CHAPTER 7

BONDING

7.1 DEFINITION OF BONDING. As used in these Volumes, bonding refers to the process by which a low impedance path for the flow of an electric current is established between two metallic objects. Other types of bonding which involve simply the physical attachment of one substance or object to another through various mechanical or chemical means are not treated.

7.2 PURPOSES OF BONDING.

In any realistic electronic system, whether it be only one piece of equipment or an entire facility, numerous interconnections between metallic objects must be made in order to provide electric power, minimize electric shock hazards, provide lightning protection, establish references for electronic signals, etc. Ideally, each of these interconnections should be made so that the mechanical and electrical properties of the path are determined by the connected members and not by the interconnection junction. Further, the joint must maintain its properties over an extended period of time in order to prevent progressive degradation of the degree of performance initially established by the interconnection. Bonding is concerned with those techniques and procedures necessary to achieve a mechanically strong, low impedance interconnection between metal objects and to prevent the path thus established from subsequent deterioration through corrosion or mechanical looseness.

In terms of the results to be achieved, bonding is necessary for the:

a. protection of equipment and personnel from the hazards of lightning discharges,

b. establishment of fault current return paths,

c. establishment of homogeneous and stable paths for signal currents,

d. minimization of rf potentials on enclosures and housings,

e. protection of personnel from shock hazards arising from accidental power grounds, and

f. prevention of static charge accumulation.

With proper design and implementation, bonds minimize differences in potential between points within the fault protection, signal reference, shielding, and lightning protection networks of an electronic system. Poor bonds, however, lead to a variety of hazardous and interference-producing situations. For example, loose connections in ac power lines can produce unacceptable voltage drop at the load, and the heat generated by the load current through the increased resistance of the poor joint can be sufficient to damage the insulation of the wires which may produce a power line fault or develop a fire hazard or both. Loose or high impedance joints in signal lines are particularly annoying because of intermittent signal behavior such as decreases in signal amplitude, increases in noise level, or both. Poor joints in lightning protection networks can be particularly dangerous. The high current of a lightning discharge may generate several thousand volts across a poor joint. Arcs produced thereby present both a fire and explosion hazard and may possibly be a source of interference to equipments. The additional voltage developed across the joint also increases the likelihood of flashover occurring to objects in the vicinity of the discharge path.

A degradation in system performance from high noise levels is frequently traceable to poorly bonded joints in circuit returns and signal referencing networks. As noted previously, the reference network provides low impedance paths for potentially incompatible signals. Poor connections between elements of the reference network increase the resistance of the current paths. The voltages developed by the currents flowing through these resistances prevent circuit and equipment signal references from being at the same reference potential. When such circuits and equipments are interconnected, the voltage differential represents an unwanted signal within the system.

Bonding is also important to the performance of other interference control measures. For example, adequate bonding of connector shells to equipment enclosures is essential to the maintenance of the integrity of cable shields and to the retention of the low loss transmission properties of the cables. The careful bonding of seams and joints in electromagnetic shields is essential to the achievement of a high degree of shielding effectiveness. Interference reduction components and devices also must be well bonded for optimum performance. Consider a typical power line filter like that shown in Figure 7-1. If the return side of the filter (usually the housing) is inadequately bonded to the ground reference plane (typically the equipment case or rack), the bond impedance Z_B may be high enough to impair the filter's performance. The filter as shown is a low pass filter intended to remove high frequency interference components from the power lines of equipment. The filter achieves its goal in part by the fact that the reactance, X_c, of the shunt capacitors is low at the frequency of the interference. Interfering signals present on the ac line are shunted to ground along Path 1 and thus do not reach the load. If Z_B is high relative to X_c, however, interference currents will follow Path 2 to the load and the effectiveness of the filter is compromised.

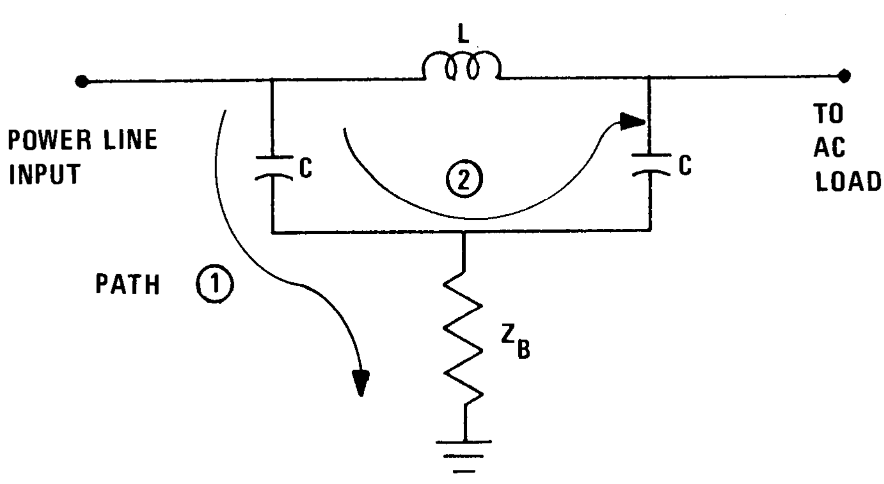


Figure 7-1. Effects of Poor Bonding on the Performance of a Power Line Filter

If a joint in a current path is not securely made or works loose through vibration, it can behave like a set of intermittent contacts. Even if the current through the joint is at dc or at the ac power frequency, the sparking which occurs may generate interference signals with frequency components up to several hundred megahertz.

Poor bonds in the presence of high level rf fields, such as those in the immediate vicinity of high powered transmitters, can produce a particularly troublesome type of interference. Poorly bonded joints have been shown to generate cross modulation and other mix products when irradiated by two or more high level signals (7-1). Some metal oxides are semiconductors and behave as nonlinear devices to provide the mixing action between the incident signals. Interference thus generated can couple into nearby susceptible equipments.

