraft can mount a battery in relatively close proximity to the engine. Perhaps on the forward side of the firewall or (as in many RV's) on the aft side of the firewall between the pilot and copilot's rudder pedals. In some cases, the battery might be aft of occupant seating for the purpose of moving the center of gravity aft. View -A- is typical of all tractor engine situations.

If the airplane is composite, then both (+) and (-) leads to the battery need to be wired. In an all metal or tubular fuselage aircraft, the builder might consider grounding the battery locally to the airframe.

Remote appliances that are not potential victims nor strong antagonists for noise such as pitot heat, nav lights, landing and taxi lights and strobe power supplies can be grounded locally to airframe also.

For all other systems and accessories, use the single point ground at the firewall to terminate grounds for either engine or cabin mounted equipment.

Canard pusher aircraft often place the battery and engine on opposite ends of the aircraft. Further, canard pushers are always composite. Run a pair of 2AWG wires side-by-side for the length of the aircraft to complete the heavy current connections to the battery.

Seaplanes often locate the battery forward in close proximity to the instrument panel ground block. They often require a mid-ship ground for hydraulic motors (landing gear), bilge pumps or perhaps a second battery. In View -C- I've suggested a segmented ground system. Long runs in seaplanes always call for at least 2AWG wire in the ground and cranking circuit paths. Large seaplanes like the TA-18 Trojan use **paralleled** runs of 2AWG to maintain cranking performance of the large, 250 HP engine.

Figure Z-16. Rotax 912/914 System is a "stone simple" electrical system typical of many aircraft fitted with permanent magnet alternators. A noteworthy feature in this figure is the means by which I've added OV protection to the alternator system. Many airplanes flying with a Rotax 912 have relatively small batteries. Even the limited 18 amps of alternator output can push the bus voltage up rather quickly on a small battery. Adding the relay and OV module as shown provides automatic protection from unobserved regulator failure.

Figure Z-17. Small Rotax System (or Aircraft with SD-8 Alternator as Primary Engine Driven Power Source was requested by builders with the smaller Rotax engines having 10-12 amp alternators. This diagram shows how to wire a small system without a battery master contactor. This same architecture applies to small aircraft using the B&C SD-8 alternator as the primary engine driven power source. This system is flying in dozens of Vari-Ez and Long-Ez airplanes.

Figure Z18. Single Battery and LOM engine shows how to wire one of the very few generators still in production for installation on new aircraft. The LOM engines come fitted with 28 volt GENERATORS which require a unique OV protection scheme. This figure also illustrates interconnection of the LOM starting vibrator (similar to Shower-of-Sparks) and the various filters that LOM recommends for use with their engine.

Figure Z-19 was crafted to suggest a dual power path and redundant batteries for an electrically dependent engine. *Note that this drawing was too complex to put on a single page and still have readable details. Make copies of the two pages (blow them up if the machine has that capability) and tape them together to make a nice big drawing. You'll have to trim one page at the overlap to get the wires to line up across the sheets.*

Figure Z-20 shows a power distribution diagram unique to

the smaller Jabiru engines.

Figure Z-21 Not Used.

Figure Z-22. Fix for “Run-On” in Starters with Permanent Magnet Motors shows how to delete the recommended starter contactor and add a heavy-duty (Our S704-1 or similar) relay to control the built in contactor and pinion engagement solenoid found on some permanent magnet starters.

A permanent magnet motor will act as a generator during its spin-down cycle and create enough current flow to keep the pinion engaged for several seconds after the START button is released. The relay isolates the panel mounted start button or switch from high inrush currents typical of modern starters. The relay can be mounted under the cowl and wired as shown.

Figure Z-23. Generic Regulator and OV Protection for Externally Regulated Alternator (with diagnostics)..

There are hundreds of generic automotive regulators that will adequately control about any alternator configured to use external regulation. Here we illustrate the connections for a generic “Ford” regulator sold by many automotive stores as a p/n VR-166 by Standard. There are dozens of other manufacturers of equivalent devices.

When you elect to go generic, be sure to include over-voltage protection as shown. Make some provisions for acquiring active notification of alternator failure in the form of light or tone that activates below 13.0 volts.

No matter what alternator/regulator combination you choose, consider adding the diagnostic measurement accessory circuit described here. The cockpit mounted connection to monitor field voltage from the cockpit is an important tool for accurate diagnosis of charging system problems. See Note 8.

Figure Z-24. Adding OV Protection to an Internally Regulated Alternator.

Z-24 has been the subject of much debate concerning a tendency for some alternators to be damaged when turned OFF under load using Figure Z-24 OV and control architecture. After considerable study, we find that some aftermarket alternators (virtually all of them rebuilds of some genre') are not routinely tested for an ability to withstand their own load dump events.

Consequently, there have been some unhappy events where the operator turned their alternator OFF while the engine rpms were greater than idle . . . resulting in damage to the alternator's built in regulator.

Know two things about this drawing:

(1) It is not a good idea to go flying with an alternator that is NOT fitted with positive control of a voltage runaway failure. ALL internally regulated alternators have some risk of regulator failure. This begs adding Z-24 (or equivalent) for the purpose of corralling an alternator bent upon smoking stuff on your panel.

(2) There is a replacement system in the works that will upgrade a Z-24 installation to allow ON-OFF control of any internally regulated alternator at any time under any conditions. If you'd like to take advantage of modern, exceedingly attractive automotive alternators, Z-24 is recommended in the interim with an upgrade at a later date.

The only caution is that you don't sit and fiddle with the alternator switch in any manner not consistent with normal operations of the airplane. Turn alternator ON at engine idle after starting. Turn alternator OFF at engine idle before shutting the engine down.

Understand too that most aftermarket alternators are not subject to this caution . . . but I have no way to guide you as to the appropriate purchase. So treat all aftermarket alternators gently as described above until the permanent fix is available.

Figure Z-25. SD-8 Auxiliary Alternator Installation.

Got an unoccupied vacuum pump pad? How about populating it with an SD-8 alternator from B&C Specialty Products? Wire it right to the main battery as shown so that in case of main alternator failure, you can shut down the main alternator, shed the main bus loads by killing the DC Power Master switch, close the Endurance Bus Alternate Feed, turn on the Aux Alternator and enjoy indefinite electrical system endurance for the E-Bus irrespective of battery size or present condition with respect to capacity.

With two alternators, one may comfortably and logically be less stringent about battery testing and replacement - a replacement cycle of 2-3 years seems practical.

Revision 12 to the ‘Connection adds a diode bridge rectifier and two resistors to the SD-8 installation to make it “self exciting”. See Note 25.

Figure Z-26 Ignition Switch Options - Two Magneto with Key-Lock Switch If you really gotta have a key-locked ignition switch a-la spamcan, here's how it works and how you wire it up. Note the jumper between GRD and R terminals. A study of the switch's position-connection chart shows how this junction becomes grounded during engine cranking. This feature is used to disable a non-impulse coupled magneto (usually the right magneto).

If both magnetos are fitted with impulse couplers, delete the

jumper.

Figure Z-27. Magneto and One Electronic Ignition (with toggle switches) Here's my favorite way to wire the magneto and starter circuits. Two-pole switches accommodate the need to short out a magneto's p-leads to shut down the engine. A second pole provides a means for interconnecting the switches such that the starter is disabled while the right (non impulse coupled) magneto is ON.

Toggle switches for ignition control offer the ultimate flexibility for later upgrading to electronic ignition using switches that are inexpensive and look like they belong on the panel with the rest of the system's electrical controls.

Figure Z-28. Dual Electronic Ignition with One Alternator. If you plan dual electronic ignition, you should consider adding an auxiliary battery (Figure Z-30) to support the second ignition in the rare event that the main alternator is lost. Figure Z-28 shows how the two ignition systems and starter get their power.

Figure Z-29. Always-Hot Battery Bus. It occurs to me that any time the magneto switches are ON in an airplane so equipped, the engine is HOT and ready to run. A desirable feature of magnetos over electronic ignition is the fact that the engine runs irrespective of the condition of the airplane's electrical system. So why not retain this advantage when you go to electronic ignition?

I'll suggest that electronic ignition systems should enjoy a direct connection to the ship's always-hot battery bus. Wired as suggested, the pilot may shut down the entire electrical system without affecting engine operations. If you have strange smells in the cockpit, you don't have to think twice about killing the DC POWER MASTER and alternator switches. The engine will continue to run while you sort out the problem and select your plan for continued flight . . . hopefully to intended destination.

Figure Z-30. Auxiliary Battery and Bus. If you have an electrically dependent engine . . . either by virtue of dual electronic ignition, electronic controlled fuel injection or an engine that depends on electrically delivered fuel, then a second battery should be considered to distribute power sources among the primary and secondary systems.

If both batteries are hefty (12 AH or more and capable of delivering energy into the starter system) then you would run BOTH batteries for all normal operations including engine cranking.

If you wish to run an auxiliary battery smaller than the main battery, then the S701-1 contactor (big guy capable of helping crank the engine) may be replaced with an S704-1 relay. In this case, the AUX BATTERY MASTER would be

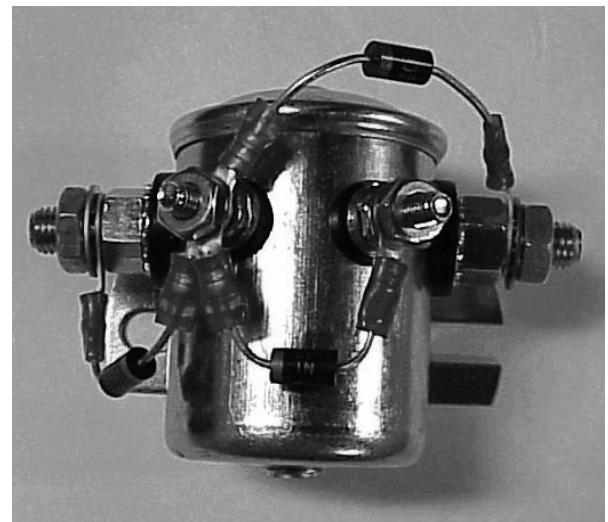
OFF during engine cranking and ON for all but failed alternator operations.

There is a distinct service and reliability advantage to equalized main and auxiliary batteries. You can replace the main battery every annual with a fresh battery (a very low cost activity when compared with the total cost of owning and operating an airplane). Move last year's main battery into the auxiliary battery slot. This means that you never have a battery more than two years old and one battery is always less than one year old . . . *a very robust, reliable combination for dealing with potential alternator-out operations.*

Figure Z-31 Ground Power Jacks. This figure illustrates two popular versions of a ground power jack installation that can be added to any airplane. One uses the military style, 3-pin connector popular with Cessna and the larger Beech products. The other illustrates a single pin connector adapted from the trucking industry and popular with Piper and the smaller Beech products. Most airports will be able to connect to either style ground power jack.

Figure Z-32. Heavy Duty E-Bus Feeder. As a rule of thumb we try to avoid long runs of always hot wire fused at more than 7A. This is a crash-safety issue. If your E-Bus really needs a feeder protected at more than 7A, consider adding a power relay contactor or AEC9030-14 Solid State Relay as a "mini" battery contactor right at the battery bus to control the e-bus alternate feed line.

Figure Z-33. Dual Power Feeds for Battery Contactors. Note that the cross-feed contactor of Z-14 can be energized if either the main or auxiliary bus is hot. This is accomplished by wiring diodes from both fat terminals of the contactor to the hot side of the coil. In some cases,



especially if any of your alternator(s) is/are self exciting, then modifying your battery contactor with a trio of diodes as shown is a useful thing to do. For example: After hand-

propping the engine with a dead battery . . . or after starting the engine with only one of two batteries (as in Z-14 or a dual-battery installation) you can get the dead battery's contactor closed with power from the ship's system.

Obviously, this mod precludes the use of a 3-terminal contactor. You'll need a 4-terminal device with diodes installed as shown here. Note the banded ends of all diodes tie to one coil terminal. Either fat terminal can go to the battery. The other small terminal is the coil connection to the battery master switch. The diodes are uncovered in the photo for clarity. Your installation should include heat-shrink over the diodes.

Figure Z-34. Not used.

Figure Z-35. Non-Cranking (small) Aux Battery and Bus It's perfectly valid to consider adding a second battery to any system shown for the purpose of supporting certain equipment items in the aircraft. Small batteries not designed for delivering high current (generally 15 AH or less and don't feature bolt-tabs for connecting fat wires) may be paralleled through a relay that's much smaller than the classic battery contactor. In this case, I've illustrated a 30A, "plastic cube" as the aux battery master relay. Obviously, the small aux battery master should be left OFF until after the engine is started and the alternator is on line.

Numbered Notes from the Drawings

References to numbered notes are sprinkled about the face of each drawing. The following notes will offer additional information about the tagged feature.

Note 1. The minimum recommended wire size for all wiring is 22AWG except as noted. Try to keep wires marked with an asterisk (*) limited to 6" or less in length.

Note 2. Contemporary magneto switches are fat, ugly, expensive and heavy. They provide only a modicum of protection against airplane theft. They also contribute to occasional engine kick-back with possible damage to engine and/or starter. Consider using two double-pole, double-throw switches with one position spring loaded to center. The AeroElectric Connection S700-2-5 switch is suitable.

Note that p-leads are grounded out with the switches in the lower, OFF position. The center position of each switch un-grounds a mag, allowing the engine to run. The spring loaded upper position of the left mag switch controls both magneto and starter contactor. The starting circuit is completed through lower, MAG OFF contacts on the right mag switch. This interlocking prevents inadvertent engine cranking with the right mag energized. If both magnetos have impulse couplers, the right mag, starter lockout feature should be eliminated. Of course, electronic ignition systems used to replace the non-impulse coupled magneto do not

have to be OFF while cranking an engine . . . indeed they're better left ON.

Using toggle switches for magnetos has an important future benefit: you have the option to replace a magneto with an electronic ignition. An OFF-L-R-BOTH-START key-switch cannot be used to control some electronic ignitions. On the other hand, a toggle switch has circuits which close in both the up and down positions. You simply use the opposite set of contacts on the same switch for control of an electronic ignition.

Note 3. Use shielded 20 or 22AWG wire to control the mags. Attach the shield to engine ground at the magneto end. Attach the shield to one and only one switch terminal at the cockpit end as shown. In the switch OFF position, the shields are used as a ground return for the magnetos. In the MAG ON position, the shields are protection from electrostatic coupling of magneto noise. The shields should not be attached to any form of ground at the panel, just the magneto switch.

Note 4. Automobiles have been using fusible links for many years. From the outside, they appear rather "special" . . . many have a tag molded onto what looks like a piece of wire with a terminal on one end . . . the tag says, "FUSIBLE LINK." Hmm . . . well guess what, what looks like a piece of wire is indeed a piece of wire . . . and rather ordinary at that. I've deduced the rationale behind design and incorporation of fusible links after lots of e-mail, phone calls and literature searching.

All fusible protection of a wire functions the same way. A thermally weaker segment is placed in series with the wire segment to be protected. Sometimes the link is a piece of special wire inside a glass tube or block of plastic and we call it a "fuse". The purpose of the weak link is to provide an orderly failure of a faulted circuit's ability to carry current. Suppose the weak link was simply a piece of ordinary wire? It turns out that the link used on cars is 4AWG wire steps smaller than the wire being protected. 10AWG wires are protected by 14AWG links, 14AWG wires are protected by 18AWG links, etc. Obviously, should a hard fault occur, you WILL get some smoke and the smaller wire will melt and separate. Successful incorporation of fusible links takes some consideration . . . they're not for every situation which might otherwise require some form of in-line fuse.

First, 24AWG is the smallest practical wire that can be worked with terminals and tools used. A 24AWG wire will carry a 3A continuous load with a reasonable temperature rise. The downstream segment from a 24AWG fusible link has to be 20AWG. Hmm . . . a tad heavy for a 3A circuit but not outrageous. Take a look at the alternator loadmeter shunts on Figure Z-14. Short pieces (4-6 inches) of 24AWG wire are butt-spliced onto 20AWG extensions to take shunt

signals into their respective loadmeters.

Now, how likely is it that these "fusible links" will ever be called upon to do their job? . . . VERY small. What's the damage if it does happen? Not much: a short piece of 24AWG wire burns up. If we slip a piece of fiberglass sleeving over the wire, you wouldn't even toast an adjacent wire in a bundle. Why would we want to do this? Lower parts count for one, increased reliability for another. All components of this protection scheme are ordinary pieces of wire connected together with solderless splices and terminals having reliability approaching that of the wire itself . . . *much easier to install and more reliable than any form of holder for discrete fuses.*

Hmmm . . . how about the Aux Alternator B-lead feed in Figure Z-14? Here's a special challenge that is nicely met with a fusible link. Here the B&C SD-20 alternator is capable of 20 amps of continuous output. Inline fuse holders at this current level are marginal at best; fuse holder components corrode, accelerated by moisture and temperature cycles. The fusible link is a very reliable alternative for circuit protection in this location.

I show fusible links on other single line feed paths as well. Our website catalog will soon offer small quantities of 24AWG tefzel wire (not commonly offered in other folks catalogs) and small quantities of silicone rubber impregnated fiberglass sleeving to place over fusible link installations. This sleeving is not necessary but it does offer some protection to adjacent wires and equipment from effects of heat and smoke.

Note 5. When the battery and engine are on opposite ends of the airplane, heavy wires between the battery and engine compartment should be routed as close together as possible along the length of the airplane. Try to run ALL wiring in a single path down one side of the airplane. Attempts to use both sides of the airplane for electrical pathways have resulted in some bizarre noise and magnetic interference situations. Use one side for wires, the other for engine controls. Even then, make sure that jackets for engine controls do not ELECTRICALLY ground both a metal panel and the engine . . . they can easily become a SECOND ground path on the wrong side of the airplane and create the same problems we're striving to eliminate.

Note 6. The ground busses shown are fabricated from brass sheet, strips of .25-inch Fast-On tabs and a brass bolt. These are available from B&C Specialty Products.

Note 7. In composite aircraft, the B & C linear regulator requires two separate grounds to insure OV protection integrity. If you choose to use this device be sure to wire it as shown.

Note 8. When an alternator quits alternating, good data is

useful in making an accurate diagnosis of the problem. If you don't know what the alternator field voltage is doing when the system is failed or misbehaving, you're not ready to put a wrench to the airplane. There are few mechanics out there that even know what you're about to learn here . . . and even fewer that will stand behind a running propeller to gather the needed information. So consider this:

Referring to Figure Z-23, you can see where a 1K, 1/2 watt resistor can be spliced into the alternator field lead at any point along the route between the regulator and the alternator's field terminal. Splice a 22AWG wire to the other end of the resistor and then cover the whole business with heat shrink before you tie it back into the wire bundle. The resistor serves as a current limiting device to isolate the test wire from the field wire and eliminate the need for a fuse to protect the test wire. The resistor also prevents a shorted test wire from upsetting normal alternator operations.

Now, extend the wire into the cockpit where you'll attach it to a Radio Shack 274-1576 receptacle. The receptacle is small and would not take up much room on a panel but if you want it out of sight, at least make it easy to reach from the pilot's seat—perhaps on a bracket behind the panel. Ground the receptacle's shell to the instrument panel ground bus with another piece of 22AWG wire.

You'll need to make up a short cable assembly consisting of a Radio Shack 274-1573 plug (mates with receptacle above) and banana plugs on the other end to connect with a hand-held multimeter . . . preferably an analog meter but if all you have is a digital, it will do. We'll cover this in more detail in a future update to the alternator chapter. Here's how this feature becomes really useful:

- (a)** If the alternator field voltage is zero when the output is zero, then the regulator or associated wiring has failed.
- (b)** If the alternator field voltage shows some fairly healthy reading on the order of 10 volts or more and alternator output is zero, the alternator has failed.
- (c)** If the alternator has become unstable . . . loadmeter is jumpy, panel lights flicker . . . watch the field voltage and compare it with loadmeter readings. If the field voltage and loadmeter readings swing up and down together, then the regulator has become unstable. Check for increased resistance in regulator field supply wiring and components. Breakers, switches, over-voltage relays, and connectors are all contributors to regulator instability when their resistance ages upward a few milliohms in resistance.
- (d)** If the loadmeter swings UP while the field voltage is swinging DOWN, then the alternator has some unstable connections inside . . . perhaps worn brushes?
- (e)** If field voltage is high, does not drop significantly when

engine RPM increases but bus voltage seems normal under light load and sags under heavy loads, then the alternator may have one or more diodes open/shorted.

