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 attempts 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 pi times 0.350" or 1.01" inch. The circumference of the rod is pi times 0.250" or .785". The circumference of the circle at the outside of the wire is pi 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

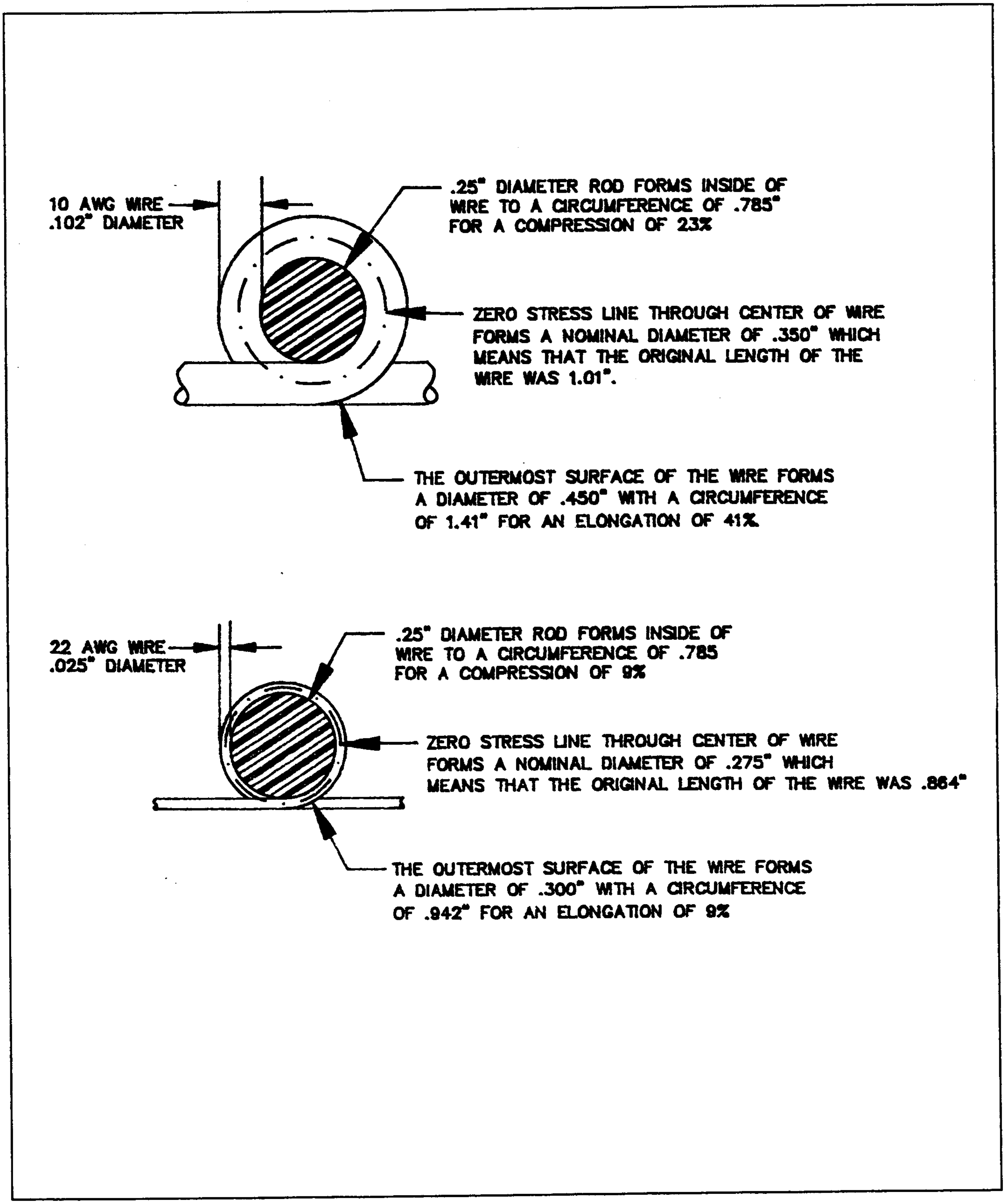

Figure 8-1. Wire Stresses Versus Wire Diameter.