7.3 RESISTANCE CRITERIA.

A primary requirement for effective bonding is that a low resistance path be established between the two joined objects. The resistance of this path must remain low with use and with time. The limiting value of resistance at a particular junction is a function of the current (actual or anticipated) through the path. For example, where the bond serves only to prevent static charge buildup, a very high resistance, i.e., 50 kilohms or higher, is acceptable. Where lightning discharge or heavy fault currents are involved, the path resistance must be very low to minimize heating effects.

Noise minimization requires that path resistances of less than 50 milliohms be achieved. However, noise control rarely ever requires resistances as low as those necessary for fault and lightning currents. Bond resistance based strictly on noise minimization requires information on what magnitude of voltage constitutes an interference threat and the magnitude of the current through the junction. These two factors will be different for every situation.

A bonding resistance of 1 milliohm is considered to indicate that a high quality junction has been achieved. Experience shows that 1 milliohm can be reasonably achieved if surfaces are properly cleaned and adequate pressure is maintained between the mating surfaces. A much lower resistance could provide greater protection against very high currents but could be more difficult to achieve at many common types of bonds such as at connector shells, between pipe sections, etc. However, there is little need to strive for a junction resistance that is appreciably less than the intrinsic resistance of the conductors being joined.

Higher values of resistance tend to relax the bond preparation and assembly requirements. These requirements should be adhered to in the interest of long term reliability. Thus, the imposition of an achievable, yet low, value of 1 milliohm bond resistance ensures that impurities are removed and that sufficient surface contact area is provided to minimize future degradation due to corrosion.

A similarly low value of resistance between widely separated points on a ground reference plane or network ensures that all junctions are well made and that reasonably adequate quantities of conductors are provided throughout the plane or network. In this way, resistive voltage drops are minimized which helps with noise control. In addition, the low value of resistance tends to force the use of reasonably sized conductors which helps minimize path inductance.

It should be recognized that a low dc bond resistance is not a reliable indicator of the performance of the bond at higher frequencies. Inherent conductor inductance and stray capacitance, along with the associated standing wave effects and path resonances, will determine the impedance of the bond. Thus, in rf bonds these factors must be considered along with the dc resistance.

7.4 DIRECT BONDS.

Direct bonding is the establishment of the desired electrical path between the interconnected members without the use of an auxiliary conductor. Specific portions of the surface areas of the members are placed in direct contact. Electrical continuity is obtained by establishing a fused metal bridge across the junction by welding, brazing, or soldering or by maintaining a high pressure contact between the mating surfaces with bolts, rivets, or clamps. Examples of direct bonds are the splices between bus bar sections, the connections between lightning down conductors and the earth electrode subsystem, the mating of equipment front panels to equipment racks, and the mounting of connector shells to equipment panels.

Properly constructed direct bonds exhibit a low dc resistance and provide an rf impedance as low as the configuration of the bond members will permit. Direct bonding is always preferred; however, it can be used only when the two members can be connected together and can remain so without relative movement. The establishment of electrical continuity across joints, seams, hinges, or fixed objects that must be spatially separated requires indirect bonding with straps, jumpers, or other auxiliary conductors.

Current flow through two configurations of a direct bond is illustrated in Figure 7-2. The resistance, R_c, of the path through the conductors on either side of the bond is given by

$$R_c = \rho \frac{\ell}{A} \qquad (7\text{-}1)$$

where ρ is the resistivity of the conductor materials, ℓ is the total path length of the current through conductors, and A is the cross-sectional area of the conductors (assumed equal). Any bond resistance at the junction will increase the total path resistance. Therefore, the objective in bonding is to reduce the bond resistance to a value negligible in comparison to the conductor resistance so that the total path resistance is primarily determined by the resistance of the conductors.

Metal flow processes such as welding, brazing, and silver soldering provide the lowest values of bond resistance. With such processes, the resistance of the joint is determined by the resistivity of the weld or filler metal which can approach that of the metals being joined. The bond members are raised to temperatures sufficient to form a continuous metal bridge across the junction.

For reasons of economy, future accessibility, or functional requirements, metal flow processes are not always the most appropriate bonding techniques. It may then be more appropriate to bring the mating surfaces together under high pressure. Auxiliary fasteners such as bolts, screws, rivets or clamps are employed to apply and maintain the pressure on the surfaces. The resistance of these bonds is determined by the kinds of metals involved, the surface conditions within the bond area, the contact pressure at the surfaces, and the cross-sectional area of the mating surfaces.