(f) While operating with full system loads, carefully observe the engine RPM where alternator field voltage peaks: i.e. begin at idle RPM with all loads ON--if your bus voltage is lower than the regulator setpoint, then the alternator is turning too slow to support present loads. Now, adjust engine RPM carefully to get the highest possible reading on field voltage. At this time, the bus voltage should be at the regulator setpoint. The engine RPM is your *minimum speed for regulation* at full load. If your system is working properly and pulley ratios are appropriate, engine RPMs should be equal to or LESS than required to sustain flight.

(g) Should your alternator suddenly become "noisy" in that alternator whine becomes markedly worse, you may have suffered a blown diode in the alternator. Before taking the alternator off the airplane, Attach a multimeter to the alternator case and the b-lead (output terminal). Set the multimeter to read AC voltage. Run the engine up and turn everything electrical ON. If the AC voltage exceeds 500 millivolts, there's a good chance that a diode is bad. If it's less than 200 millivolts, then it's more likely that the noise is getting into your audio system via a ground loop (noise is present even when radio volume is all the way down) or failed noise filter (noise goes up and down with radio volume control).

The above paragraphs describe about 100 times more than most mechanics know about alternator troubleshooting but none of it is possible unless you can measure field voltage (sometimes in flight), observe a combination of effects and deduce their meaning. The parts cost a few dollars and the feature adds significantly to the efficient and safe maintenance of your airplane.

Note 9. Not used

Note 10. There are good reasons for not bringing high current feeders or loads into the cockpit. High performance production airplanes use a special, heavy duty fuse-like device called a *current limiter*. Alternator B-Lead protection is best accomplished with MANL or ANL series current limiters used throughout the industry for similar applications.

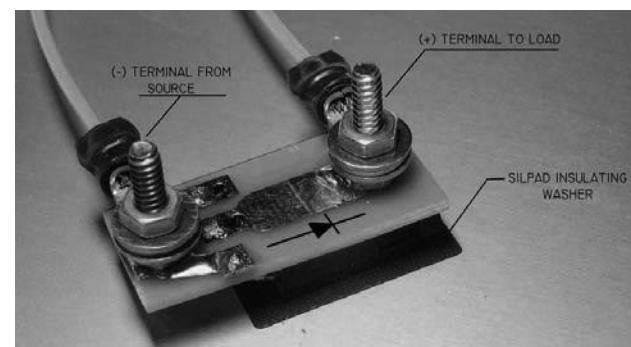
Alternator noises in the system are reduced by *not mounting the alternator breaker on the panel* in the traditional fashion. The likelihood of recovering use of the alternator should this breaker trip is very close to zero. Consider installing a current limiter as close as possible to the starter contactor and wired per the Z-figures.

ANL/MANL limiters should also be considered as supply

protection for electric hydraulic pumps.

Note 11. Not Used

Note 12. A silicon diode having a forward current rating of 20 amps or more can be used to eliminate a bus tie switch and provide automatic isolation of the power distribution bus from the endurance bus during failed alternator operations. If your endurance bus is configured per our recommendations for 3-4 amps MAXIMUM continuous load, the rectifier diode array requires no heat sinking. A Radio Shack cat #276-1185 is suitable. Its metal case may be bolted directly to the structure. If you absolutely must have higher endurance bus loading, consider ordering your endurance bus normal feed diode from us. We'll put it on a suitable heat sink for you -OR- a Digikey HS117-ND heat sink cut in half is about right for diode cooling.



AEC9001-1 Schottky Diode Assembly

For builders interested in a more efficient diode with less voltage drop, the AeroElectric Connection offers the AEC9001-1 Schottky Diode Assembly which may be reviewed at <http://aeroelectric.com>

Note 13. The battery minus (-) wire should go directly to the nearest ground system tie point. I recommend some combination of the Fast-On tabs ground busses (B&C or equal) screwed to firewall. Where ever possible, the battery (-) lead should bolt to the 5/16" brass stud that comes with the ground bus kit. Then a 2AWG equivalent bonding jumper to ground the engine's crankcase to the Fast-On bus.

Note 14. Consider installing an electric solenoid valve between the pressure side of your fuel system and the primer ports on your engine. Aircraft Spruce offers a suitable electrically operated valve for primer service. Further, consider using a 4 or 6 port primer system (depending on the number of cylinders on your engine). Two advantages: (1) no wet fuel lines in the cabin, (2) many an engine plagued with a plugged carburetor or broken mixture control has been kept running to an uneventful landing by a multi-port primer system. The electric primer system offers an opportunity to craft a completely redundant fuel delivery system!

Put a needle valve in the downstream line from valve to the primer nozzles. Set the valve to produce a 60% power fuel flow when the primer is in operation. If you loose the primary fuel delivery path, turn on the primer and adjust throttle for smoothest running engine. If you elect to incorporate the primer backup fuel delivery system, you may want to change out the 2-50 switch on-on-(on) for a 2-10 switch on-on-on so that you don't have to hold the switch in the PRIME position for operation with the second fuel delivery source.

Note 15. In order to take advantage of the unique switching features of special switches shown in these diagrams, a means of calling out mounting orientation is needed. Switches supplied by the AeroElectric Connection (and other quality devices) are fitted with a keyway groove along one side of the threaded mounting bushing. The numbers given on this drawing for wiring the switch assume that you mount these switches with their keyways up. Your switch should also come with a keyed and tabbed washer used to prevent rotation of the switch in the mounting hole should the nuts loosen. We recommend its use.

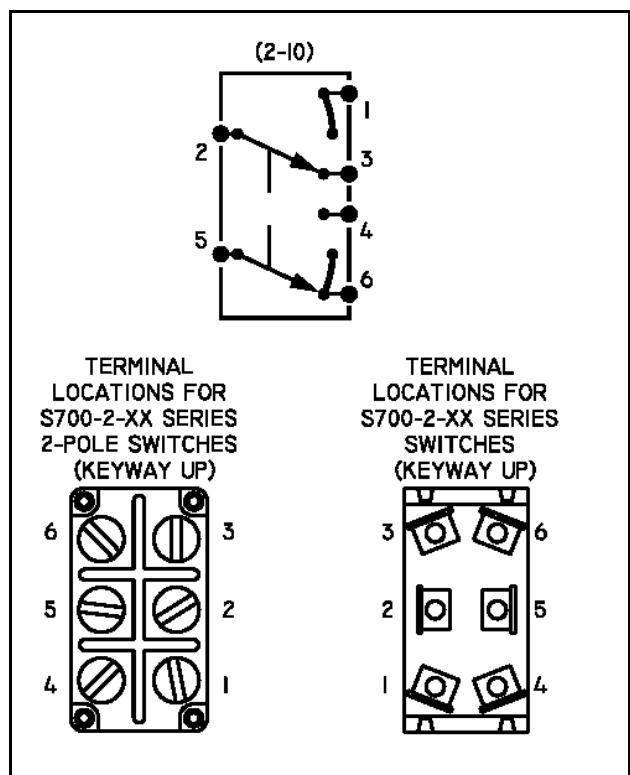
We've discovered that since this note was first crafted some 15 years ago, Carling has modified their progressive transfer switches to conform to the convention described in military standards for such switches. Use an ohmmeter to check your progressive transfer switch of any brand to deduce the true column orientation. Just know that most switches purchased recently will conform to the Microswitch numbering convention.

Note 16. The fuel boost/prime switch has special internal features. It's described as a two-pole, ON-ON-(ON) switch. An AEC S700-2-50 or equivalent switch is needed.

Note 17. If you have not yet selected a battery; do consider the new recombinant gas (RG) or vent regulated lead-acid (VRLA) batteries. These are truly maintenance free batteries that crank like ni-cads! Flooded batteries need to go the way of the buggy whip.

Note 18. B&C Specialty Products supplies a crowbar OV module ready to install (p/n OVM-14). See their website catalog or contact them directly. If you've a mind to "roll your own", check out our website for an article with a schematic and bill of materials.

Note 19. All of these diagrams show fuses on low cost fuse blocks. Obviously traditional panel mounted bus bars with circuit breakers are functionally interchangeable with fuses. I recommend you consider fuses carefully. There are many savings in weight, cost and time to install. The fuse blocks shown are a Bussmann products now generally available



Note 15. Terminal Locations for Microswitch vs. S700 (Carling) SEE TEXT.

from many suppliers to the OBAM aircraft community.

Note 20. Unlike their fielded cousins, permanent magnet alternators may run well with a battery off line if you add a computer grade electrolytic capacitor across its output for filtering. The capacitor should be 20,000 to 50,000 microFarads and rated anywhere between 15 and 50 volts. CAUTION . . . some regulators supplied with PM alternators still require a battery to be present before they will "start up" . . . if you'd like to depend on your PM alternator to operate in spite of a battery contactor failure, investigate this operation for the regulator you've selected. A different regulator -OR- some small, stand-by battery installation may be indicated.

Note 21. An aftermarket FORD regulator (Standard Parts VR166 or equal) is a low cost, solid state regulator suitable for use on airplanes IF you add OV protection as shown. This particular regulator has been duplicated and offered under a variety of part numbers by other suppliers. You can hit your parts guy up with this list:

TVI_Globe	p/n	VR166
Ford Motor	p/n	GR540B
Standard	p/n	VR166
Neihoff	p/n	FF169B
Echlin	p/n	VR440
Filko	p/n	VRF330HD

Ampco/Wells p/n VR749
 KEM p/n KVR202B
 GP p/n VR301

Another interesting feature of this part is its appearance. I'm aware of no version of this regulator that doesn't look like the adjacent photograph.

Note 22. Most alternators do not run well without also having a battery on line. The infamous "split rocker" switch was developed for light aircraft in the mid 1960s when generators were being phased out in favor of the much more efficient alternator. A two-pole, split-rocker switch controlled the battery master contactor with one pole and



Note 21. Generic "Ford" Regulator

alternator field excitation with the other pole. The switch halves were mechanically interlocked such that the battery could not be turned OFF without taking the alternator OFF as well. The Z-figures always show a two-pole switch as a DC PWR MASTER, one pole for the battery contactor, a second for the alternator field supply.

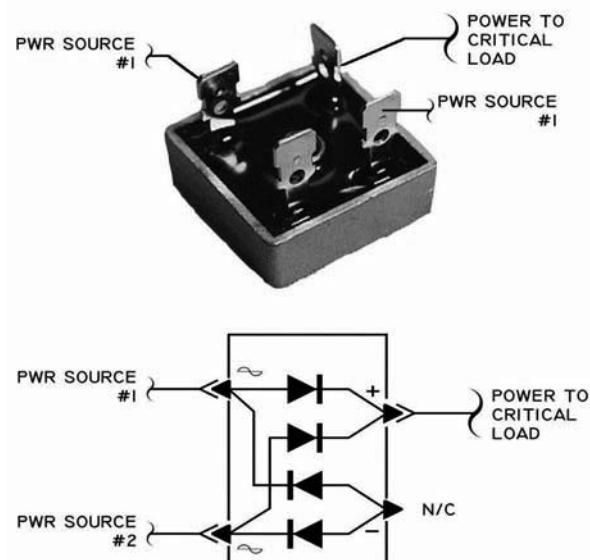
The progressive transfer, 2-10 style switch can emulate the popular split-rocker switch by offering an OFF-BAT-BAT+ALT function. This configuration allows battery-only ops for ground maintenance and covers in-flight situations where the pilot needs to shut down a mis-behaving alternator. See note 15.

If your system has an alternator field breaker to accommodate crowbar OV protection, **One may consider a 2-3 style switch** where the battery and alternator come ON and OFF together. This is perfectly acceptable for normal operations. In-flight shutdown of the alternator and/or battery-only ground maintenance may be conducted by pulling the alternator field breaker.

Note 23. Revision 11 introduces the avionics ground bus described in Chapter 18 and illustrated in the Z-figures for

the first time

Note 24. When you have critical loads that you would like to accommodate with dual power sources, the 4-diode bridge rectifier offers an easy to acquire, easy to mount, easy to wire solution. The figure for this note illustrates which terminals are used. Figure Z-19 shows one example of how the device is used.



NOTE 24. USING DIODE BRIDGE TO JOIN CRITICAL POWER FEEDERS

If your critical system draws more than 4 but less than 8 amps, the diode bridge should be mounted on a metallic surface for heat sinking. If the loads are heavier, say 8 amps up to the 25 or 30 amp rating of the device, perhaps a finned heat sink is called for. Consult the membership of the AeroElectric List for guidance in these special cases.

In any case, the diode bridge should be located as close as practical to the critical system's input power connection.

Note 25. Making the SD-8 Come-Alive without a battery: Subsequent to some excellent 'skunk works' efforts on the part of Jim McCulley, the 'Connection is pleased to offer a work-around to older SD-8 alternator installations that encourages this useful product to come on line without benefit of a battery. Adding a pair of diodes and a start-up bias resistor as shown in Z-25, the SD-8 will come up and run as soon as the engine is started.

I've suggested the diode bridge rectifier for this application but you can use wired-leaded devices like 1N5400 series devices from Radio Shack and others. The advantage of the diode-bridge is that splices between dynamo and regulator lead wires can happen in the same PIDG terminals used to

wire the rectifier.

Suitable parts include the following Digikey catalog numbers:

1 each 1GBPC1204/1 Diode Bridge
 1 each ALSR3F1.0K 1,000 Ohm/3W
 1 each ALSR3F3.0K 3,000 Ohm/3W
 2 each 1N5400 3A, 50V Diode Rectifier

These parts are chosen more for their mechanical configuration and robustness than for electrical ratings. Many other styles of parts may be substituted. With these added parts, one may connect a voltmeter across the 22,000 uFd filter capacitor. A few seconds after the engine is started, one should observe that the voltage across the capacitor jumps up to about 6 volts at engine idle. The voltage rises with RPM until the regulator takes over to maintain output at about 14.2 volts at cruise RPM.

Note 26. Do's and Don'ts of Grounding. The addendum illustration to Figure Z-15_3.1 speaks to the most common questions about achieving quality grounds in an airframe.

Grounding systems in an airframe can have multiple, linearly connected gathering points that can satisfy the design goal of “single point grounds” for individual systems. It’s important that potential victims to noise (Comm and nav radios, Audio systems, Instrumentation systems) concentrate their various system grounds in one location. The example figure shows how potentially antagonistic loads may be grounded remotely on a metal airframe as long as potential victims enjoy single point grounds.

I’ve illustrated some no-no’s in red that show a headset circuit and components of an oil pressure gage grounded across two nodes. While both cases may be “grounded” and function as desired under some conditions, they are at-risk for interference from tiny but significant voltages that exist between two “connected” but not “co-located” grounds in the system.

Devices wired in green illustrate devices that have been properly grounded including a number of accessories that are locally grounded to metal airframes.

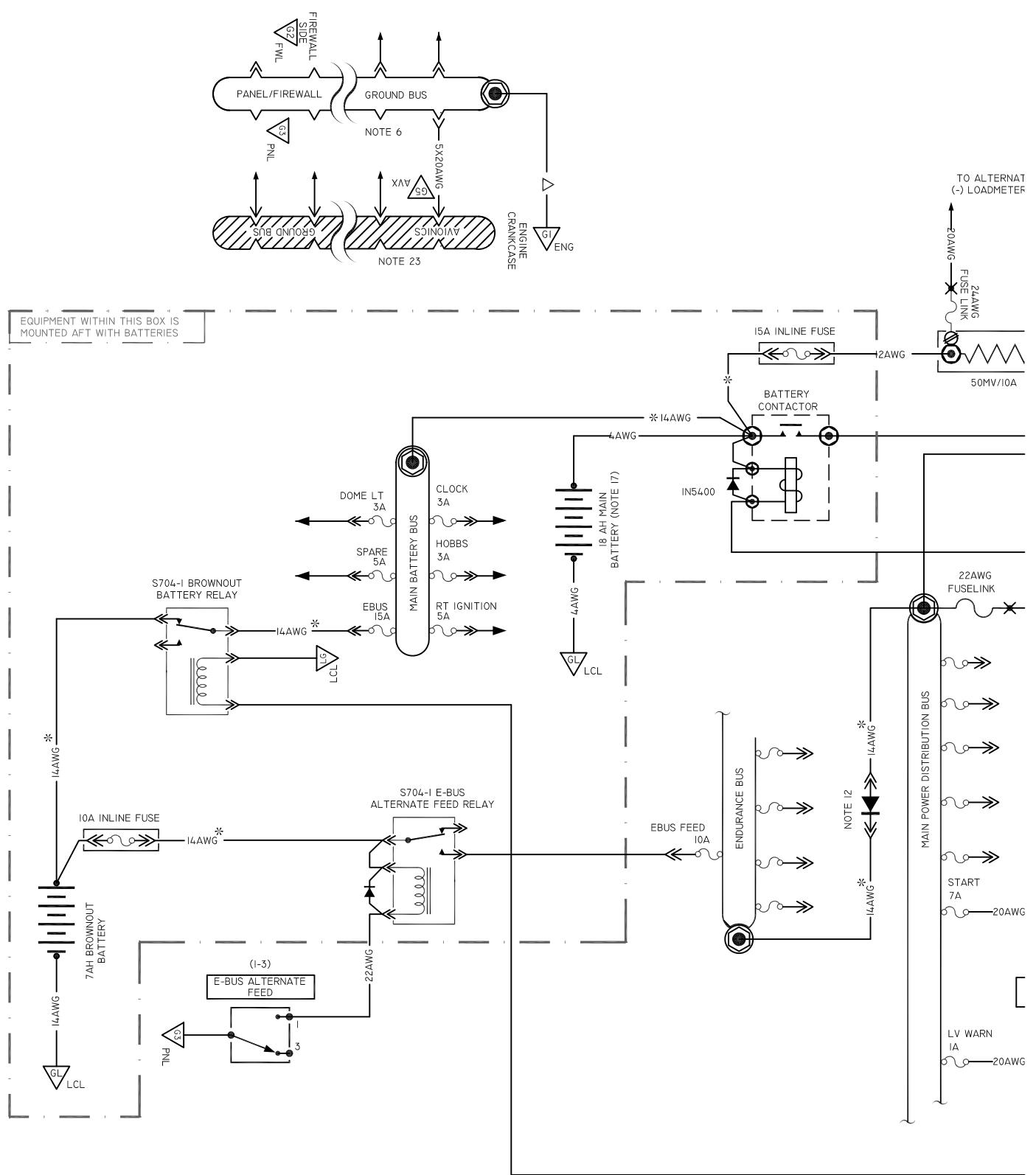
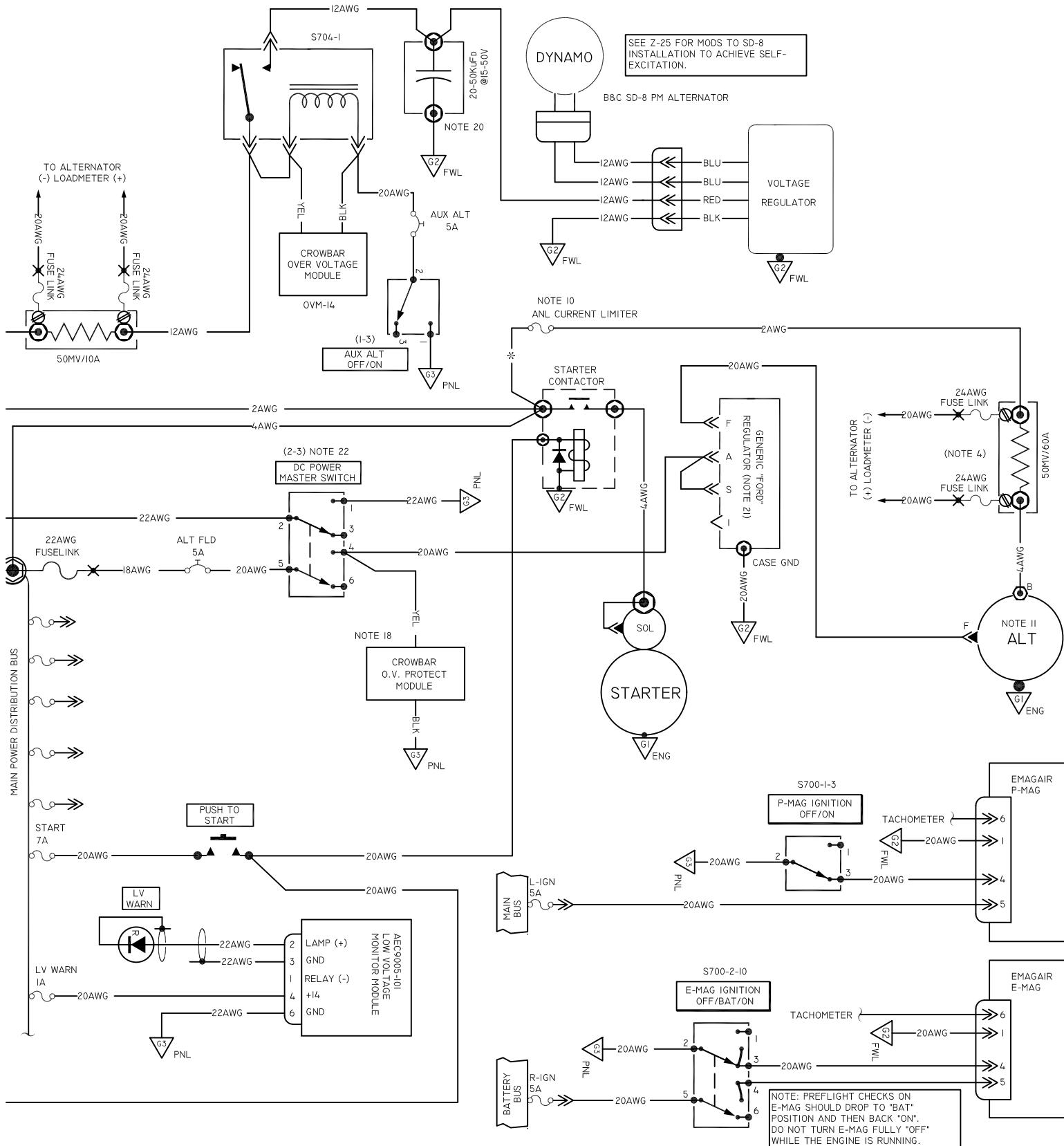