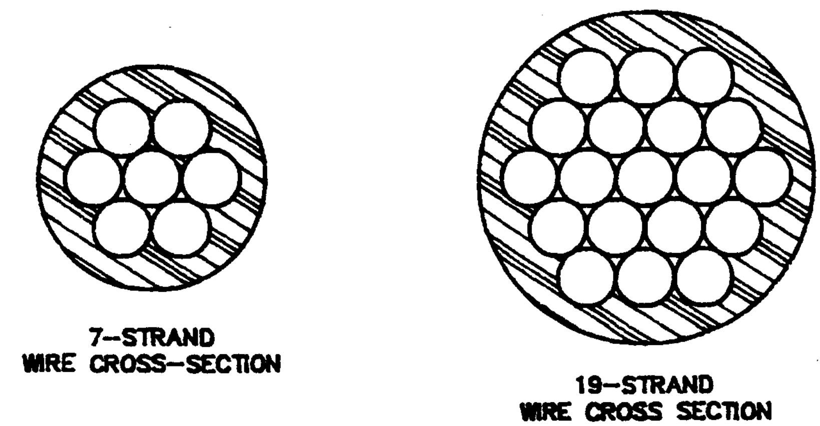

Figure 8-2. Common Layup Configurations for Stranded Wire.

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 dogfight? 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