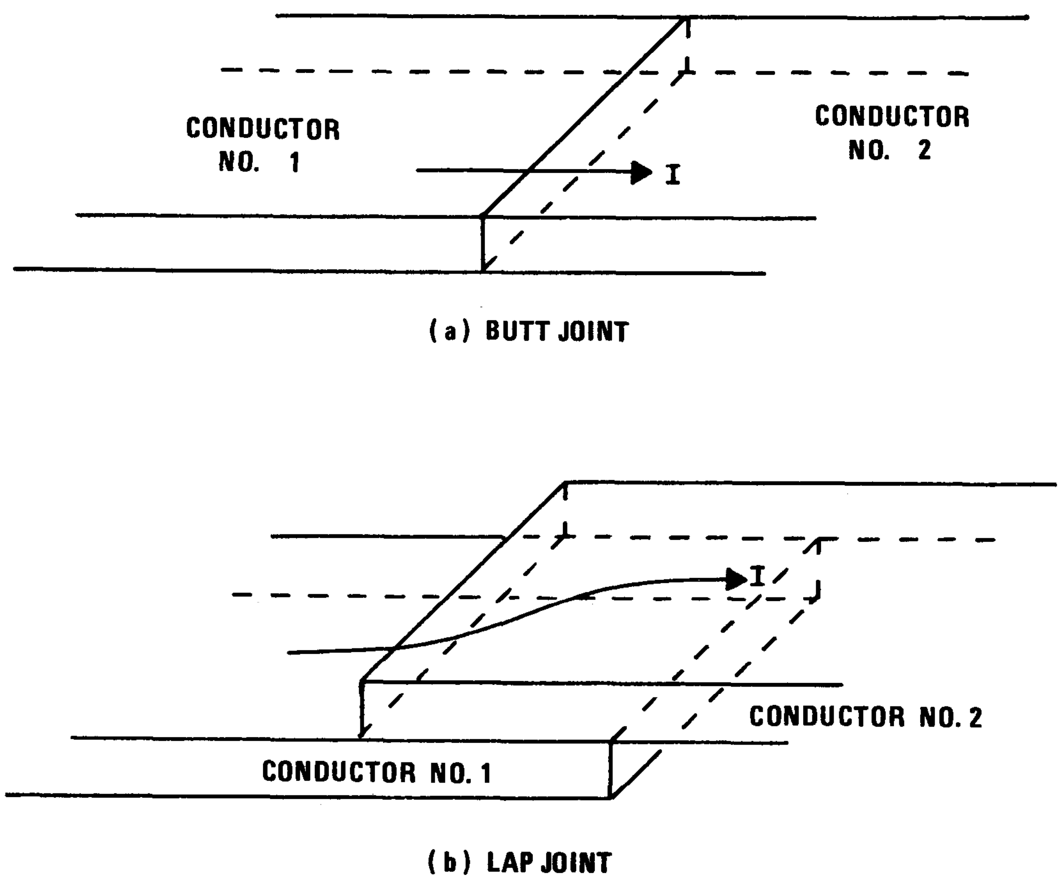


Figure 7-2. Current Flow Through Direct Bonds

7.4.1 Contact Resistance.

No metallic surface is perfectly smooth. In fact, surfaces consist of many peaks and valleys. Even the smoothest commercial surfaces exhibit an RMS roughness of 0.5 to 1 millionth of an inch (7-2); the roughness of most electrical bonding surfaces will be several orders of magnitude greater. When two such surfaces are placed in contact, they touch only at the tips of the peaks - so called asperities. Thus the actual area of contact for current flow is much smaller than the apparent area of metallic contact.

An exaggerated side view of the actual contact surfaces at a bond interface is shown in Figure 7-3. Theoretically, two infinitely hard surfaces would touch at only three asperities. Typically, however, under pressure elastic deformation and plasticity allows other asperities to come into contact. Current passes between the surfaces only at those points where the asperities have been crushed and deformed (7-3) to establish true metal contact. The actual area of electrical contact is equal to the sum of the individual areas of contacting asperities. This actual area of contact can be as little as one millionth of the apparent (gross surface) contact area (7-4).

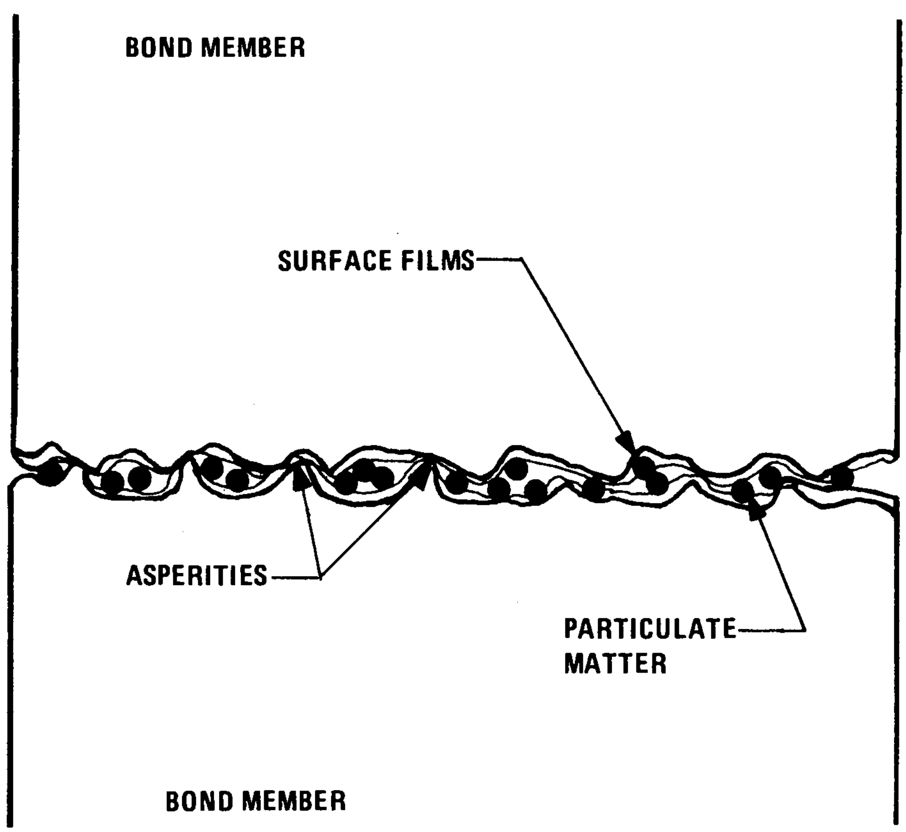


Figure 7-3. Nature of Contact Between Bond Members

7.4.1.1 Surface Contaminants.

Surface films will be present on practically every bond surface. The more active metals such as iron and aluminum readily oxidize to form surface films while the noble metals such as gold, silver, and nickel are less affected by oxide films. Of all metals, gold is the least affected by oxide films. Although silver does not oxidize severely, silver sulfide forms readily in the presence of sulfur compounds.