Figure Z-10/8 All Electric Airplane on a Budget with P-Mags & Brownout Battery



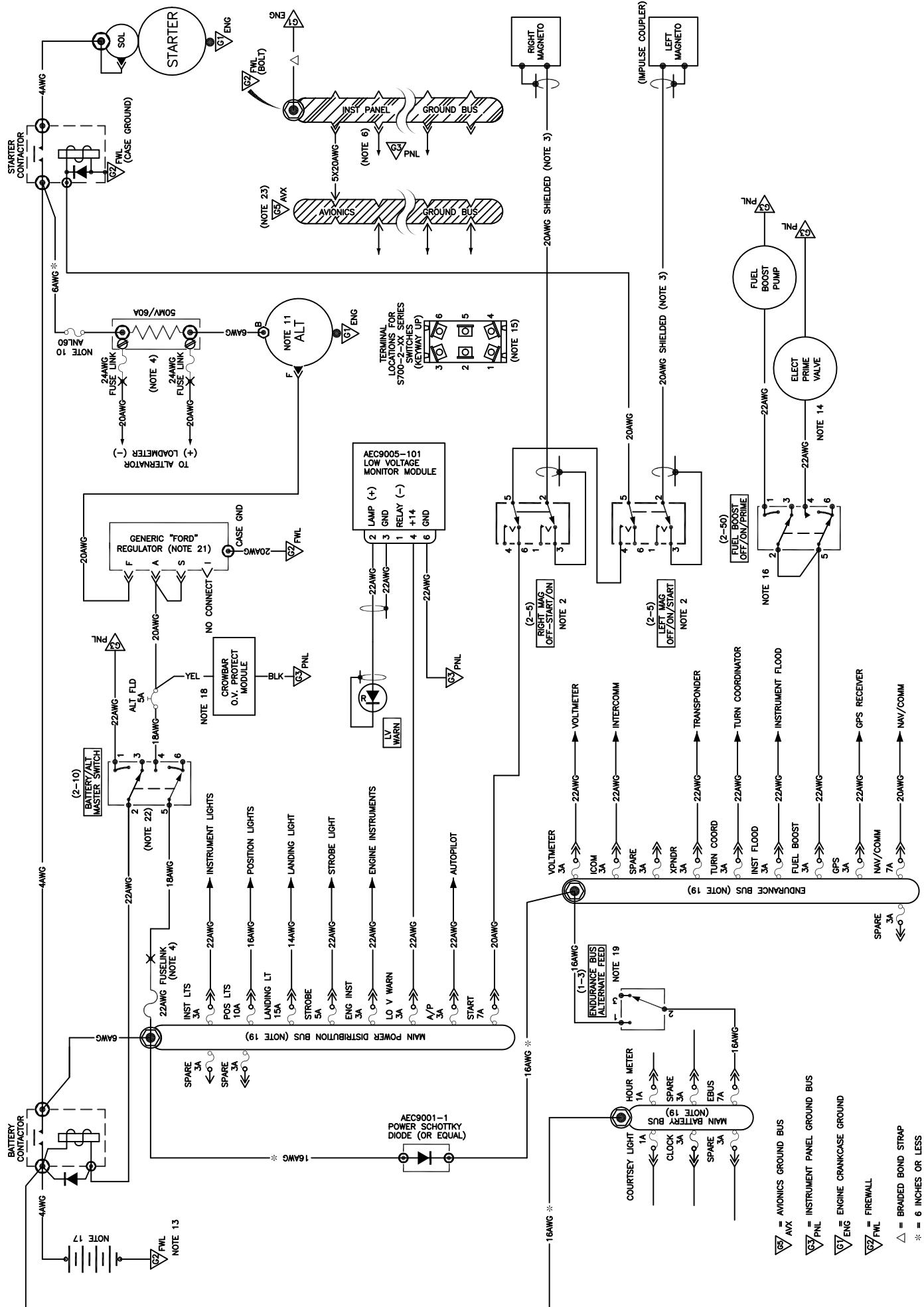


Figure Z-11. Generic Light Aircraft Electrical System

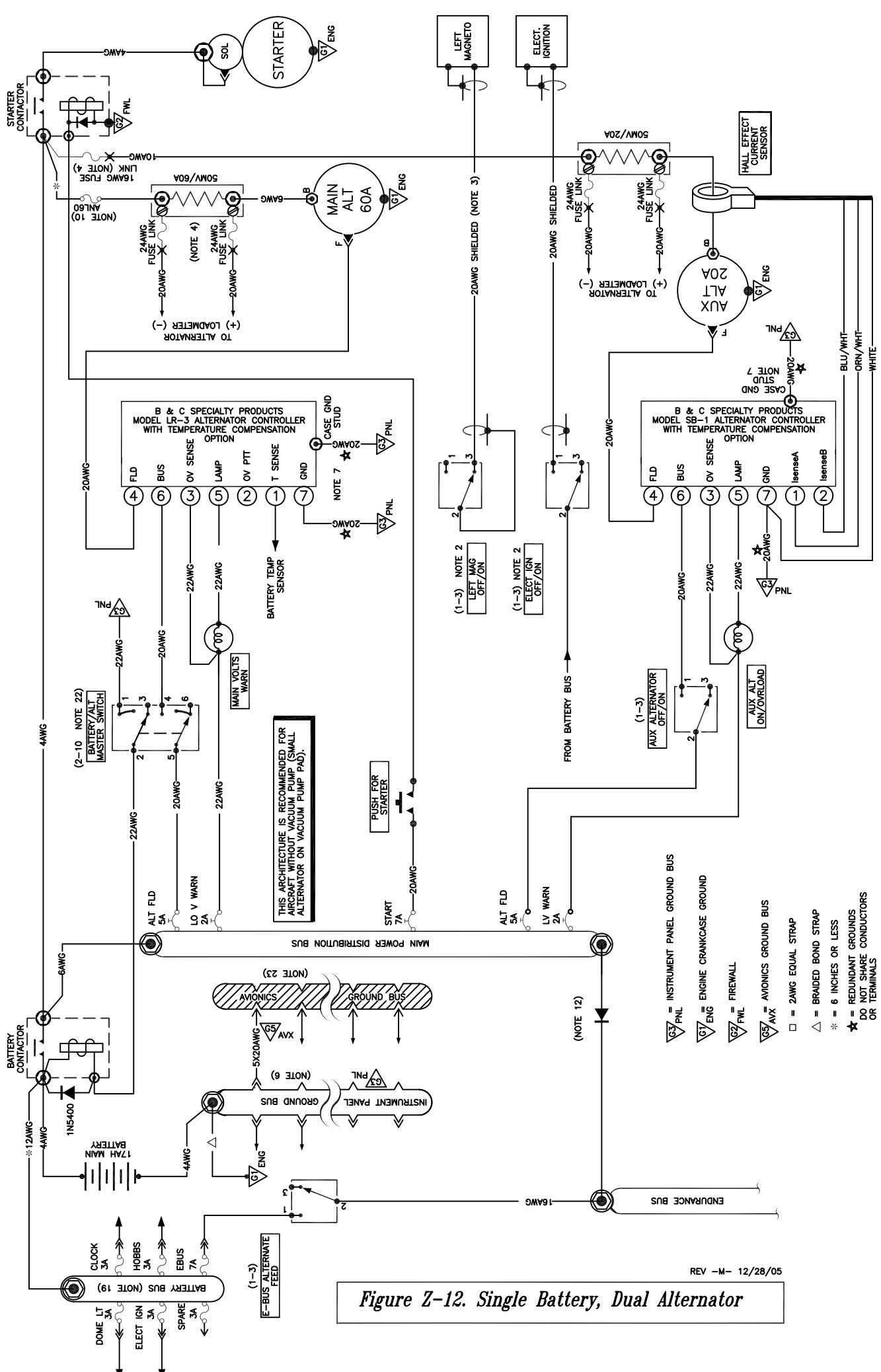
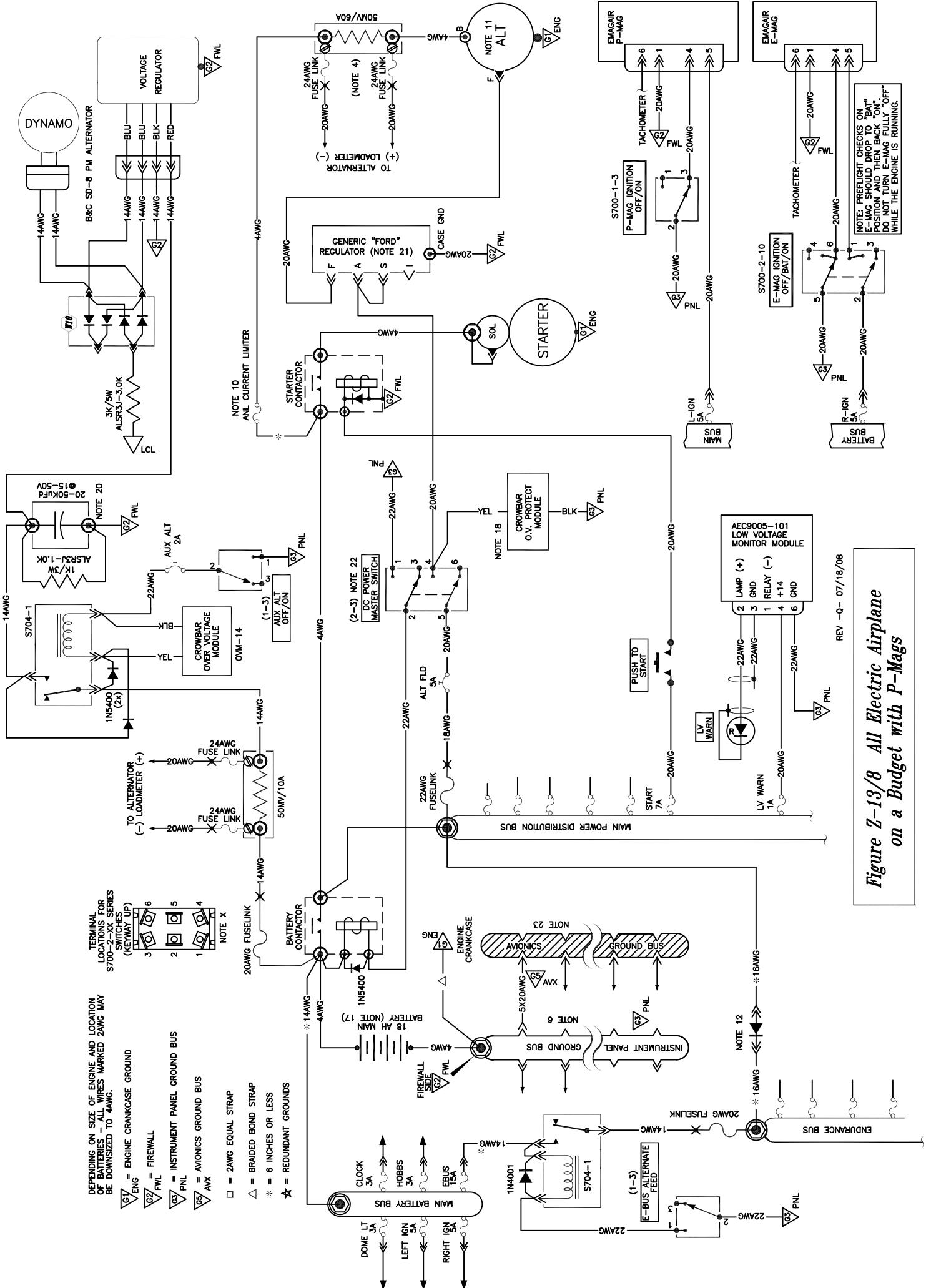
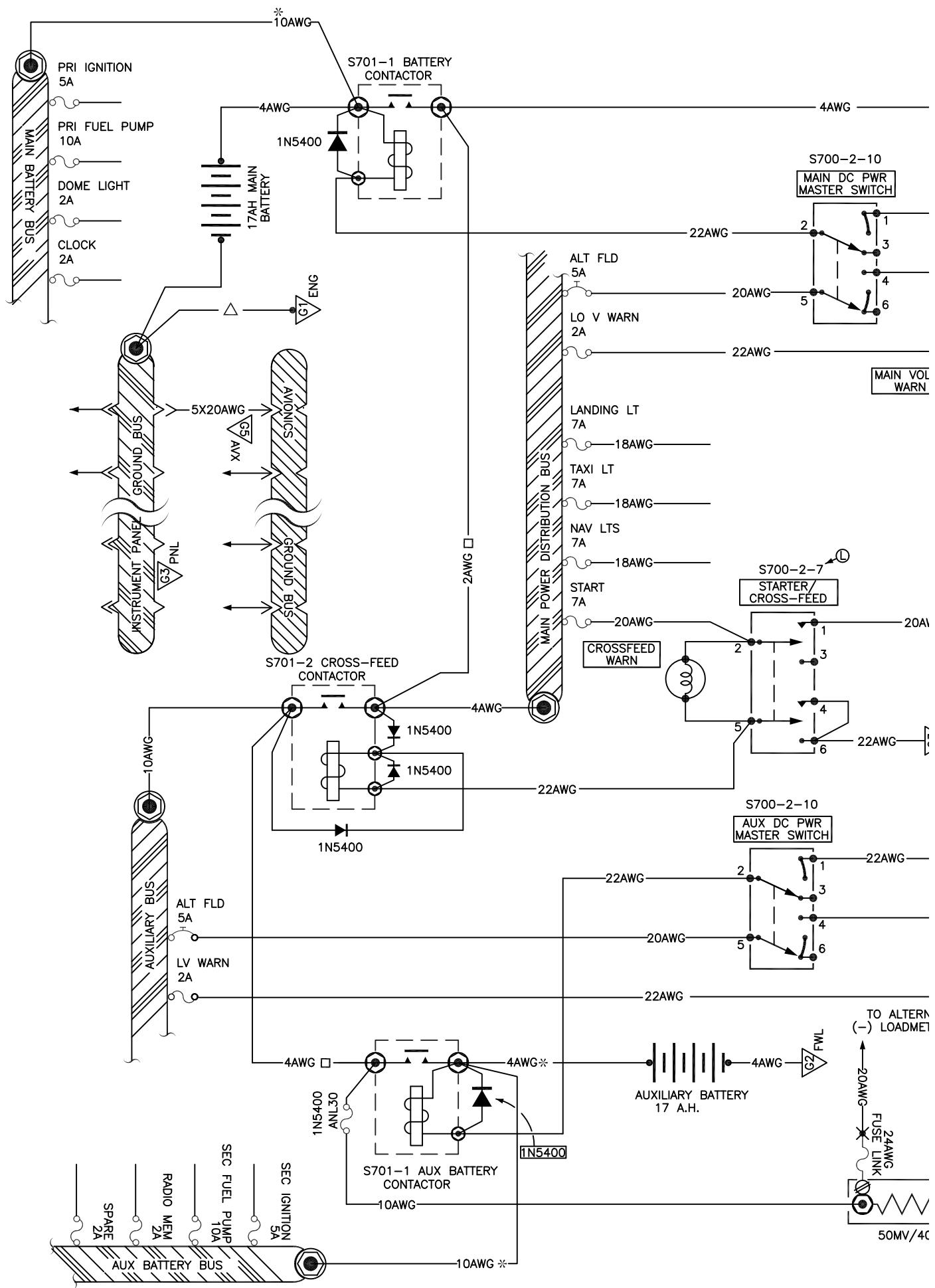


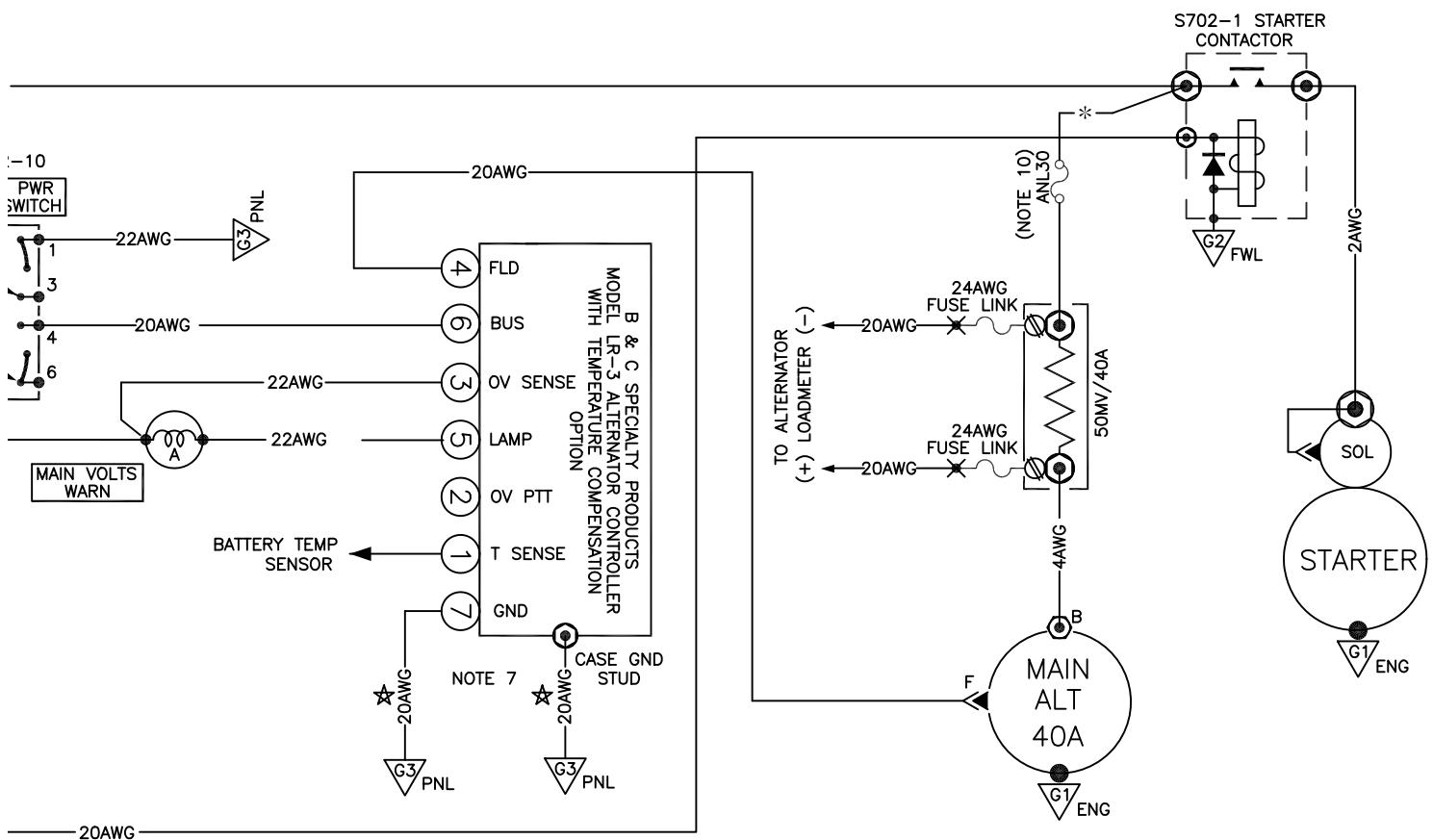
Figure Z-12. Single Battery, Dual Alternator