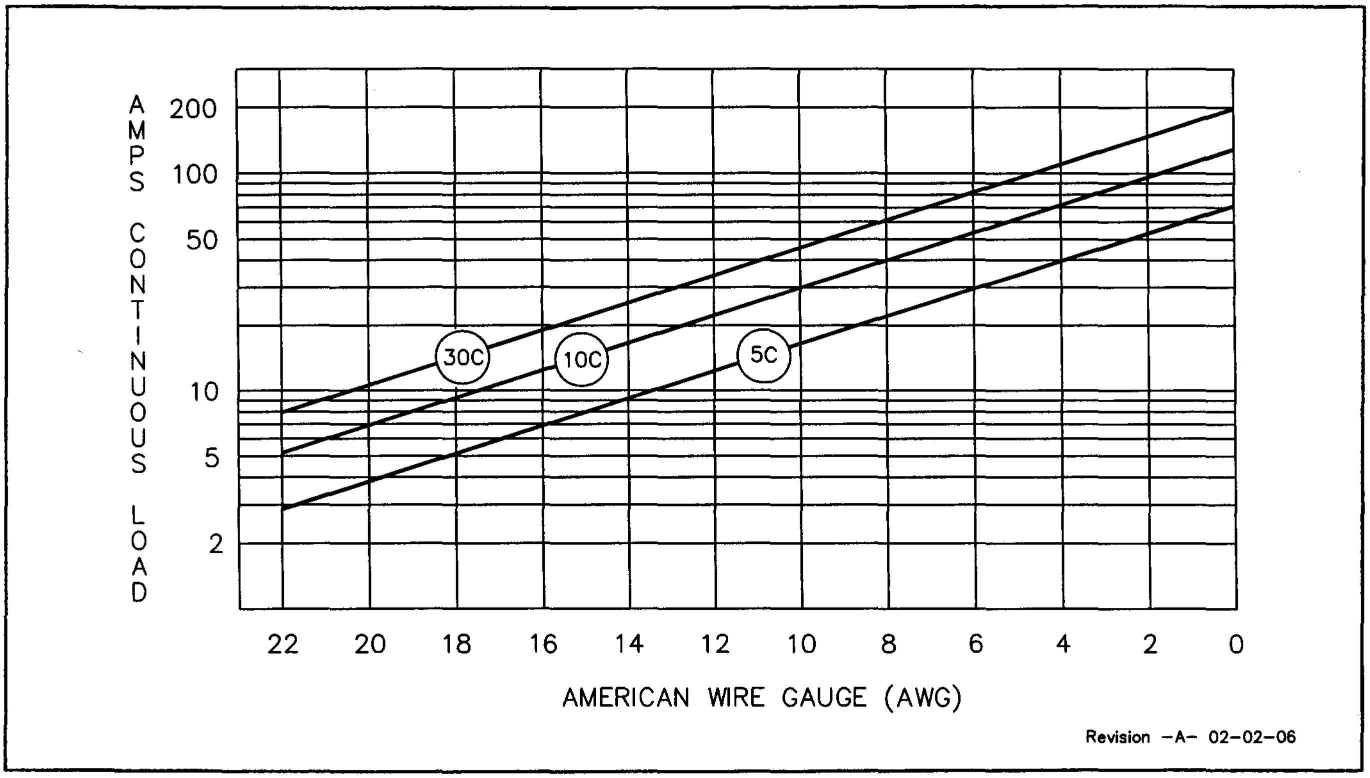

Figure 8-4. Wire Current Capacity Versus Wire Guage and Temperature Rise.

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 you 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, though 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