If the surface films are much softer than the contact material, they can be squeezed from between the asperities to establish a quasi-metallic contact. Harder films, however, may support all or part of the applied load, thus reducing or eliminating the conductive contact area. If such films are present on the bond surfaces, they must be removed through some thermal, mechanical, or chemical means before joining the bond members. Even when metal flow processes are used in bonding, these surface films must be removed or penetrated to permit a homogeneous metal path to be established.

Foreign particulate matter on the bond surfaces will further impair bonding. Dirt and other solid matter such as high resistance metal particles or residue from abrasives can act as stops to prevent metallic contact. Therefore, all such materials must be thoroughly removed from the surfaces prior to joining the bond members.

7.4.1.2 Surface Hardness. The hardness of the bond surfaces also affects the contact resistance. Under a given load, the asperities of softer metals will undergo greater plastic deformation and establish greater metallic contact. Likewise, at a junction between a soft and a hard material, the softer material will tend to conform to the surface contours of the harder material and will provide a lower resistance contact than would be afforded by two hard materials. Table 7-1 shows how the resistance of 6.45 square cm (1 square inch) bonds varies with the type of metals being joined.

7.4.1.3 Contact Pressure. The influence of mechanical load on bond resistance is illustrated by Figure 7-4. This figure shows the resistance variation of a 6.45 square cm (1 square inch) bond held in place with a 1/4-20 steel bolt as a function of the torque applied to the bolt. The resistance variation for brass is lowest due to its relative softness and the absence of insulating oxide films. Even though aluminum is relatively soft, the insulating properties of aluminum oxide cause the bond resistance to be highly dependent upon fastener torque up to approximately 40 in.-lb torque (which corresponds to a contact pressure of about 1200 psi). Steel, being harder and also susceptible to oxide formations, exhibits a resistance that is dependent upon load below 80 in.-lb or about 1500 psi (for mild steel). Above these pressures, no significant improvement in contact resistance can be expected.

Table 7-1

DC Resistance of Direct Bonds Between Selected Metals

Bond Composition	Resistance (Micro-ohms)
Brass-Brass	6
Aluminum-Aluminum	25
Brass-Aluminum	50
Brass-Steel	150
Aluminum-Steel	300
Steel-Steel	1500

Notes: Apparent Bond Area: 1 $in.^2$ (6.45 cm^2)
Fastener Torque: 100 in -lb

Source: Adapted from Reference (7-5)

7.4.1.4 Bond Area.

Smaller bond areas with the same loadings would produce higher contact pressure which would decrease the resistance. However, as shown in Figure 7-4, an increase in pressure over 1500 psi for steel and 1200 psi for aluminum produces relatively slight changes in bond resistance. Further, the improvement in resistance due to increased pressure is offset by the smaller overall bond area. In a similar fashion, a larger bond area (with no change in fastener size) under the same torque results in a lowered pressure at the bond surfaces. The reduced pressure would be counterbalanced to some extent by the increased bond area, but the net effect can be expected to be an increase in bond resistance. Thus, when larger bond areas are used, larger bolts at correspondingly higher torques should be used for fastening. (See Para 7.4.2.4)