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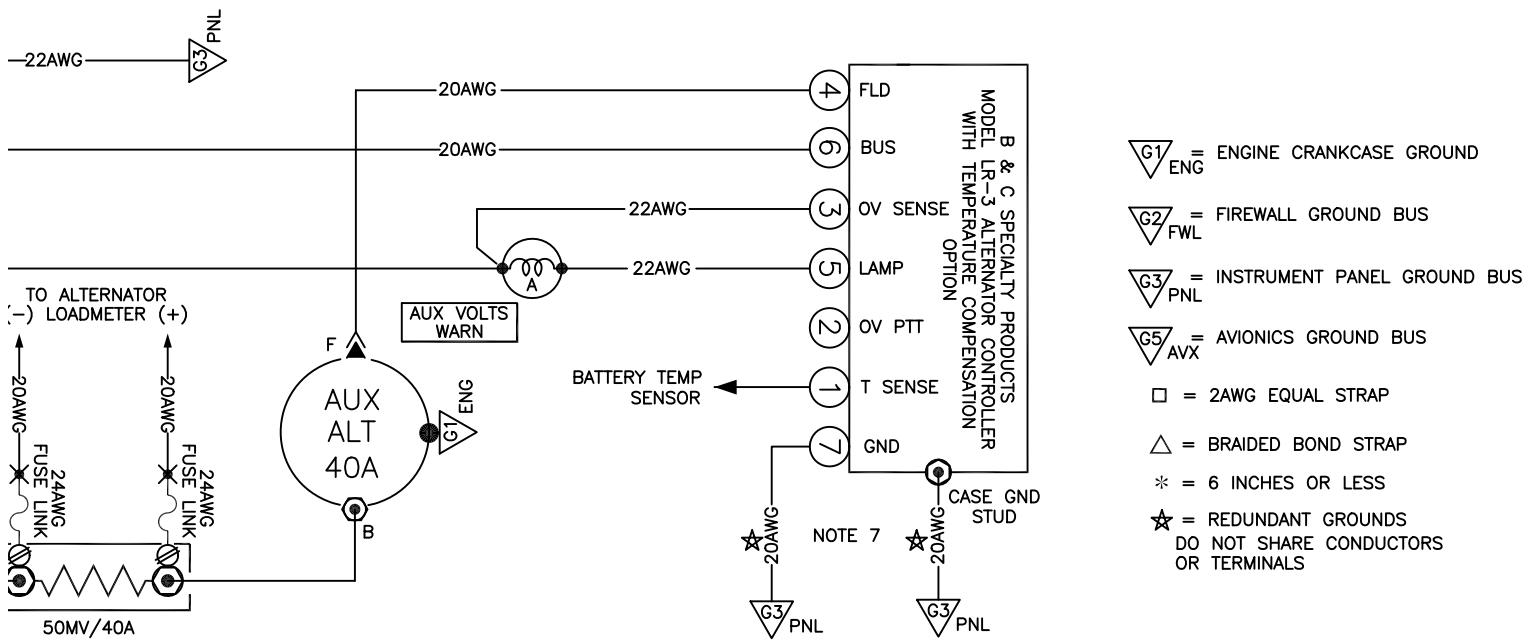
*Figure Z-13/8 All Electric Airplane
on a Budget with P-Mags*





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Figure Z-14 Dual Battery, Dual Alternator, Split Bus



\triangle = ENGINE CRANKCASE GROUND

\triangle = FIREWALL GROUND BUS

\triangle = INSTRUMENT PANEL GROUND BUS

\triangle = AVIONICS GROUND BUS

\square = 2AWG EQUAL STRAP

\triangle = BRAIDED BOND STRAP

* = 6 INCHES OR LESS

★ = REDUNDANT GROUNDS
DO NOT SHARE CONDUCTORS
OR TERMINALS

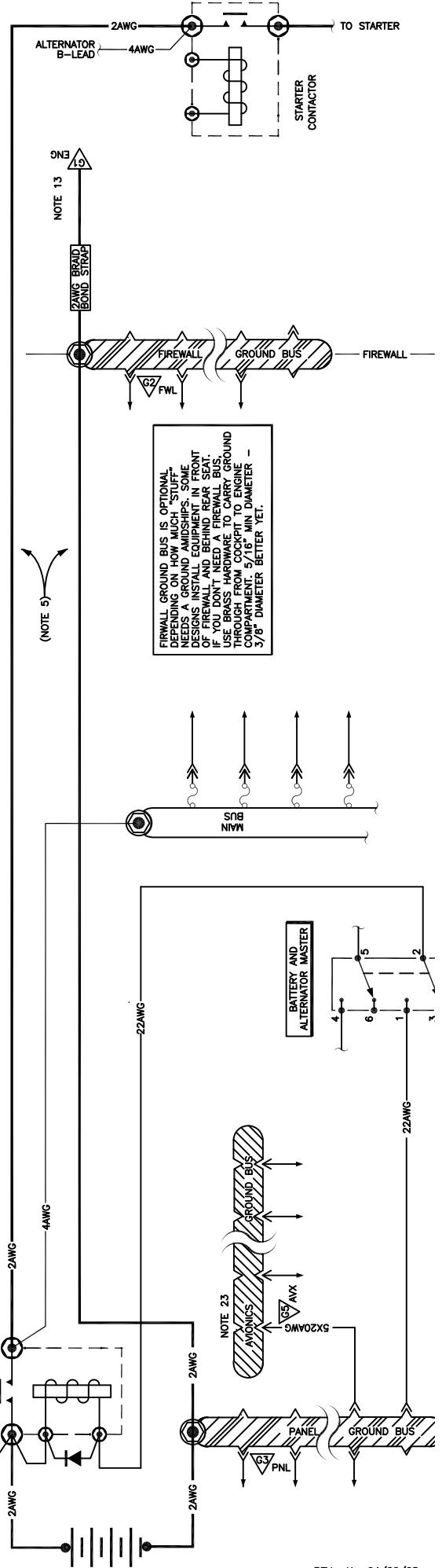
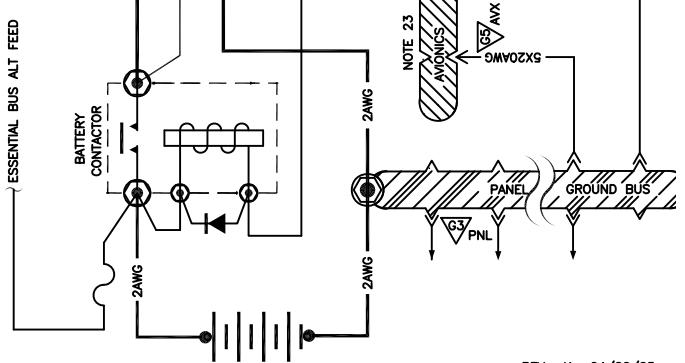
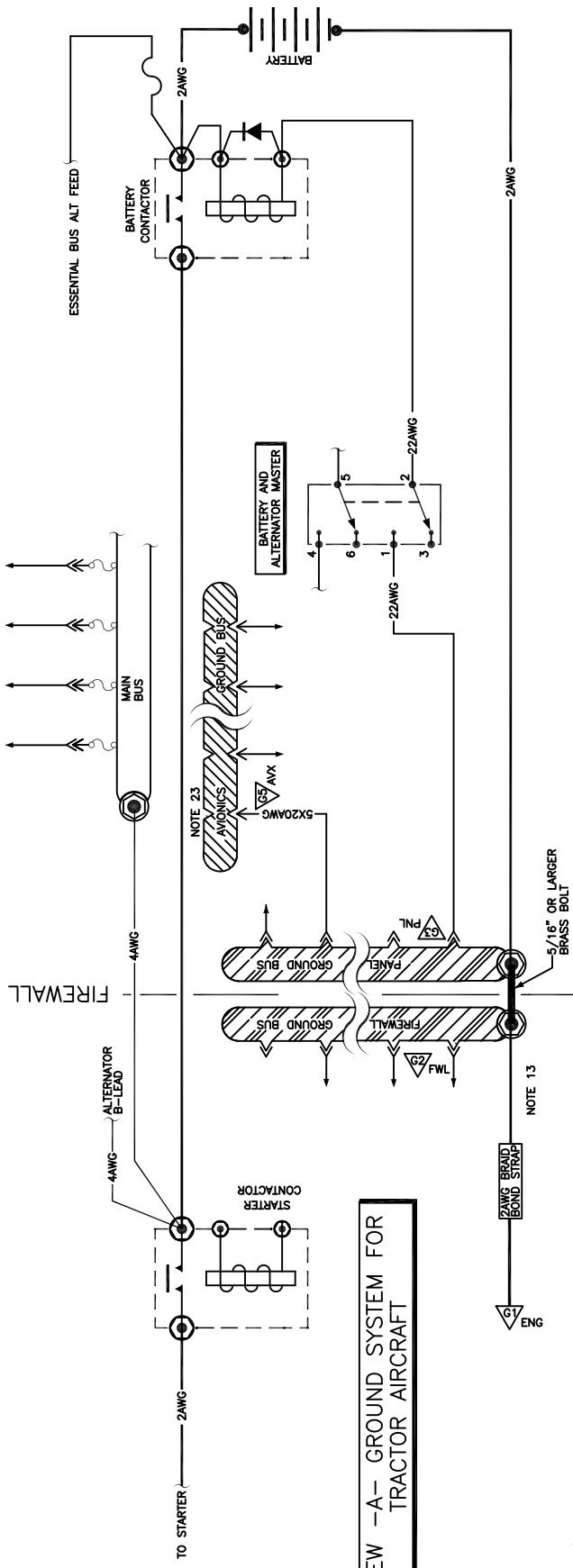
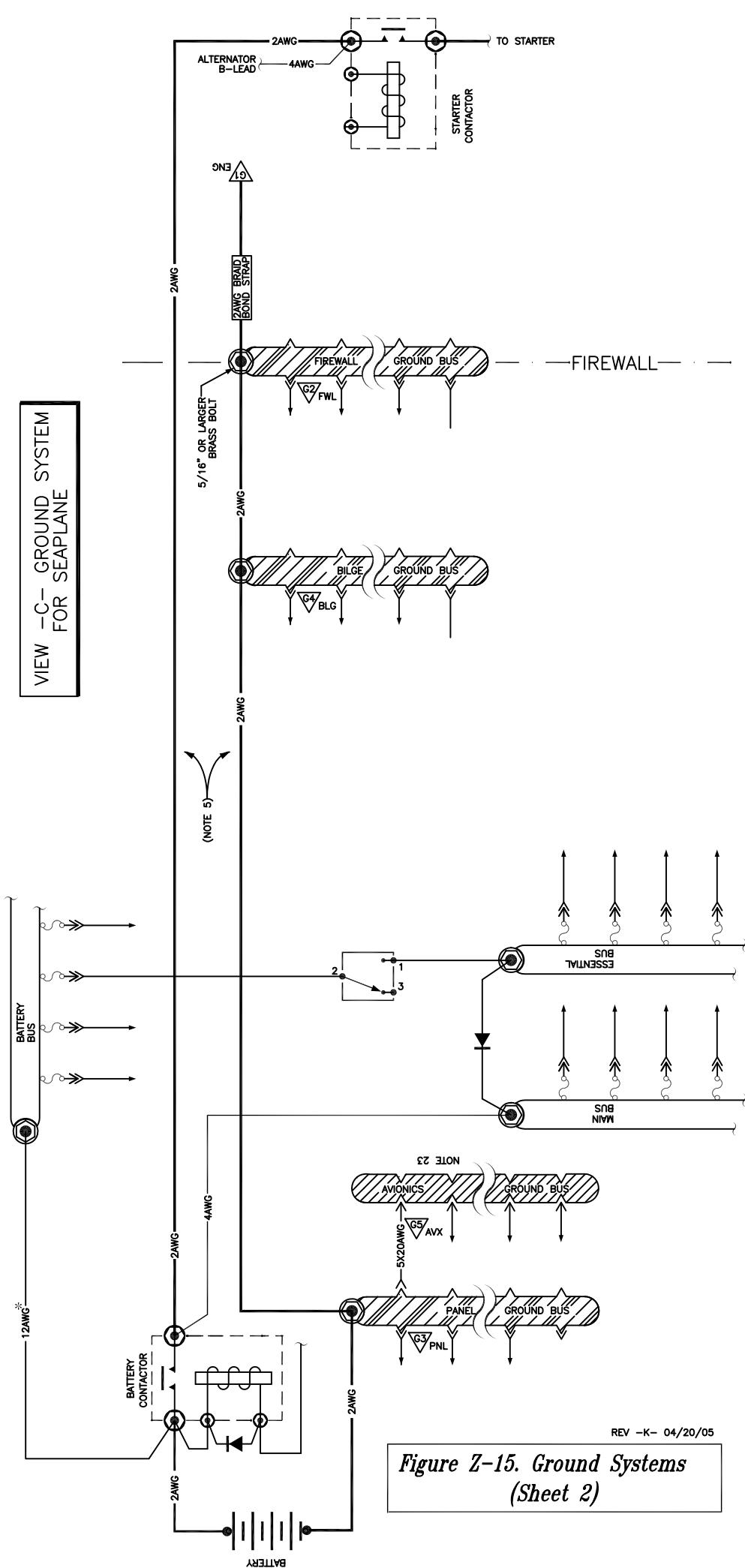
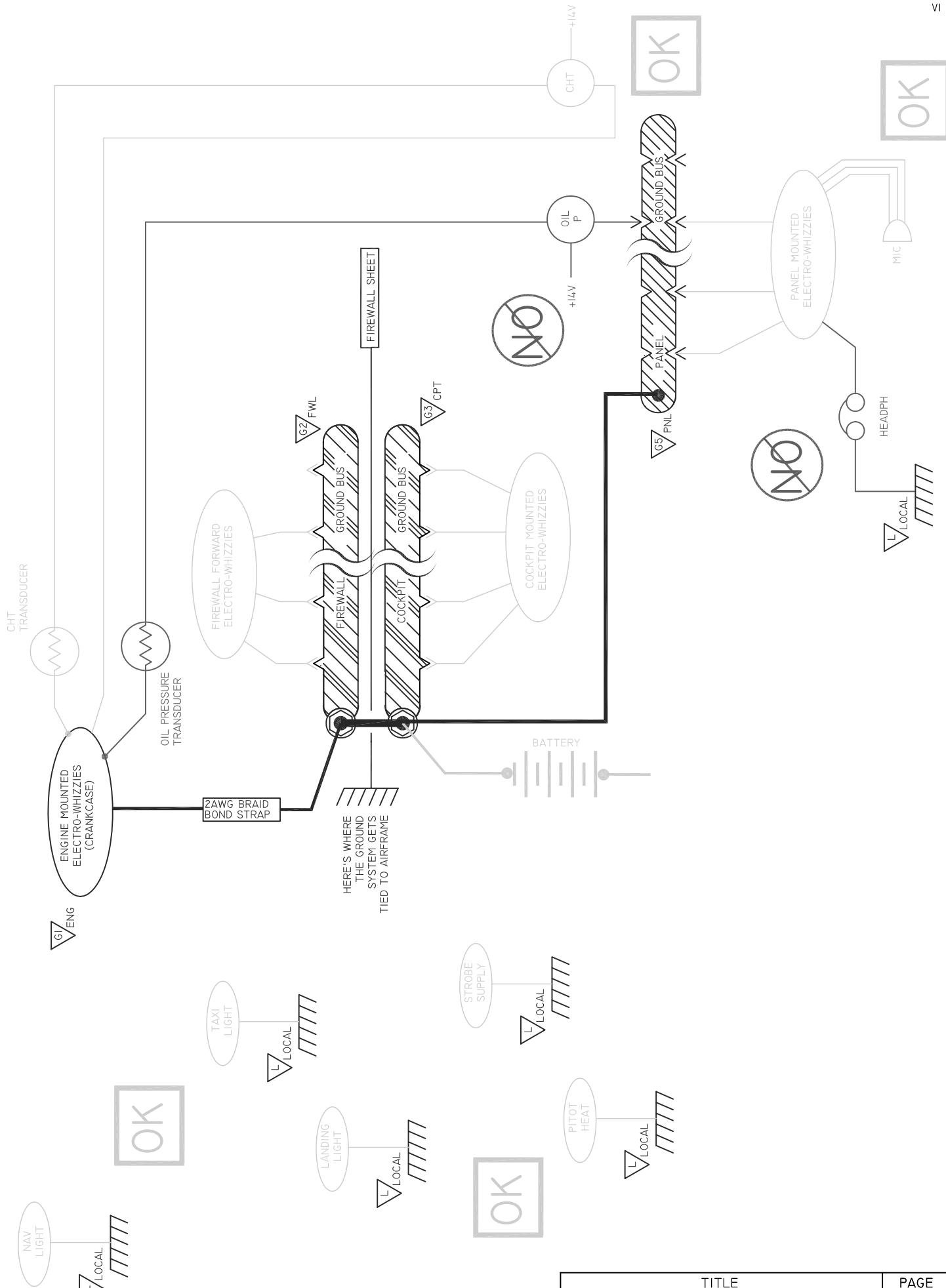


Figure Z-15. Ground Systems (Sheet 1)