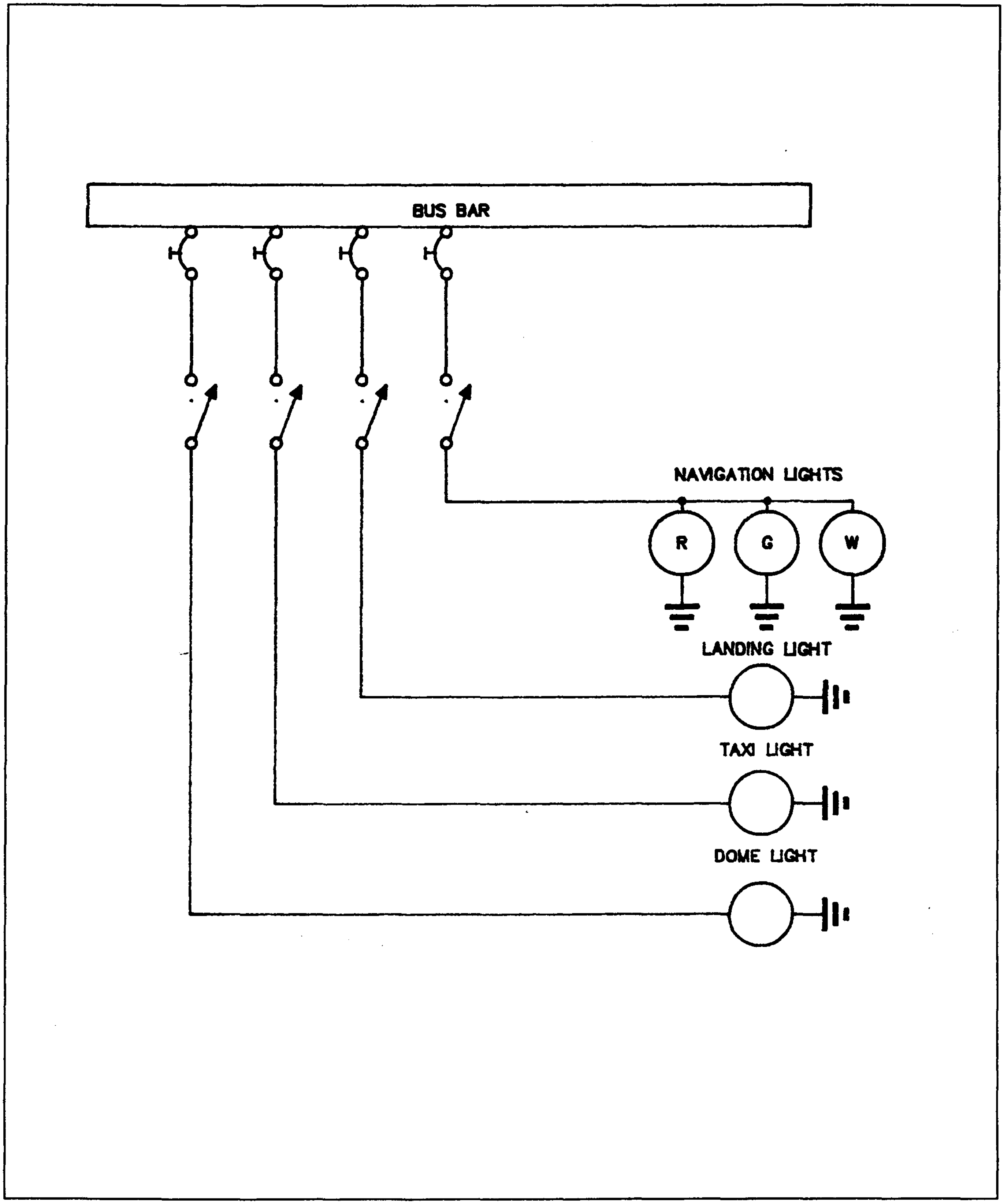

Figure 8-5. Schematic Diagram, Lighting System

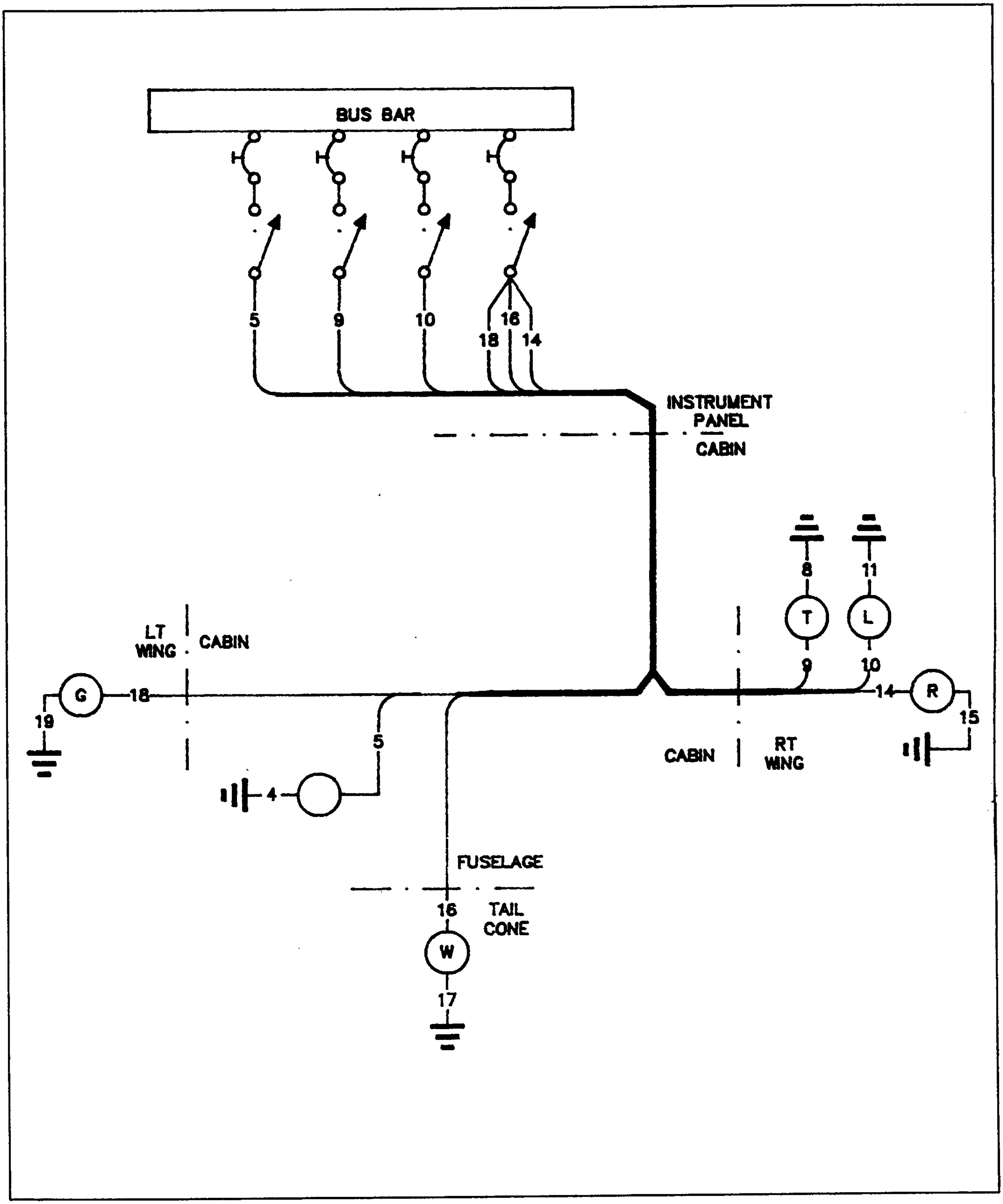

Figure 8-6. Wiring Diagram, Lighting System.