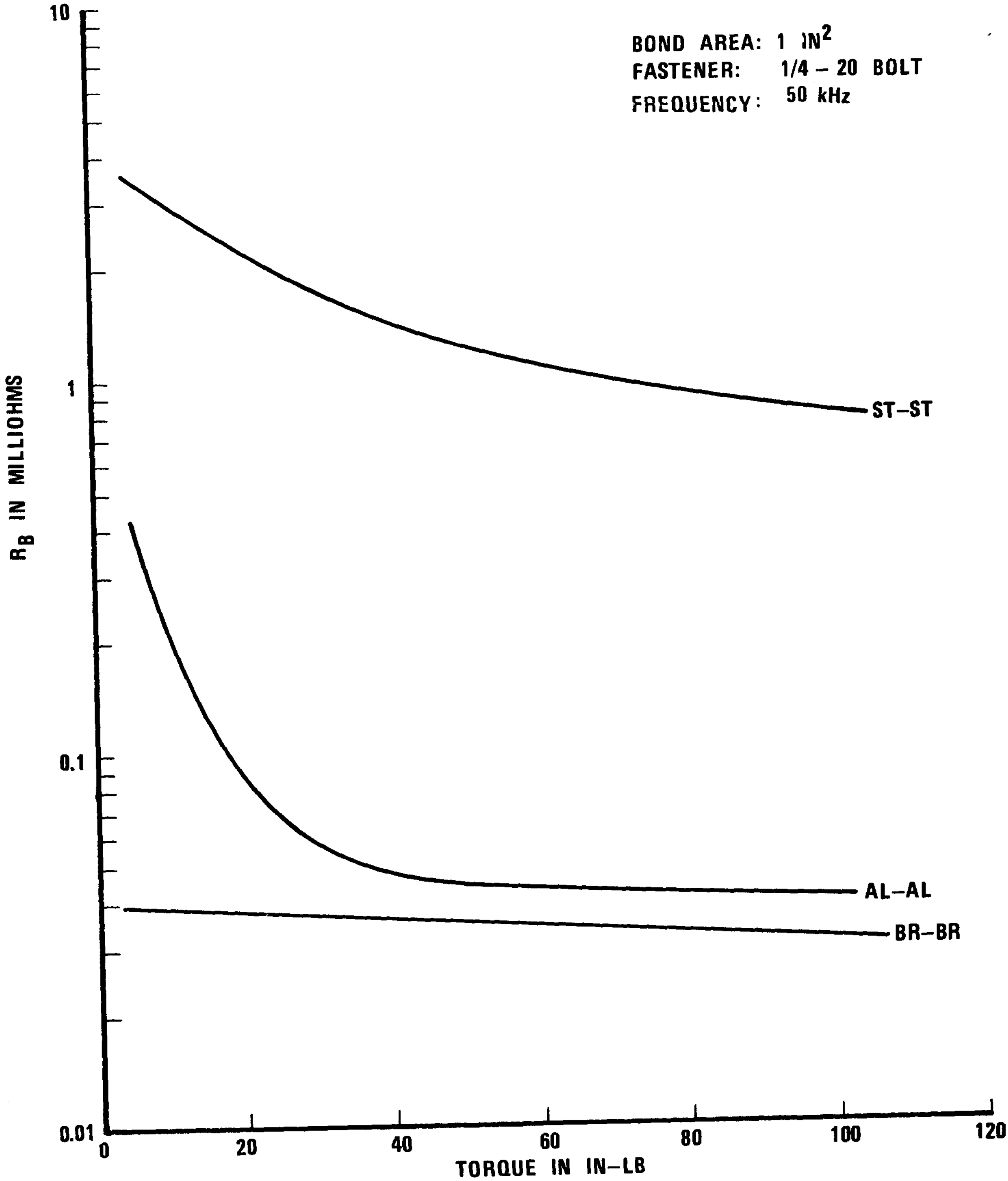


Figure 7-4. Resistance of a Test Bond as a Function of Fastener Torque (7-5)

Bond mating surfaces with areas as large as practical are desirable for several reasons. Large surface areas maximize the cross-sectional area of the path for current and correspondingly maximizes the total number of true metallic contacts between the surfaces. In addition to the obvious advantage of decreased bond resistance, the current crowding which can occur during power fault conditions or under a severe lightning discharge is lessened. Such current crowding produces a higher effective bond resistance than is present during low current flow. The increased bond resistance raises the voltage drop across the junction to even higher values and adds to the heat generated at the junction by the heavy current flow. Large bond areas not only lessen the factors which contribute to heat generation, they also distribute the heat over a larger metallic area which facilitates its removal. A further advantage of a large bond is that it will probably provide greater mechanical strength and will be less susceptible to long term erosion by corrosive products because only a small portion of the total bond area is exposed to the environment.

7.4.2 Direct Bonding Techniques.

Direct bonds may be either permanent or semi-permanent in nature. Permanent bonds may be defined as those intended to remain in place for the expected life of the installation and not required to be disassembled for inspection, maintenance, or system modifications. Joints which are inaccessible by virtue of their location should be permanently bonded and appropriate steps taken to protect the bond against deterioration.

Many bonded junctions must retain the capability of being disconnected without destroying or significantly altering the bonded members. Junctions which should not be permanently bonded include those which may be broken for system modifications, for network noise measurements, for resistance measurements, and for other related reasons. In addition, many joints cannot be permanently bonded for cost reasons. All such connections not permanently joined are defined as semipermanent bonds. Semipermanent bonds include those which utilized bolts, screws, rivets, clamps and other auxiliary devices for fasteners.

7.4.2.1 Welding.

In terms of electrical performance, welding is the ideal method of bonding. The intense heat (in excess of 4000° F) involved is sufficient to boil away contaminating films and foreign substances. A continuous metallic bridge is formed across the joint; the conductivity of this bridge typically approximates that of the bond members. The net resistance of the bond is essentially zero because the bridge is very short relative to the length of the bond members. The mechanical strength of the bond is high; the strength of a welded bond can approach or exceed the strength of the bond members themselves. Since no moisture or contaminants can penetrate the weld, bond corrosion is minimized. The erosion rate of the metallic bridge should be comparable to that of the base members; therefore, the lifetime of the bond should be as great as that of the bond members.

Welds should be utilized whenever practical for permanently joined bonds. Although welding may be a more expensive method of bonding, the reliability of the joint makes it very attractive for bonds which will be inaccessible once construction is completed. Most metals which will be encountered in normal construction can be welded with one of the standard welding techniques such as gas, electric arc, Heliarc and exothermic.

Conventional welding should be performed only by appropriately trained and qualified personnel. Consequently, increased labor costs can be expected. In many instances, also, the welding of bonds can be much slower than the installation of fasteners such as bolts or rivets. In such cases, the added costs of welding may force the use of alternate bonding techniques.

An effective welding technique for many bonding applications is the exothermic process. In this process, a mixture of aluminum, copper oxide, and other powders is held in place around the joint with a graphite mold. The mixture is ignited and the heat generated (in excess of 4000° F) reduces the copper oxide to provide a homogeneous copper blanket around the junction. Because of the high temperatures involved, copper materials can be bonded to steel or iron as well as to other copper materials.

Two examples of exothermic bonds are shown in Figure 7-5. The top photograph shows a 4/0 copper clad cable bonded to a steel plate. The bottom photograph shows two 4/0 copper clad cables axially bonded together. The tight mechanical bond established by this process is evident from these photographs. Figure 7-6 shows examples of the various bond configurations for which molds are readily available.

This process is advantageous for welding cables together, for welding cables to rods, or for welding cables to I-beams and other structural members. It is particularly attractive for the bonding of interconnecting cables to ground rods where the use of conventional welding techniques might be awkward or where experienced welders are not available. Because of the cost of the molds (a separate mold is necessary for each different bond configuration), this process is most economical when there are several bonds of the same configuration to be made.

When using this process, the manufacturer's directions should be followed closely. The mold should be dried or baked out as specified, particularly when the mold has not been used for several hours and may have absorbed moisture. The metals to be bonded should be cleaned of dirt and debris and should have the excess water dried off. Water, dirt and other foreign materials cause voids in the weld which may weaken it or may prevent a low resistance joint from being achieved. A further requirement is that the mold size must match the cable or conductor cross sections; otherwise, the molten metal will not be confined to the bond region.