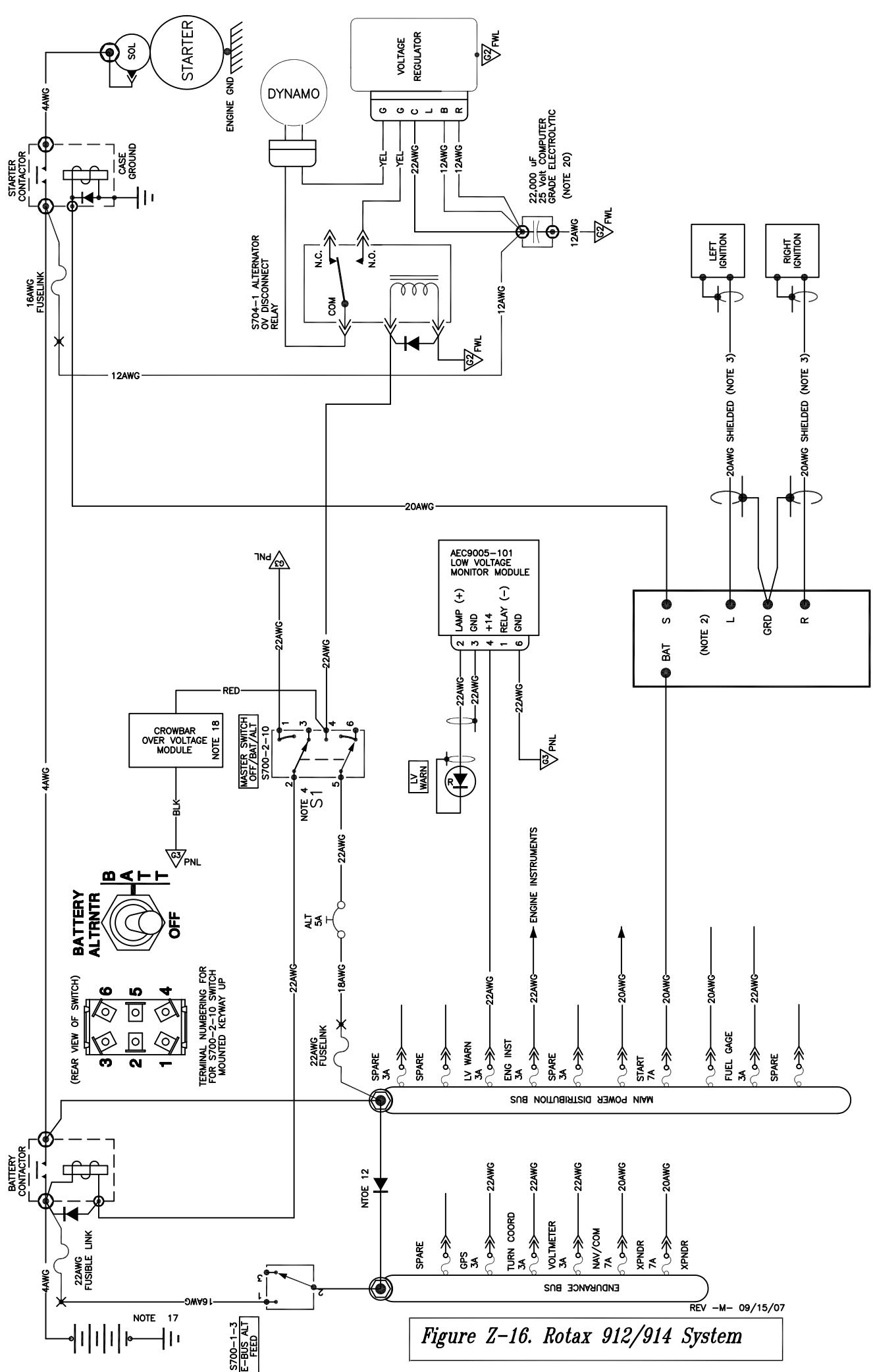


Figure Z-16. Rotax 912/914 System

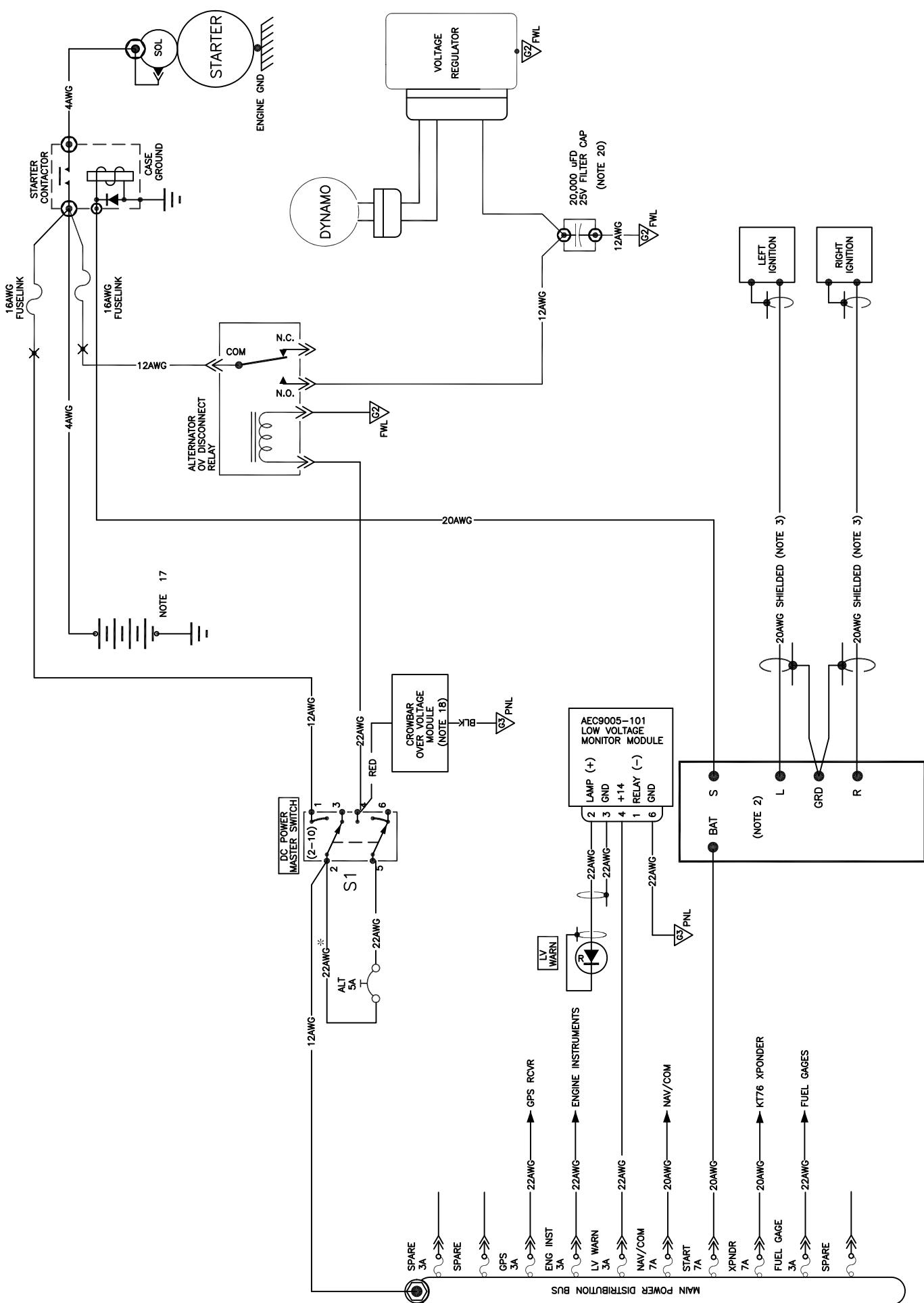


Figure Z-17. Small Rotax System
(or Aircraft with B&C SD-8 Alternator
as Primary Engine Driven Power).

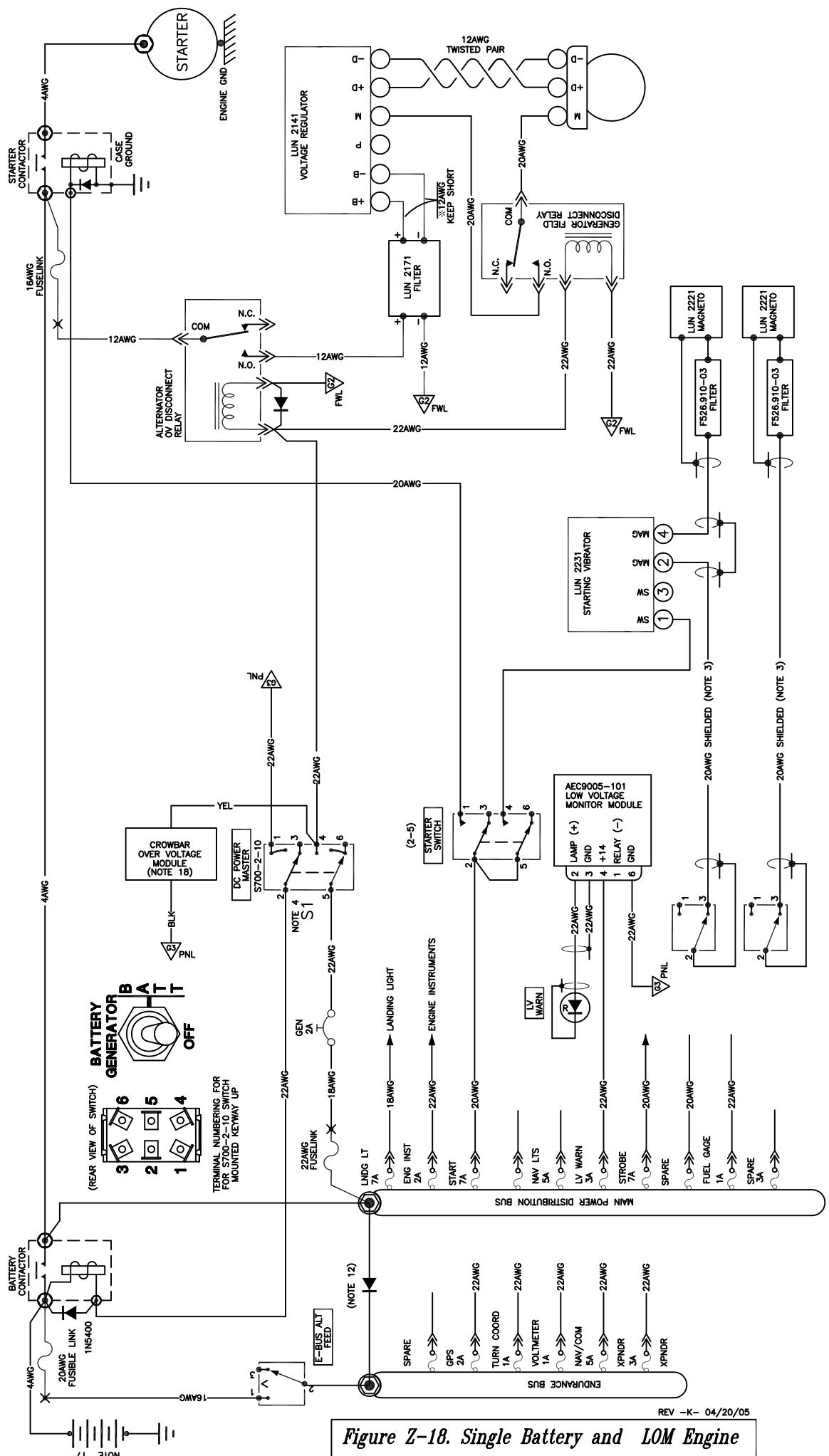
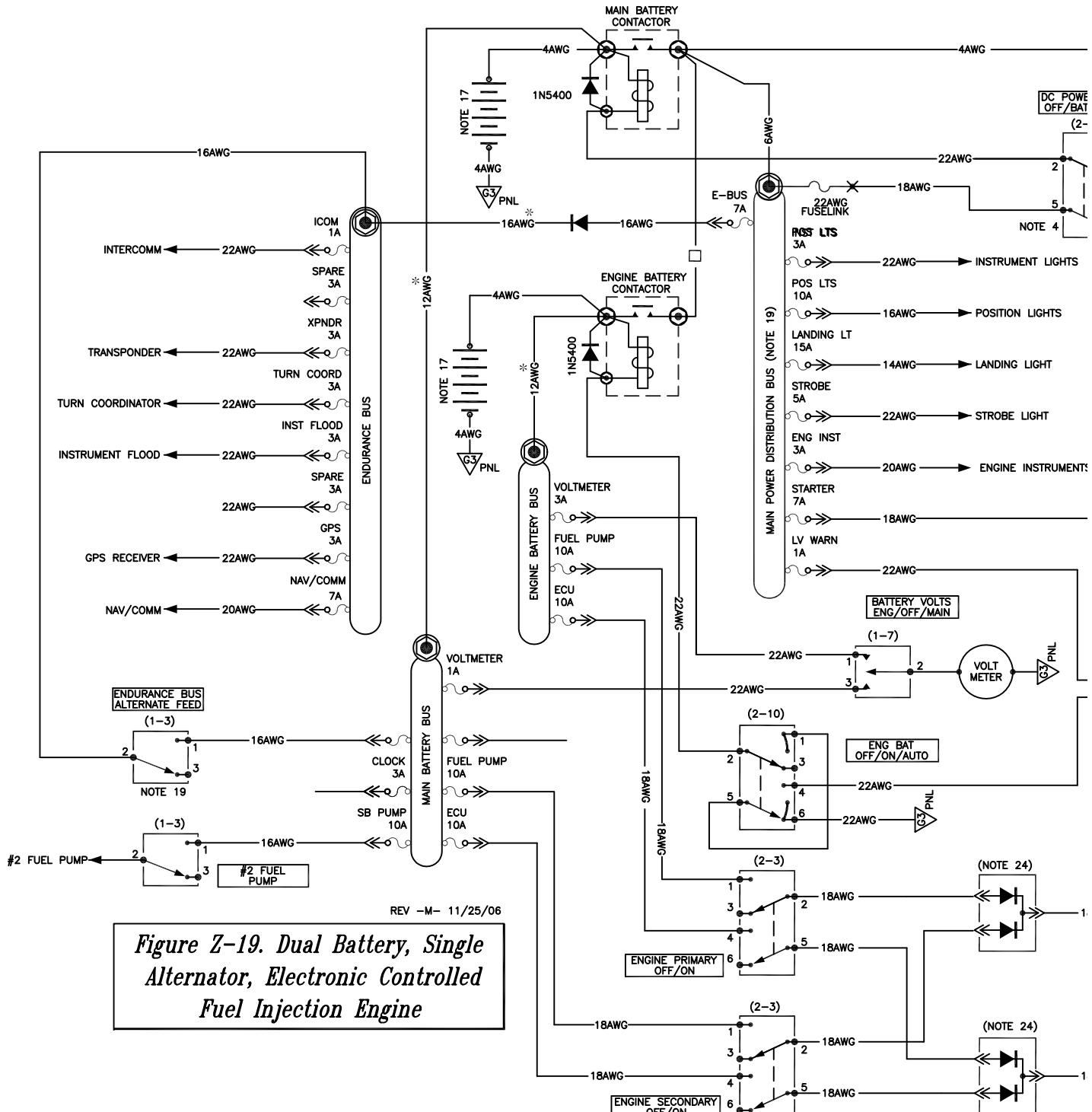
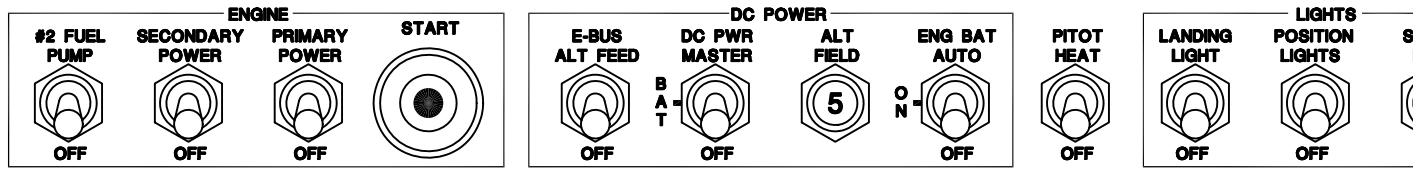
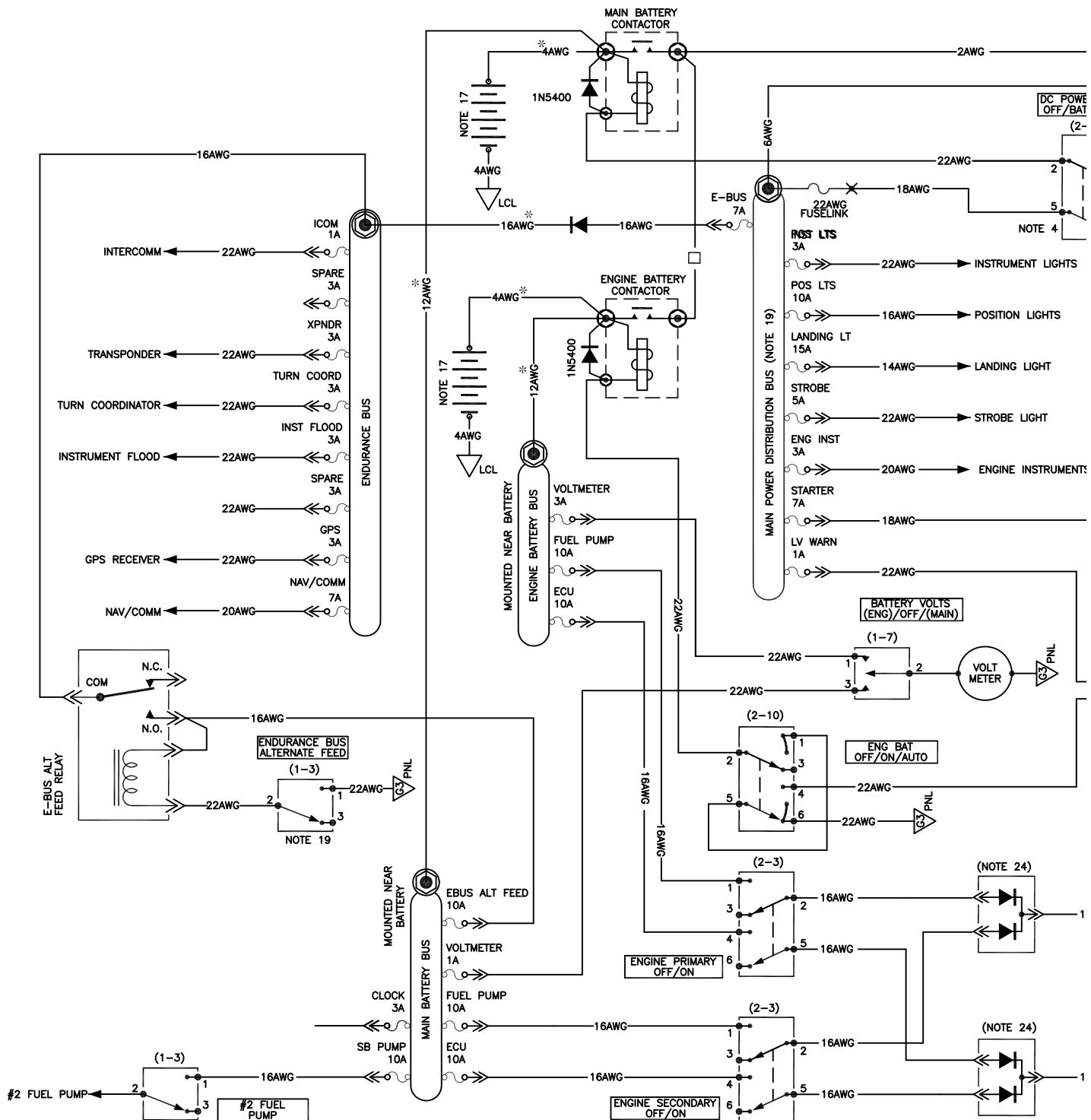
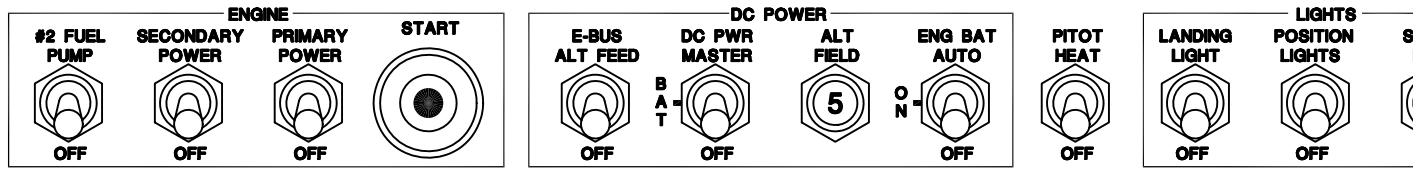
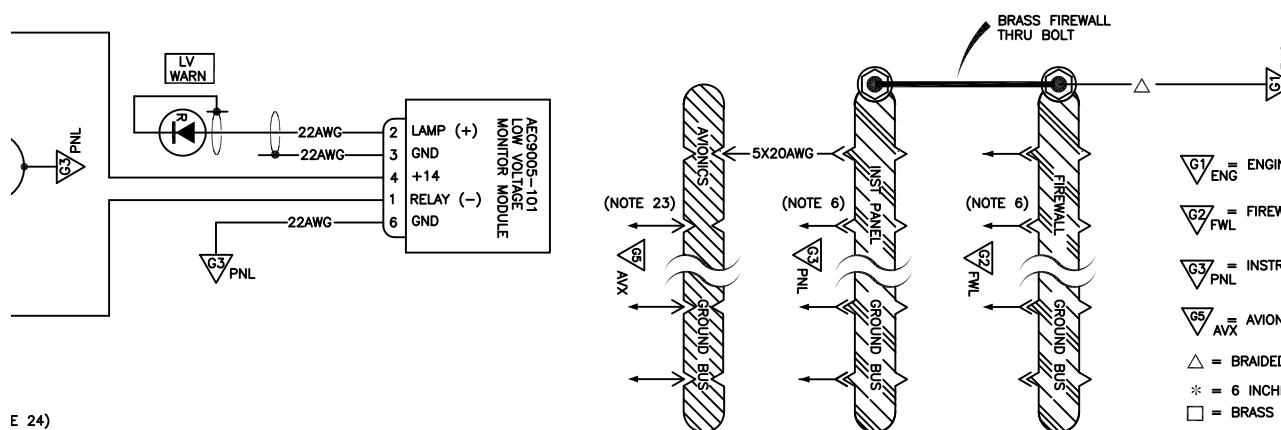
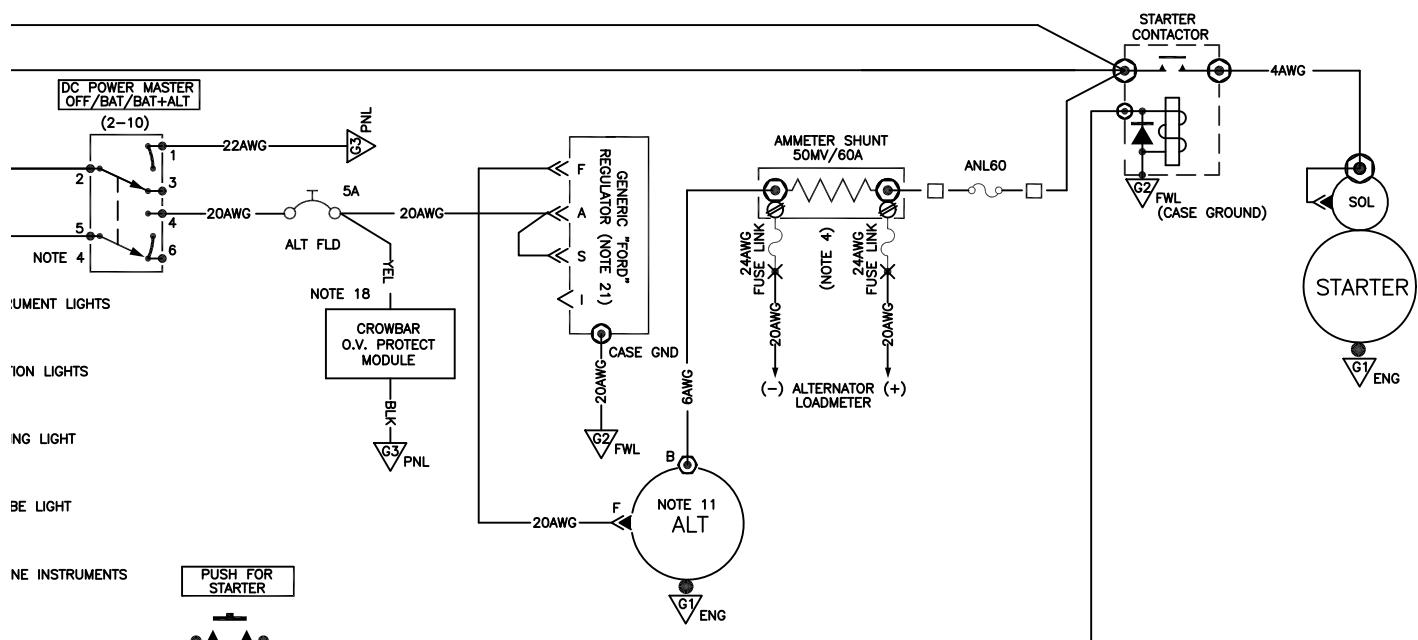
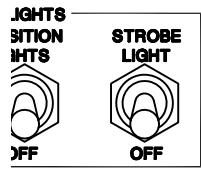