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!

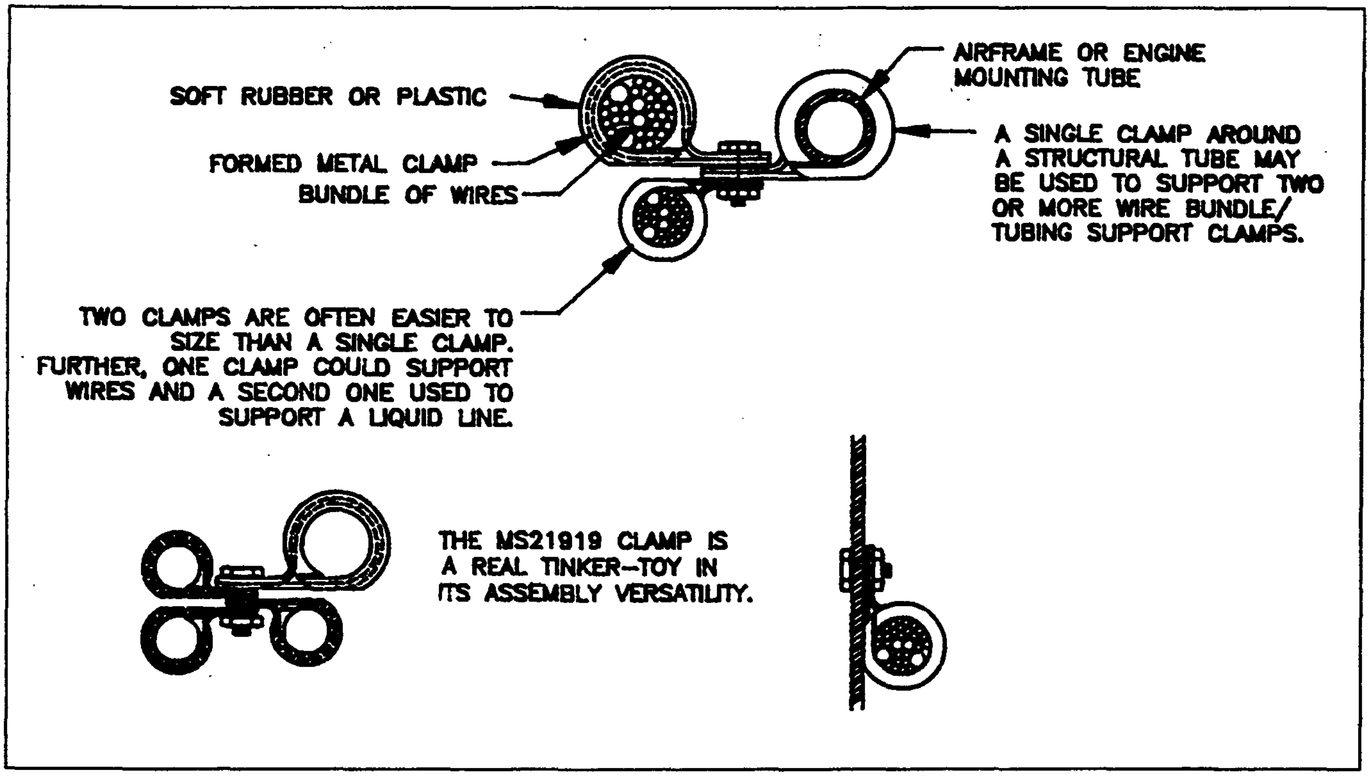

Figure 8-7. Applications of the MS21919 Padded Clamps.

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. A a general rule, I wouldn't use plastic clamps in any area of the airplane that is not periodicly looked at and touched. Wire routings with inacessable 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 though the plys as though they were sheet metal. The resulting threaded hole then provides mounting support for wire bundles. 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!