7.4.2.2 Brazing.

Brazing to include silver soldering is another metal flow process for permanent bonding. In brazing, the bond surfaces are heated to a temperature above 800° F but below the melting point of the bond members. A filler metal with an appropriate flux is applied to the heated members which wets the bond surfaces to provide intimate contact between the brazing solder and the bond surfaces. As with higher temperature welds, the resistance of the brazed joint is essentially zero. However, since brazing frequently involves the use of metal different from the primary bond members, additional precautions must be taken to protect the bond from deterioration through corrosion.

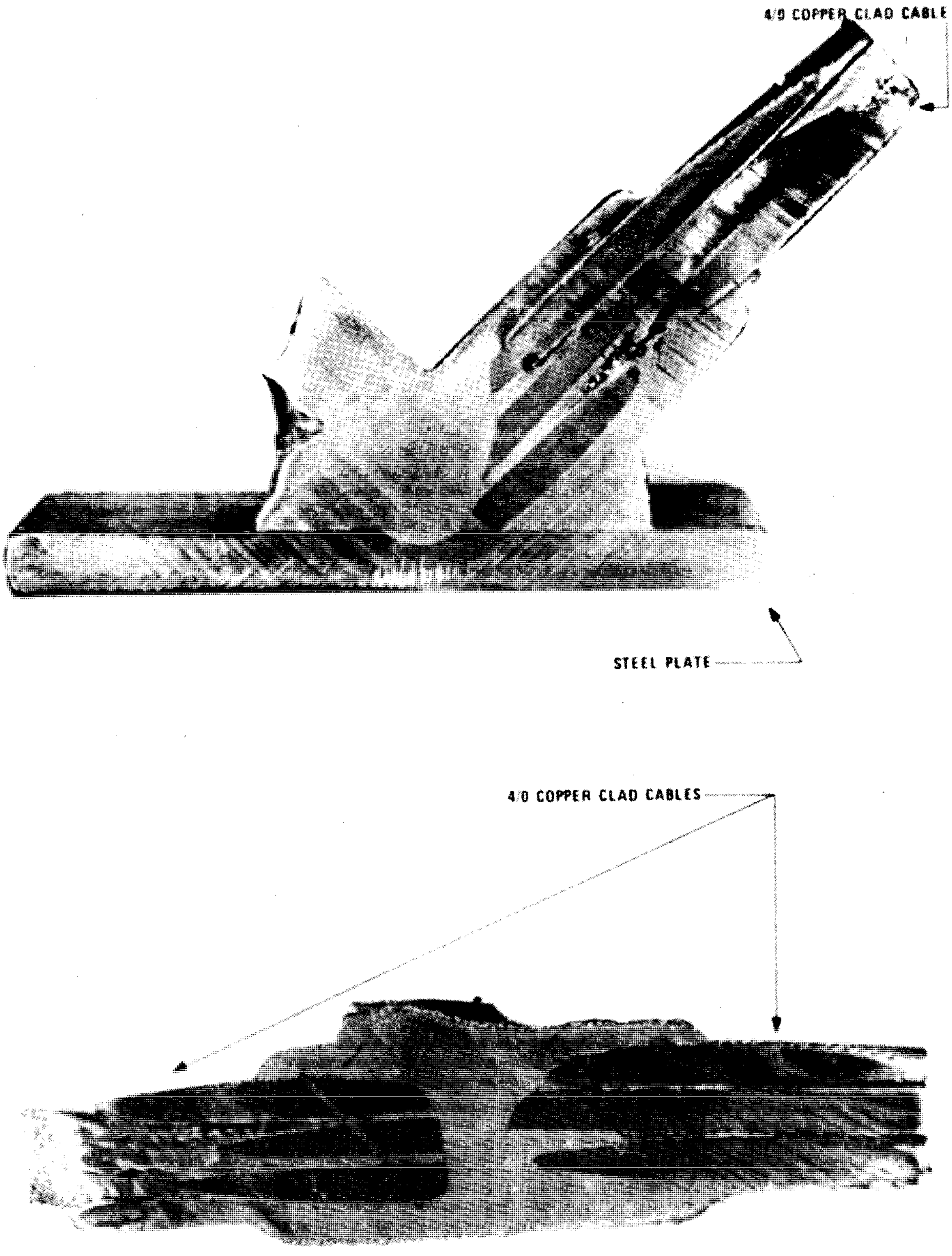
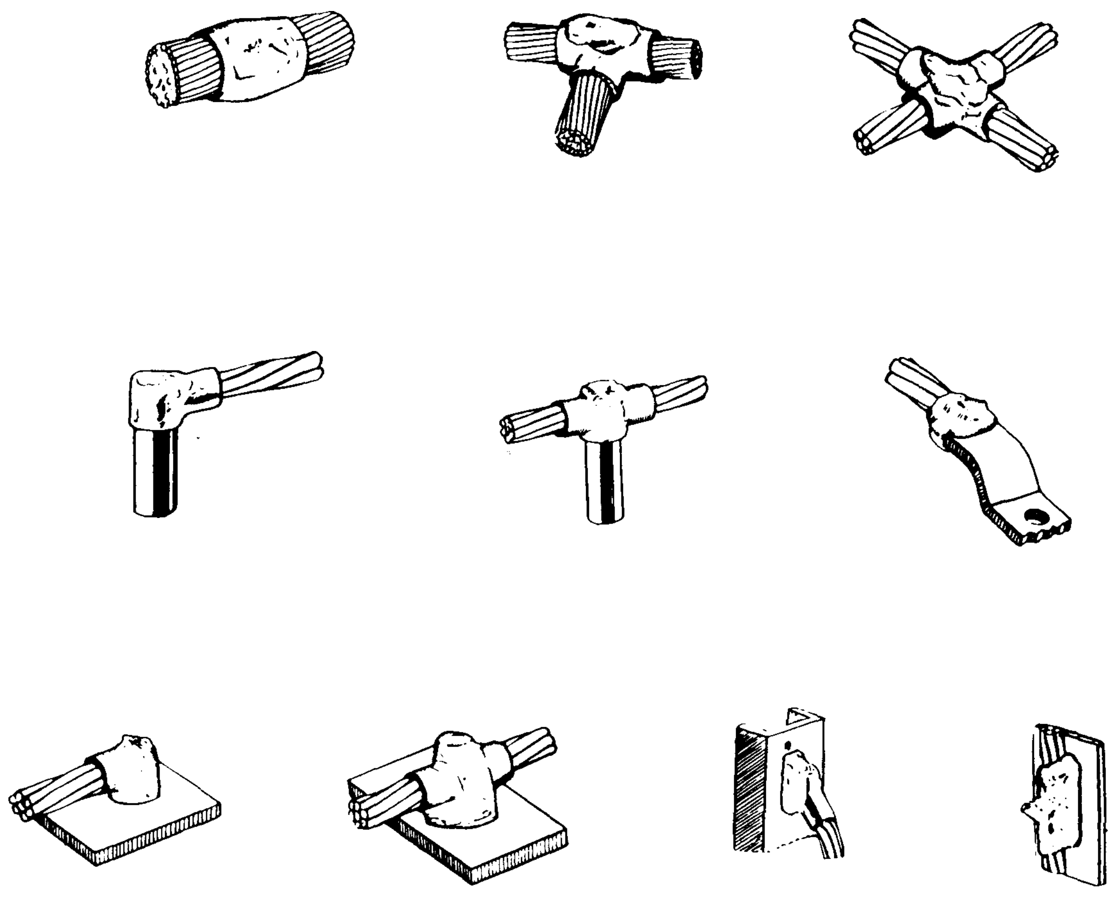