Figure Z-18. Single Battery and LOM Engine

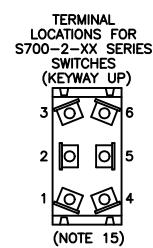






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Figure Z-19/RB. Dual Batteries, Single Alternator, Electronic Controlled Fuel Injection Engine, Rear Mounted Batteries



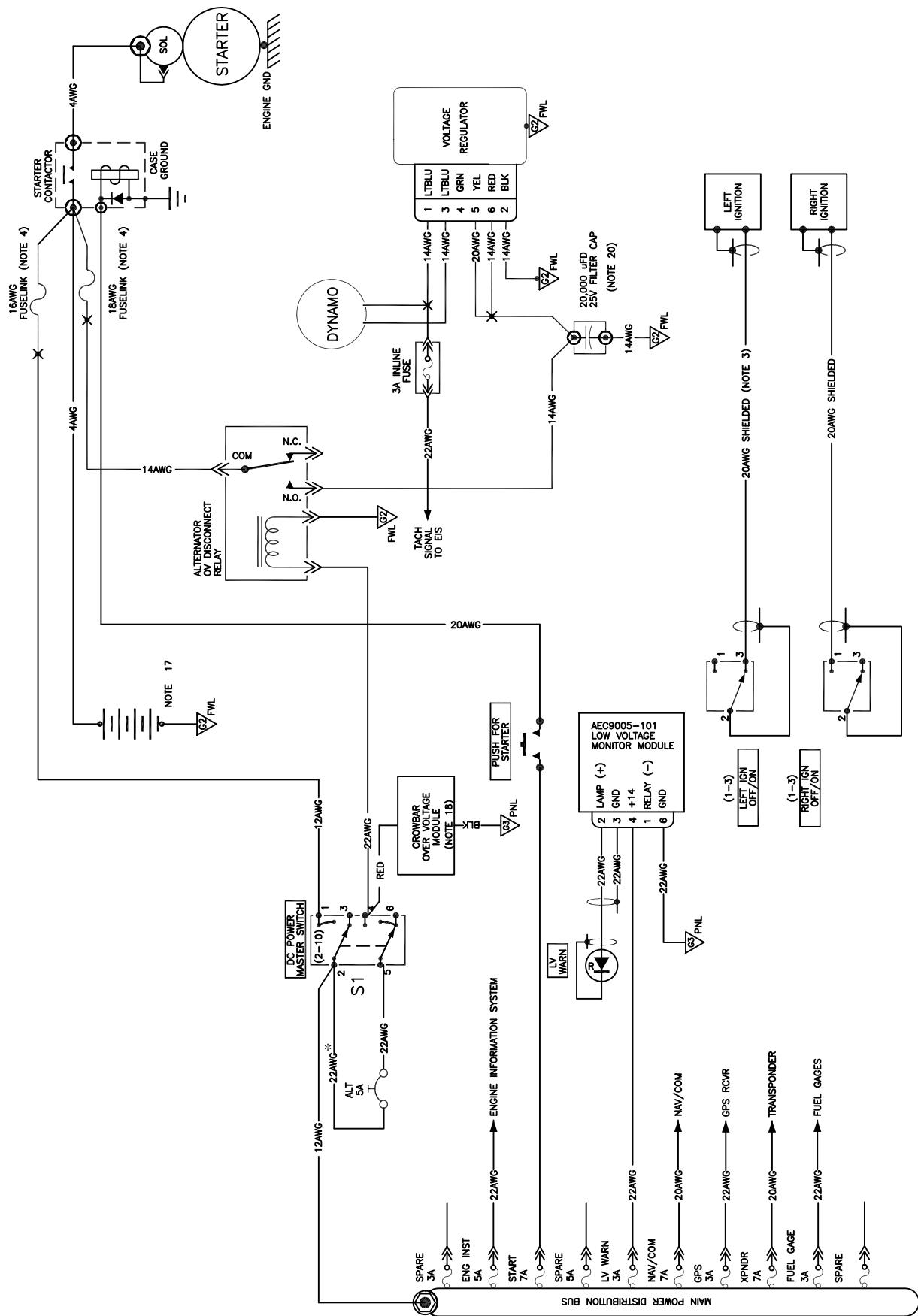


Figure Z-20. Small Jabiru System

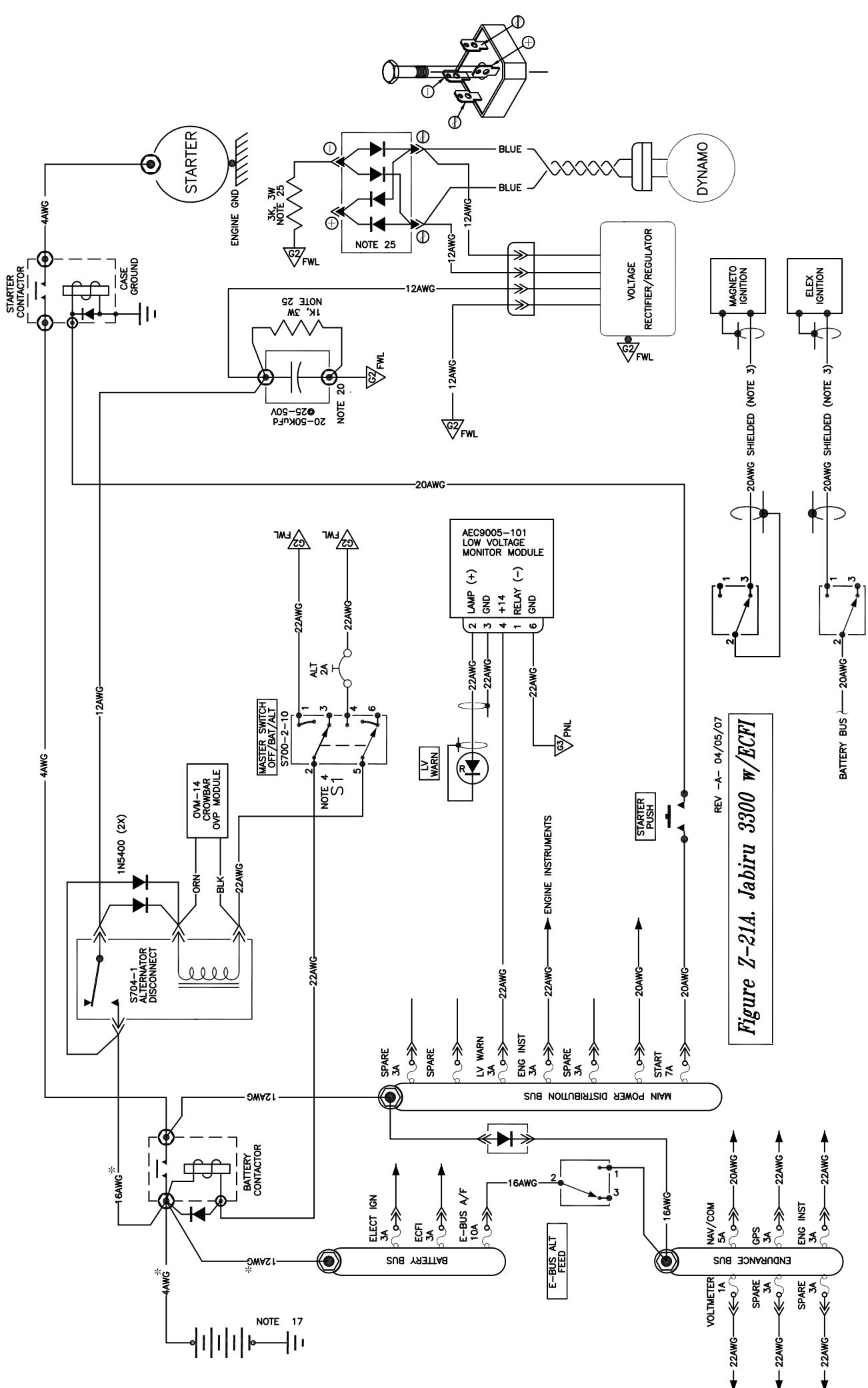


Figure 7-21A. Jabiru 3300 w/ECFI

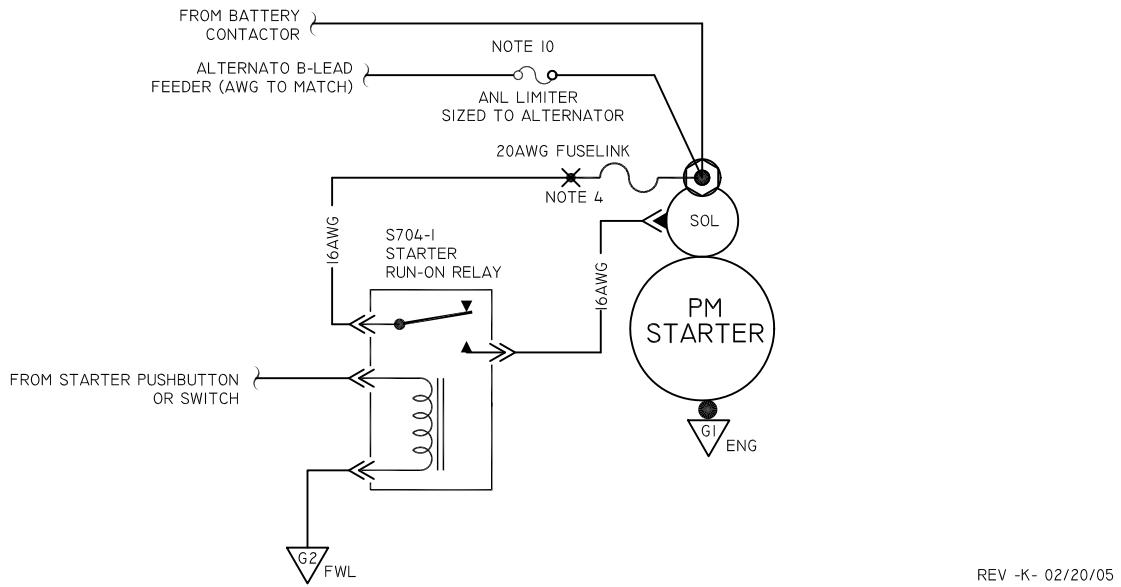
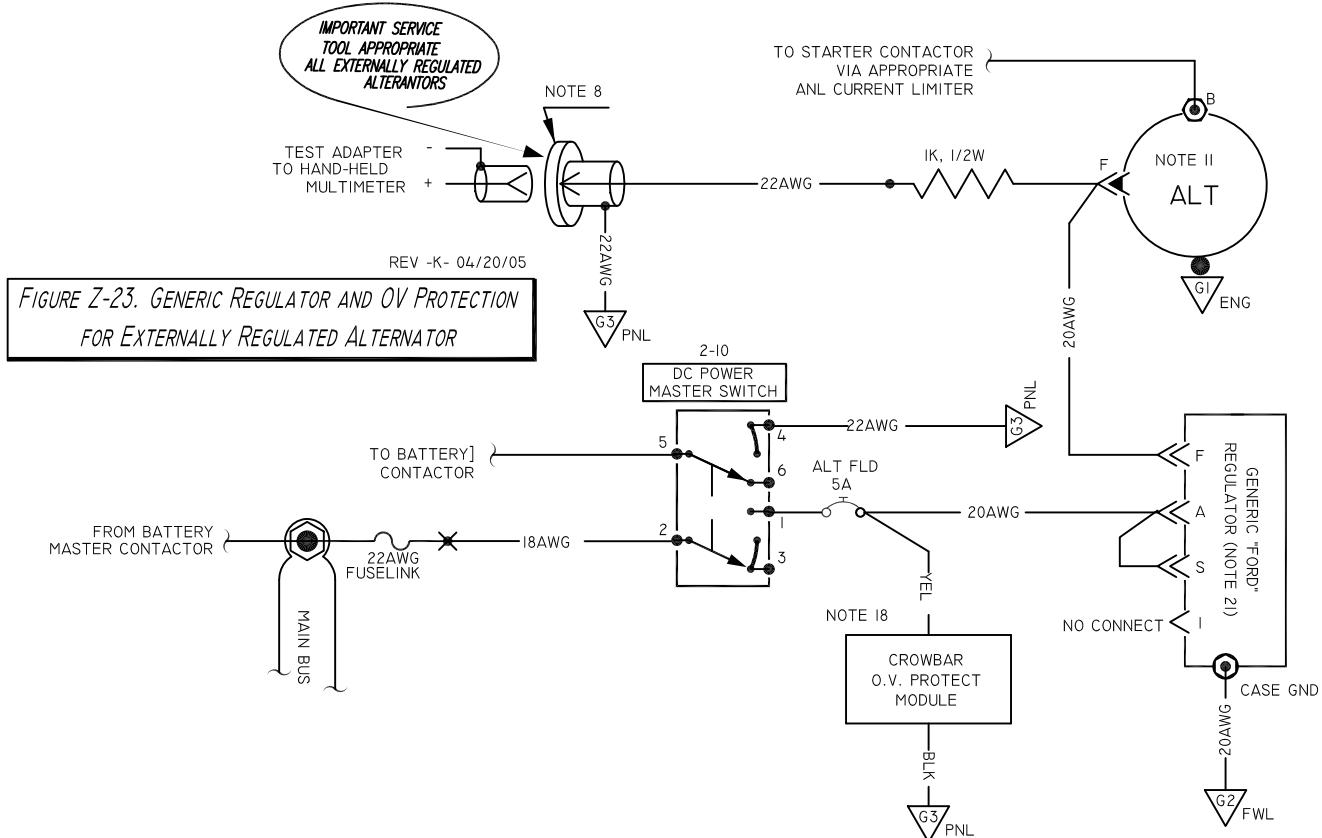


FIGURE Z-22. FIX FOR "RUN-ON" IN STARTERS WITH PERMANENT MAGNET MOTORS.



INTERIM

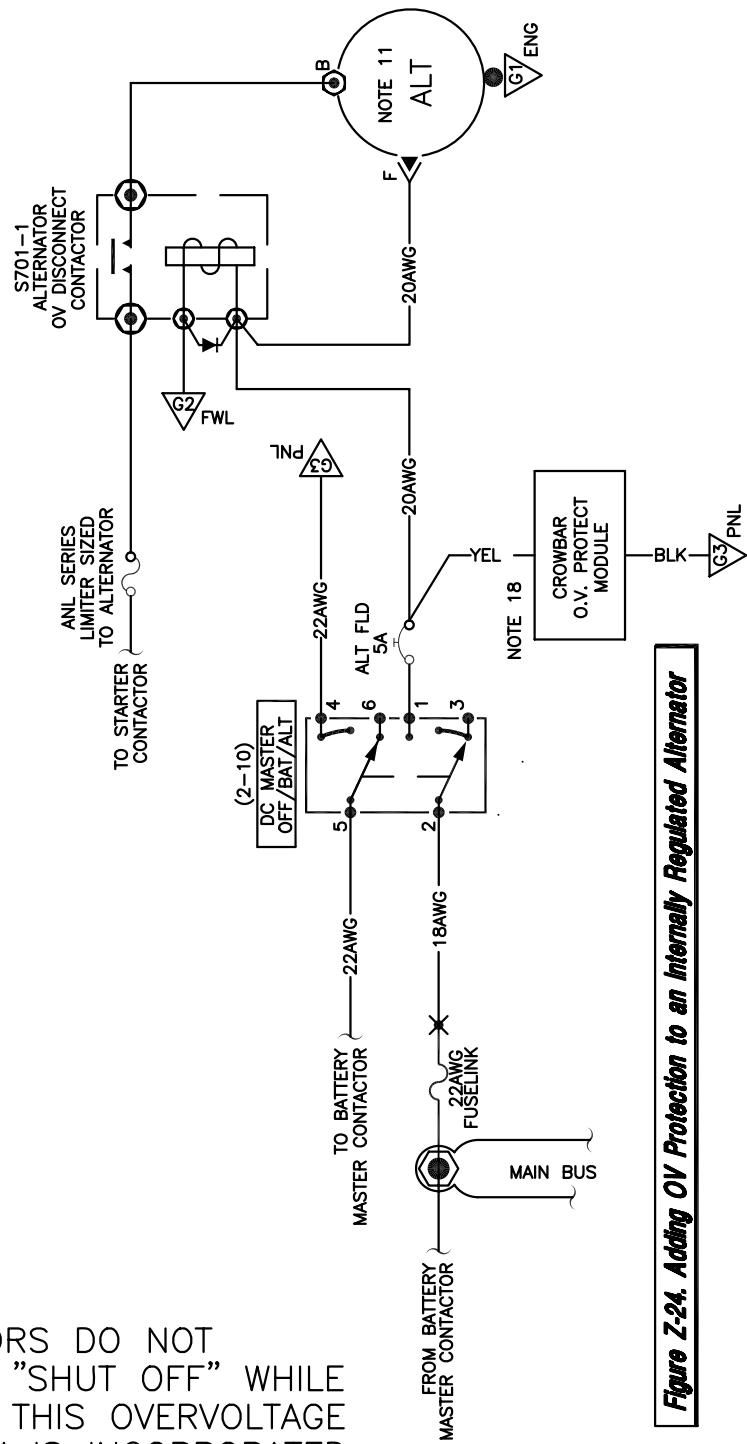


Figure 2-24. Adding OV Protection to an Internally Regulated Alternator

NOTE:
SOME ALTERNATORS DO NOT
TOLERATE BEING "SHUT OFF" WHILE
UNDER LOAD. IF THIS OVERVOLTAGE
CONTROL SYSTEM IS INCORPORATED,
IT'S IMPORANT NOT TO SHUT THE ALTERNATOR
"OFF" ANY TIME THE ENGINE IS RUNNING
EXCEPT EMERGENCIES.

THE PROPOSED SYSTEM DESCRIBED ON THE NEXT PAGE WILL EASILY REPLACE THE INTERIM SYSTEM AND HAS NO PROHIBITIONS AS TO WHEN AND HOW THE ALTERNATOR IS SWITCHED ON OR OFF.

INTERIM

PRELIMINARY

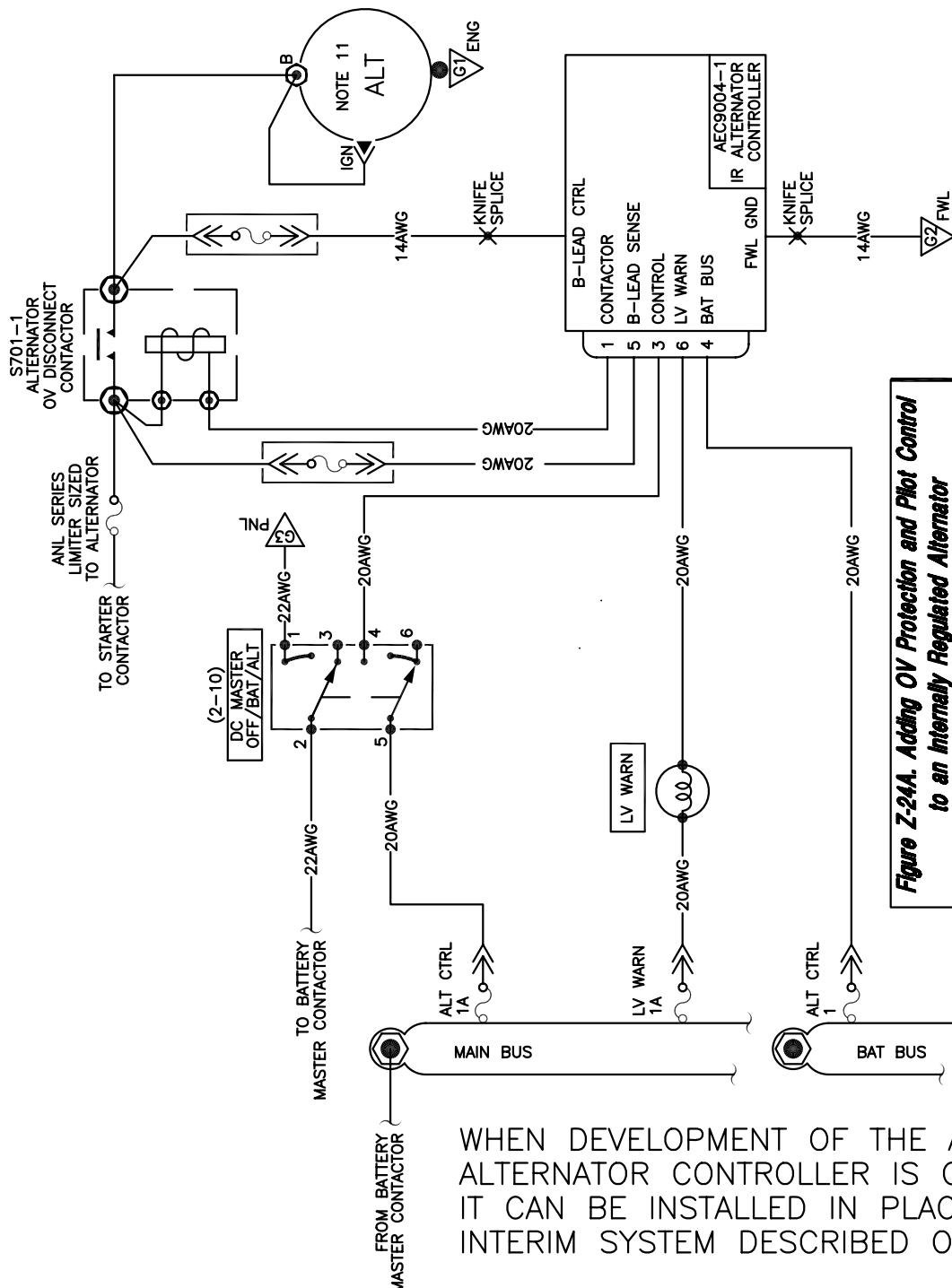
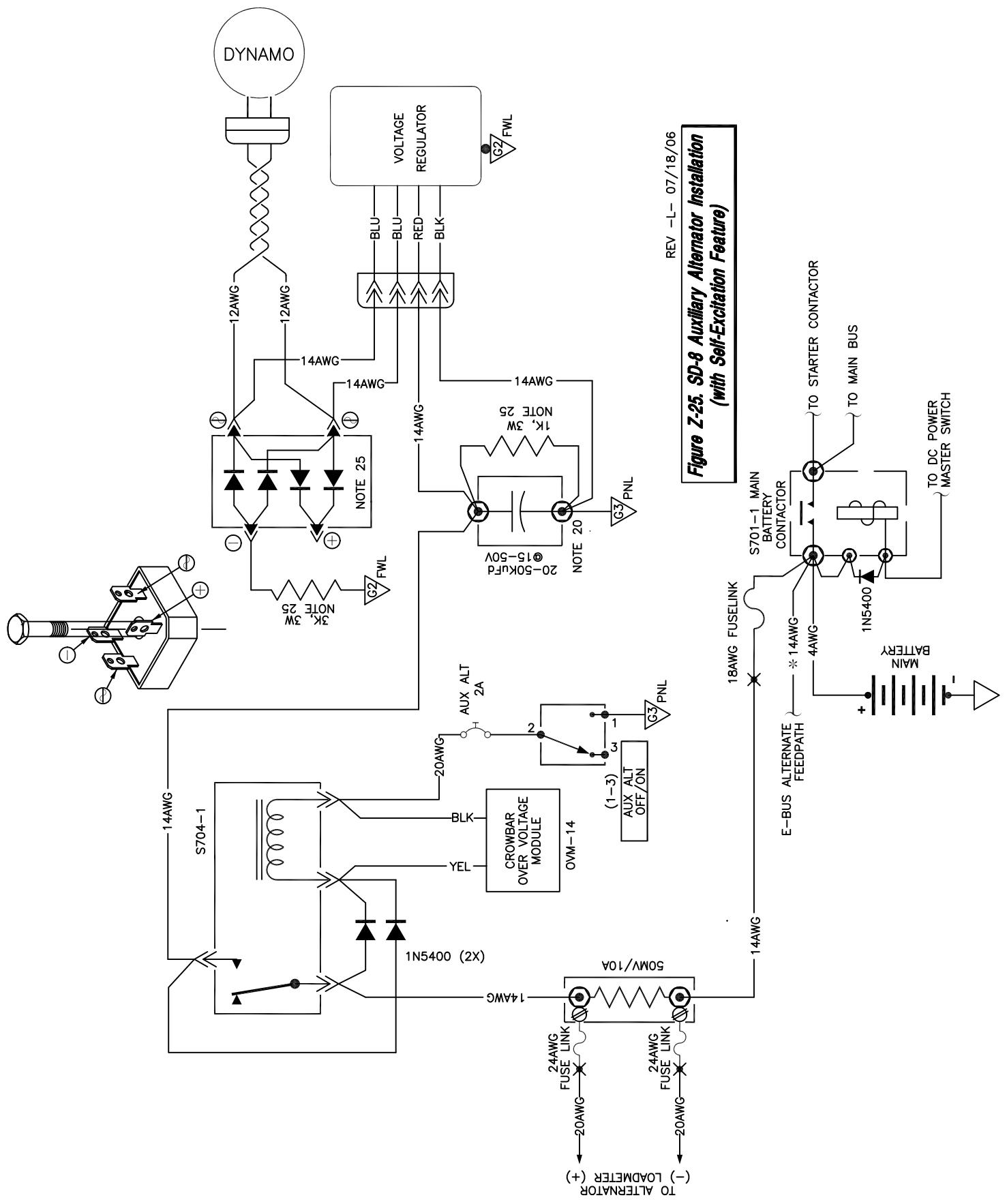


Figure 2-24A. Adding OV Protection and Pilot Control to an Internally Regulated Alternator

WHEN DEVELOPMENT OF THE AEC9004 ALTERNATOR CONTROLLER IS COMPLETE, IT CAN BE INSTALLED IN PLACE OF THE INTERIM SYSTEM DESCRIBED ON PAGE 1.0

THE SAME DISCONNECT RELAY AND CONTROL SWITCH ARE USED. THE OVM-14 MODULE IS DISCARDED. THE AEC9005 CONTROL MODULE ADDED AND A L.V. WARNING LIGHT IS ADDED.

PRELIMINARY



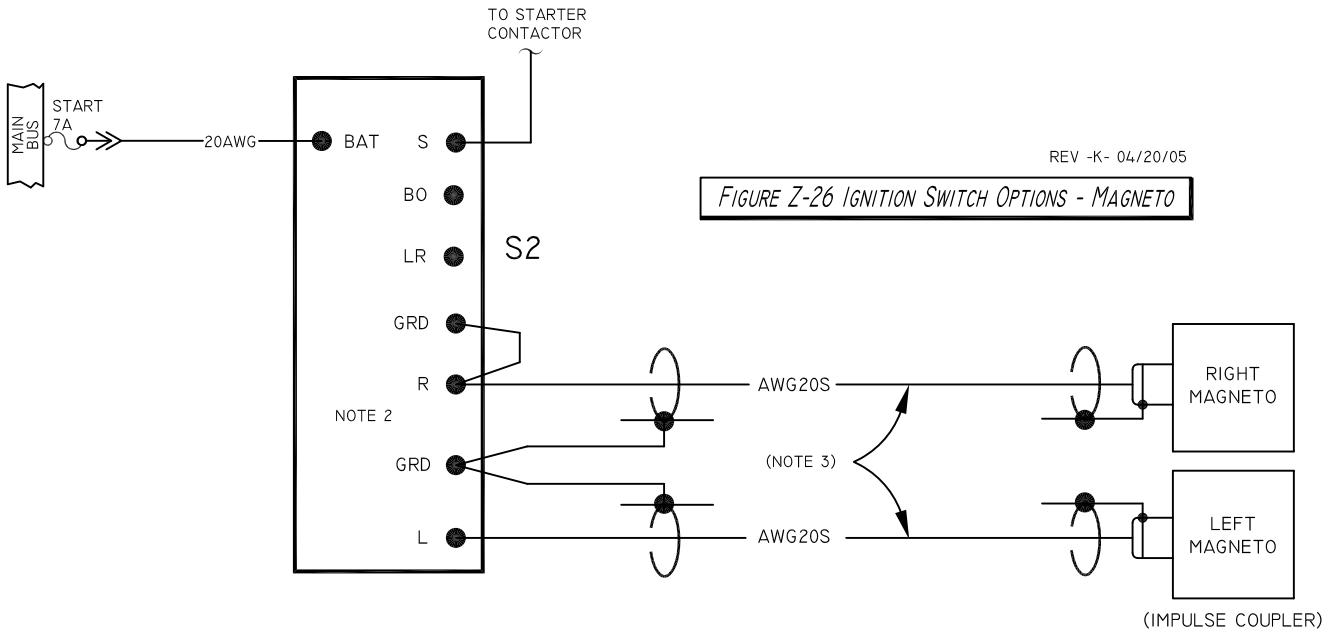
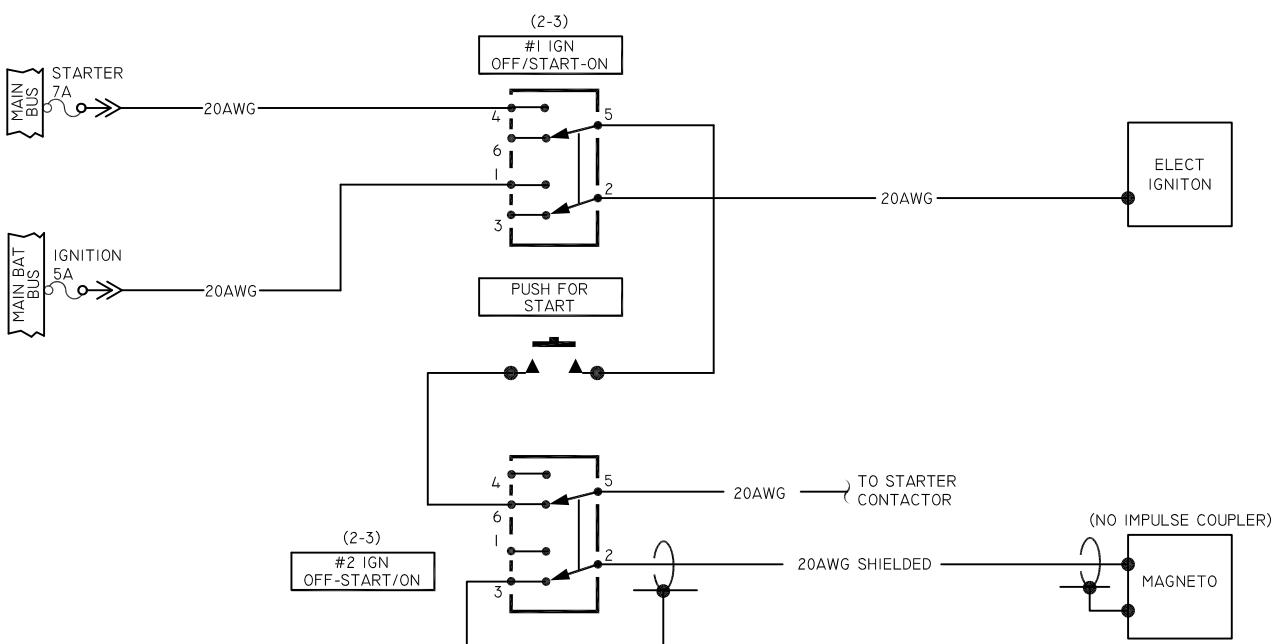
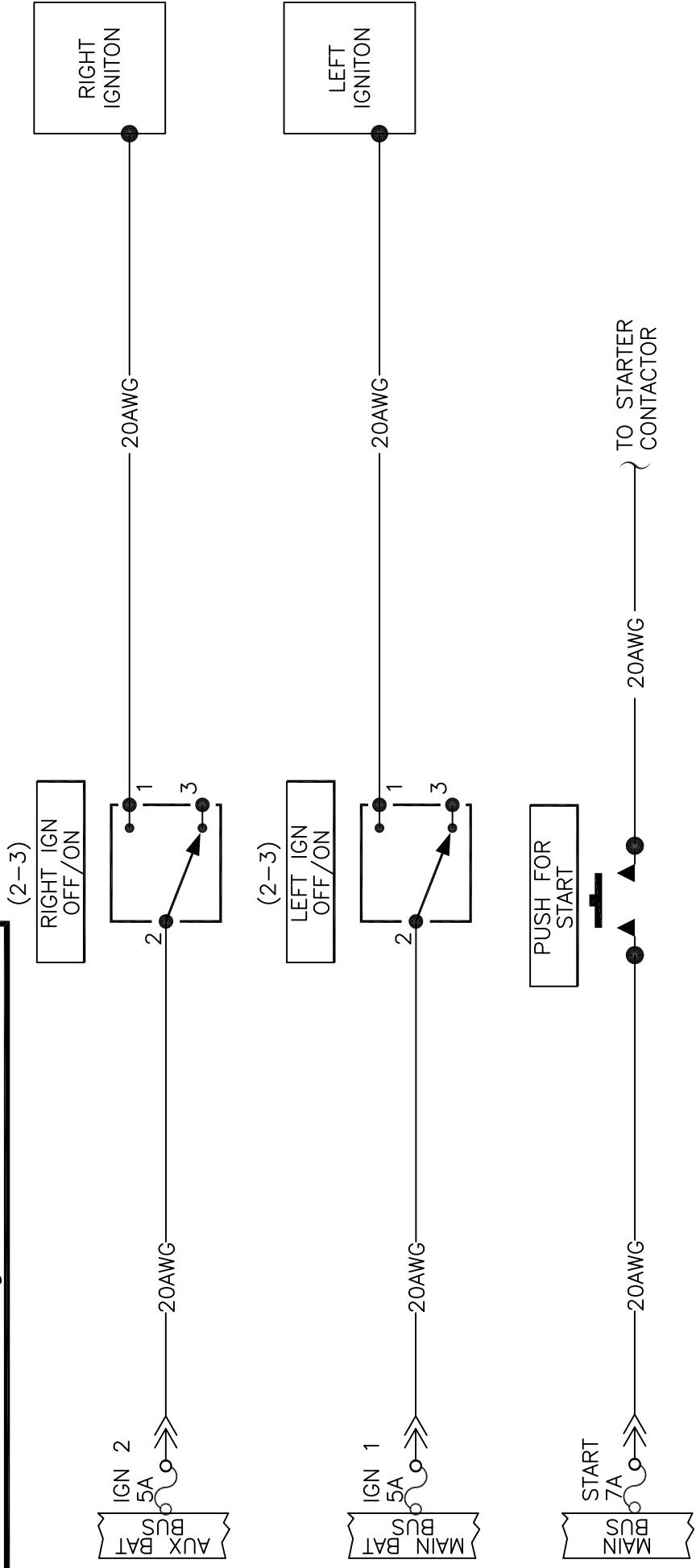


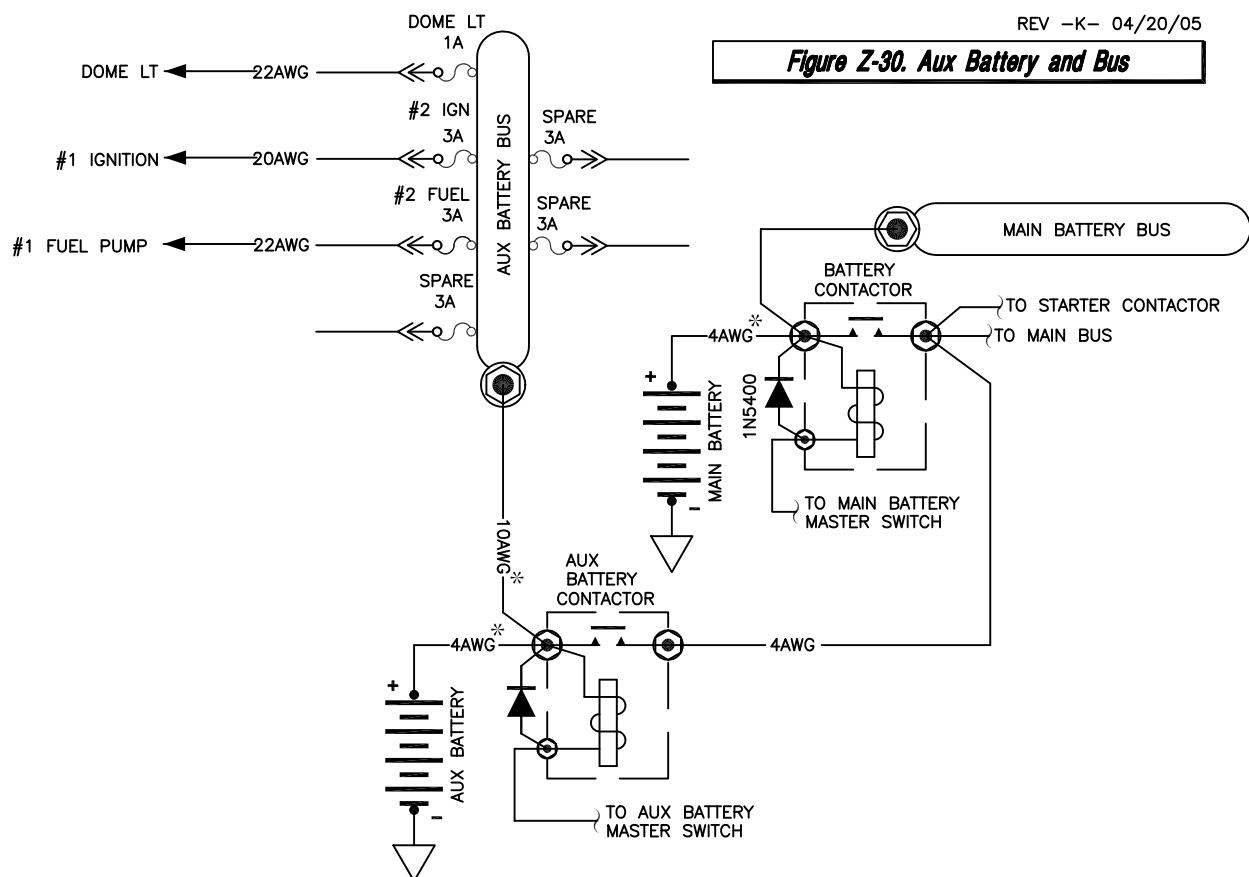
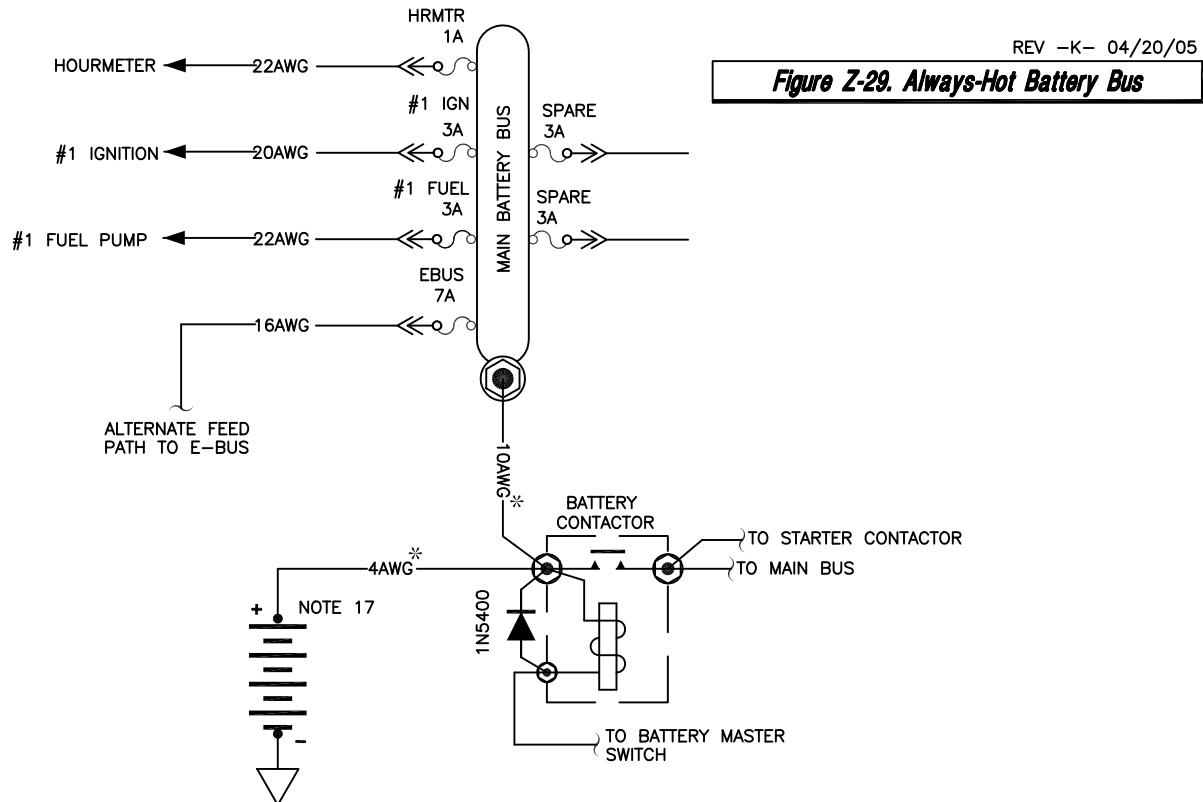
FIGURE Z-27. NON-IMPULSE COUPLED MAGNETO AND ONE ELECTRONIC IGNITION