Figure 7-5. Typical Exothermic Connections



COURTESY OF ERICO PRODUCTS, INC., CLEVELAND, OHIO

Figure 7-6. Typical Bond Configurations Which Can Be Implemented With The Exothermic Process

7.4.2.3 Soft Solder.

Soft soldering is an attractive metal flow bonding process because of the ease with which it can be applied. Relatively low temperatures are involved and it can be readily employed with several of the high conductivity metals such as copper, tin and cadmium. With appropriate fluxes, aluminum and other metals can be soldered. Properly applied to compatible materials, the bond provided by solder is nearly as low in resistance as one formed by welding or brazing. Because of its low melting point, however, soft solder should not be used as the primary bonding material where high currents may be present. For this reason, soldered connections are not permitted by MIL-STD-188-124A or the National Electrical Code in grounding circuits for fault protection. Similarly, soft solder is not permitted for interconnections between elements of lightning protection networks by either the Military Standard, the National Fire Protection Association's Lightning Protection Code or the Underwriter's Master Labeled System. In addition to its temperature limitation, soft solder exhibits low mechanical strength and tends to crystallize if the bond members move while the solder is cooling. Therefore, soft solder should not be used if the joint must withstand mechanical loading. The tendency toward crystallization must also be recognized and proper precautions observed when applying soft solder.

Soft solder can be used effectively in a number of ways, however. For example, it can be used to tin surfaces prior to assembly to assist in corrosion control. Soft solder can be used effectively for the bonding of seams in shields and for the joining of circuit components together and to the signal reference subsystem associated with the circuit. Soft solder is often combined with mechanical fasteners in sweated joints. By heating the joint hot enough to melt the solder, a low resistance filler metal is provided which augments the path established by the other fasteners; in addition, the solder provides a barrier to keep moisture and contaminants from reaching the mating surfaces.

7.4.2.4 Bolts.

In many applications, permanent bonds are not desired. For example, equipments must be removed from enclosures or moved to other locations which require that ground leads and other connections must be broken. Often, equipment covers must be removable to facilitate adjustments and repairs. Under such circumstances, a permanently joined connection could be highly inconvenient to break and would limit the operational flexibility of the system. Besides offering greater flexibility, less permanent bonds may be easier to implement, require less operator training, and require less specialized tools.

The most common semipermanent bond is the bolted connection (or one held in place with machine screws, lag bolts, or other threaded fasteners) because this type bond provides the flexibility and accessibility that is frequently required. The bolt (or screw) should serve only as a fastener to provide the necessary force to maintain the 1200-1500 psi pressure required between the contact surfaces for satisfactory bonding. Except for the fact that metals are generally necessary to provide tensile strength, the fastener does not have to be conductive. Although the bolt or screw threads may provide an auxiliary current path through the bond, the primary current path should be established across the metallic interface. Because of the poor reliability of screw thread bonds, self-tapping screws are never to be used for bonding purposes. Likewise, Tinnernman nuts, because of their tendency to vibrate loose, should not be used for securing screws or bolts intended to perform a bonding function.