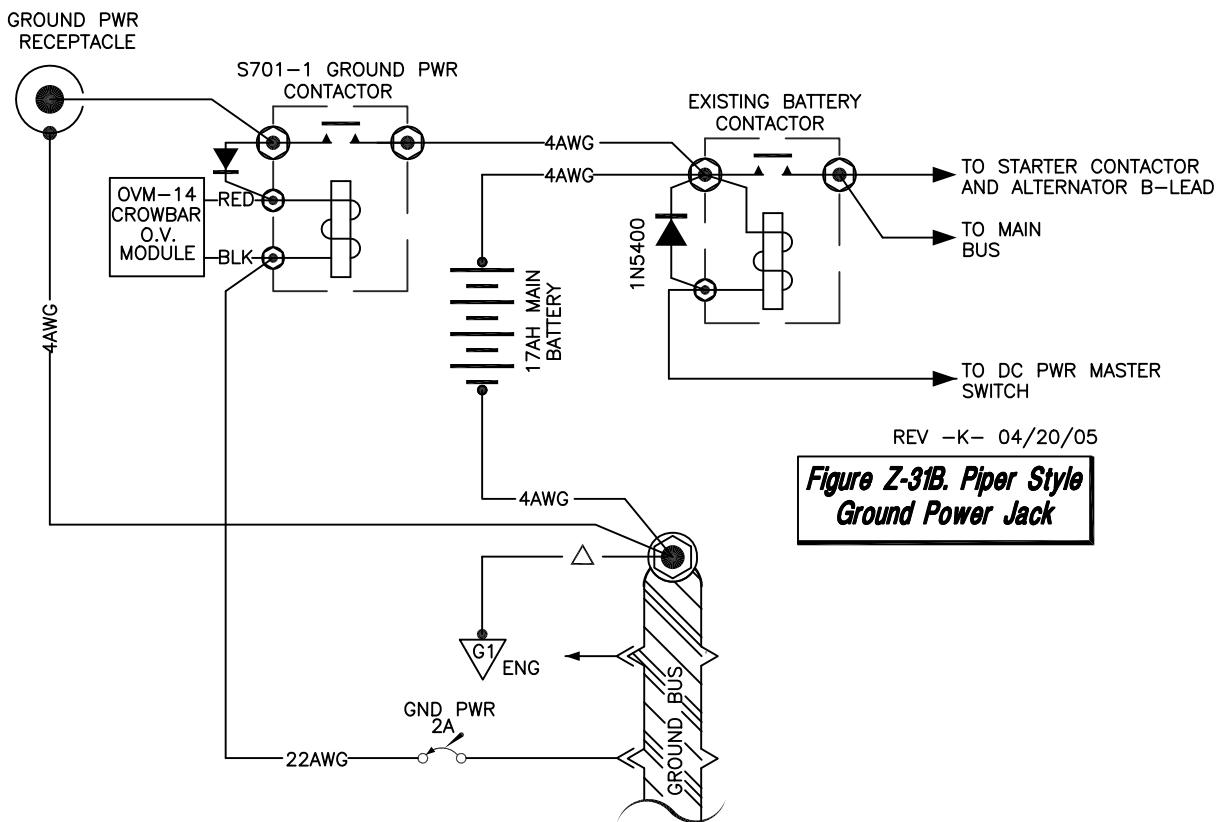
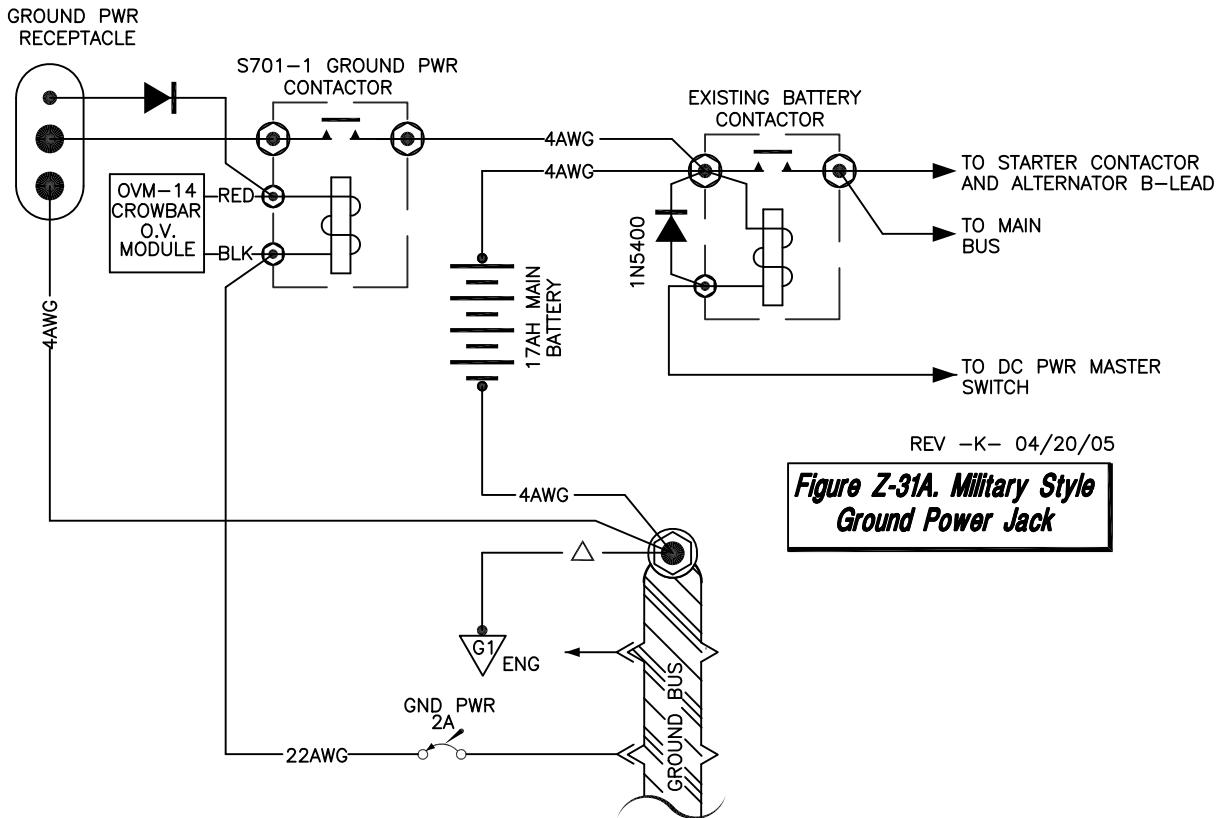


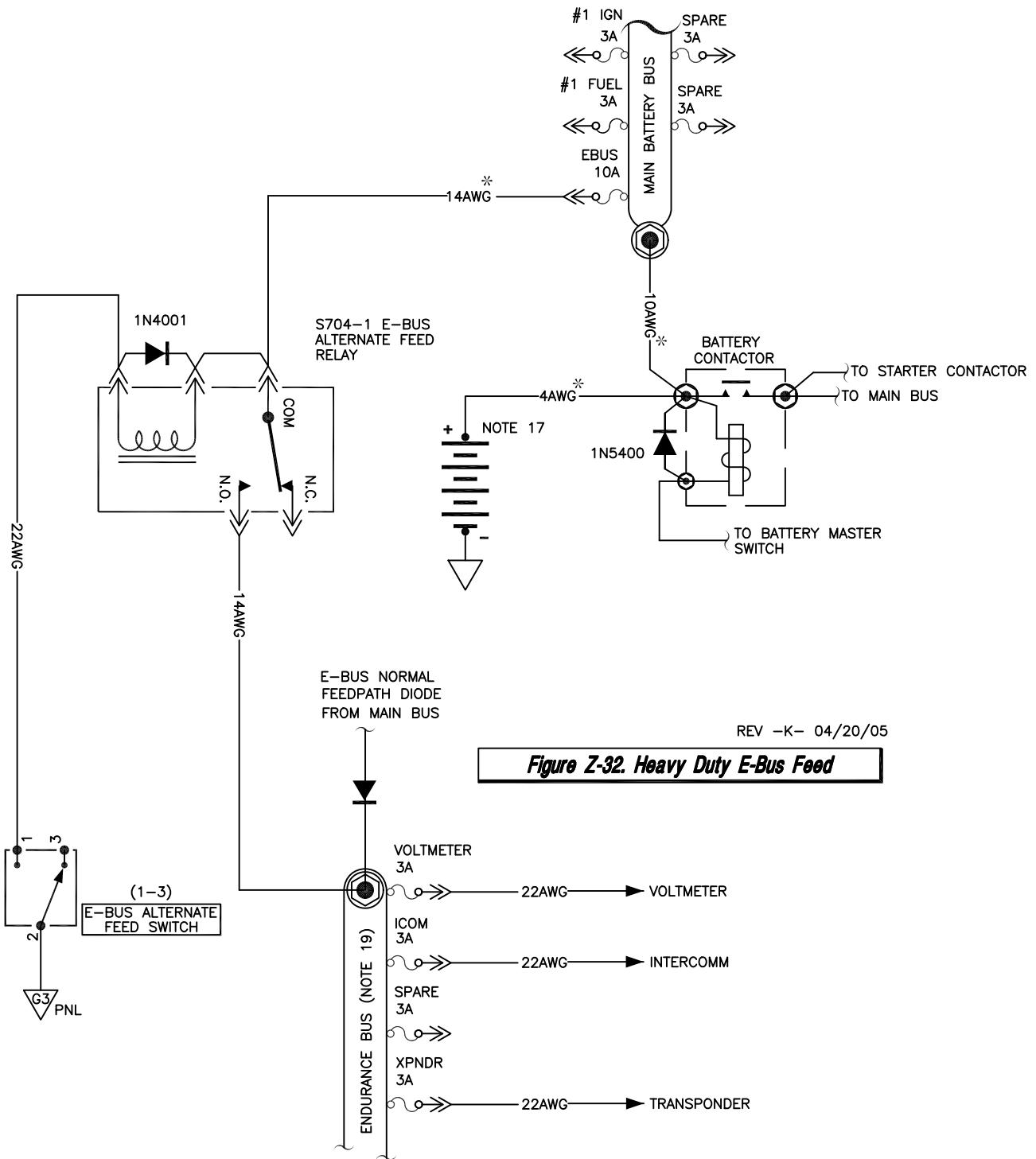
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Figure Z-28. Dual Electronic Ignition with One Alternator









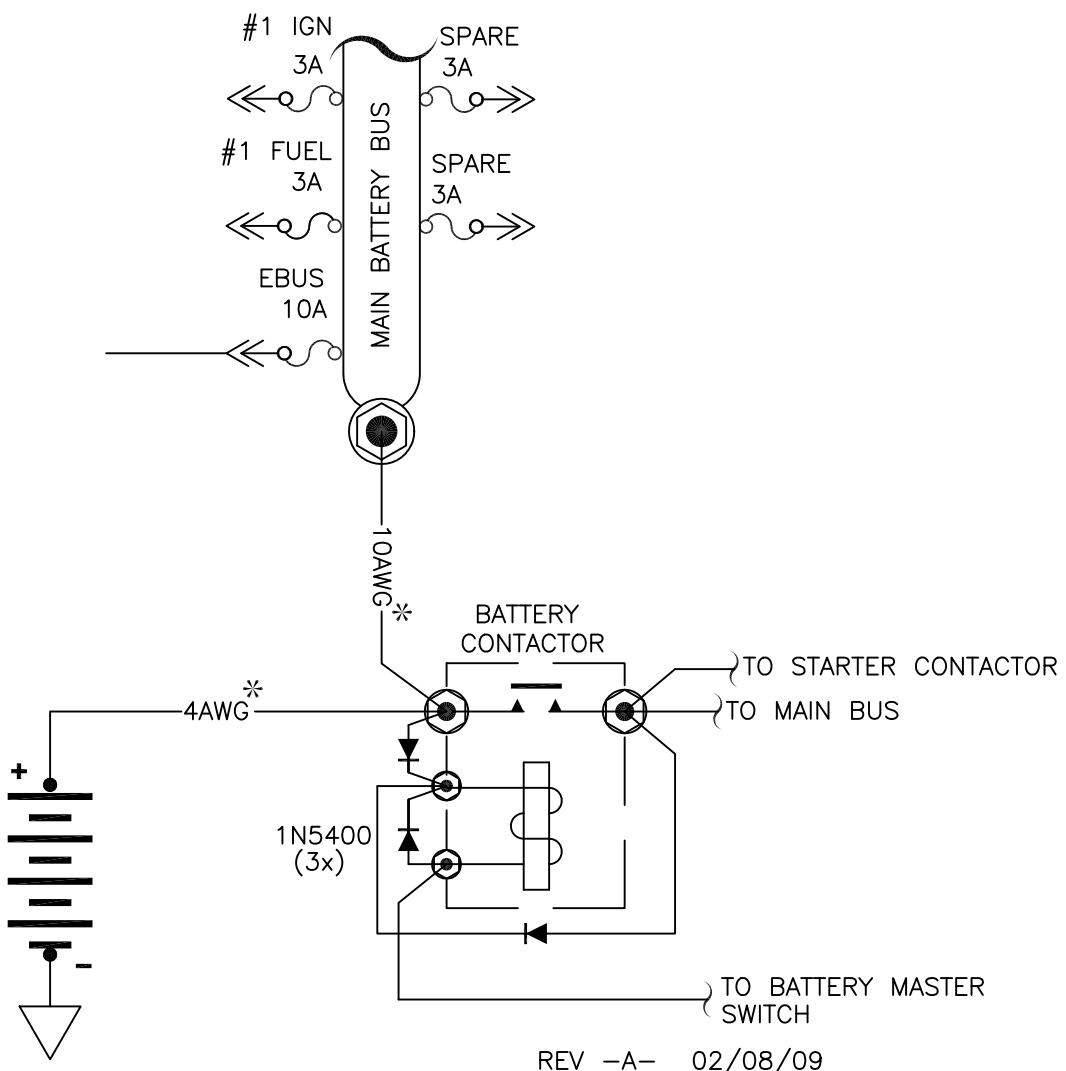


Figure Z-33. Dual Power Path for Battery Contactors

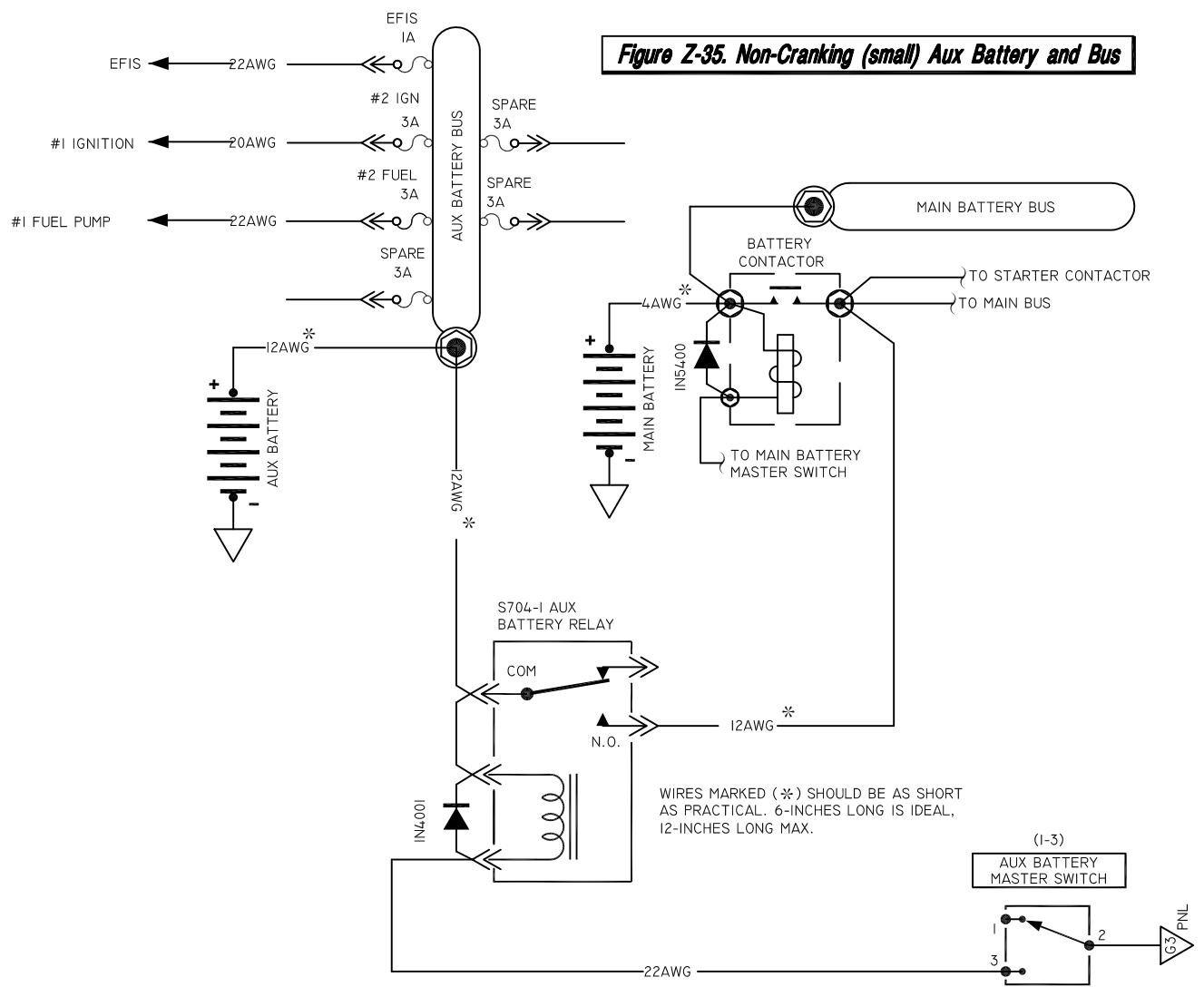


Figure Z-35. Non-Cranking (small) Aux Battery and Bus