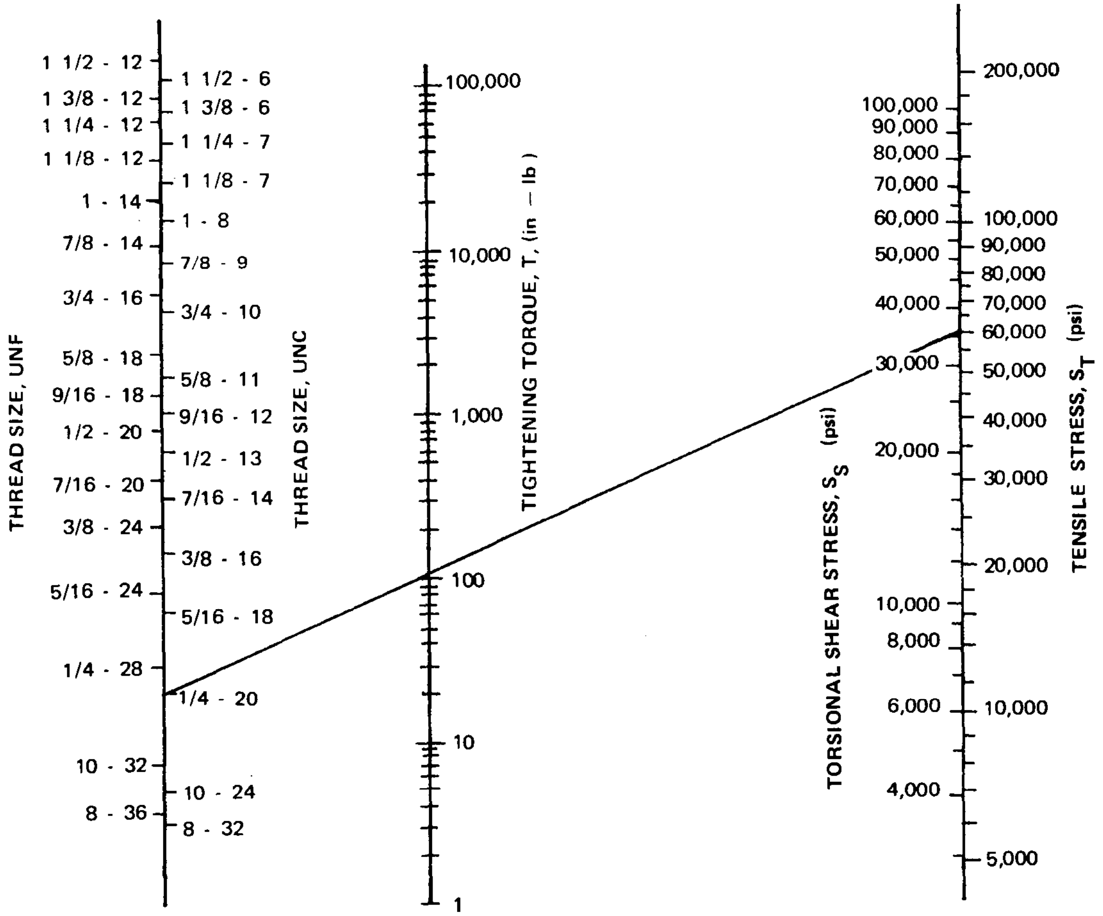


Figure 7-7. Nomograph for Torque on Bolts (7-6)

The size, number and spacing of the fasteners should be sufficient to establish the required bonding pressure over the entire joint area. The pressure exerted by a bolt is concentrated in the immediate vicinity of the bolt head. However, large, stiff washers can be placed under the bolt head to increase the effective contact area. Because the load is distributed over a larger area, the tensile load on the bolt should be raised by increasing the torque. The nomograph of Figure 7-7 may be used to calculate the necessary torque for the size bolts to be used. Where the area of the mating surfaces is so large that unreasonably high bolt torques are required, more than one bolt should be used. For very large mating areas, rigid backing plates should be used to distribute the force of the bolts over the entire area.

7.4.2.5 Rivets.

Riveted bonds are less desirable than bolted connections or joints bridged by metal flow processes. Rivets lack the flexibility of bolts without offering the degree of protection against corrosion of the bond surface that is achieved by welding, brazing or soldering. The chief advantage of rivets is that they can be rapidly and uniformly installed with automatic tools.

The bonding path established by a rivet is illustrated in Figure 7-8. The current path through a rivet is theorized to be through the interface between the bond members and the rivet body. This theory is justified by experience which shows that the fit between the rivet and the bond members is more important than the state of the mating surfaces between the bond members. Therefore, the hole for the rivet must be a size that provides a close fit to the rivet after installation. The sides of the hole through the bond members must be free of paint, corrosion products, or other non-conducting material.

For riveted joints in shields, the maximum spacing between rivets is recommended to be approximately 2 cm (3/4 inch) or less (7-7). In relatively thin sheet metal, rivets can cause bowing of the stock between the rivets as shown by Figure 7-9. In the bowed or warped regions, metal-to-metal contact may be slight or nonexistent. These open regions allow rf energy to leak through and can be a major cause of poor rf shield performance. By spacing the rivets close together, warping and bowing are minimized. For maximum rf shielding, the seam should be gasketed with some form of wire mesh or conductive epoxy to supplement the bond path of the rivets.

7.4.2.6 Conductive Adhesive. Conductive adhesive is a silver-filled, two-component, thermosetting epoxy resin which when cured produces an electrically conductive material. It can be used between mating surfaces to provide low resistance bonds. It offers the advantage of providing a direct bond without the application of heat as is required by metal flow processes. In many locations, the heat necessary for metal flow bonding may pose a fire or explosion threat. When used in conjunction with bolts, conductive adhesive provides an effective metal-like bridge with high corrosion resistance along with high mechanical strength. In its cured state, the resistance of the adhesive may increase through time. It also tends to adhere tightly to the mating surfaces and thus an epoxy-bolt bond is less convenient to disassemble than a simple bolted bond. In some applications, the advantages of conductive adhesive may outweigh this inconvenience.

7.4.2.7 Comparison of Techniques. Table 7-2 shows comparative ratings of the most commonly used bonding methods. In this table a rating from zero to 10 is assigned to each method for each performance parameter. A rating of 10 means that the method is suitable from the standpoint of the specific parameter listed in the extreme left hand column of the table. Lower ratings mean that the method is less suitable. A zero rating implies the method is a poor choice, while the dash means it does not apply. One-hundred percent consistency in ratings is impossible because any given method may vary widely in workmanship. A low-rated method expertly performed, will work better than a high-rated poorly performed method. When using the table assume that all methods are equally well implemented.

7.5 INDIRECT BONDS. The preferred method of bonding is to connect the objects together with no intervening conductor. Unfortunately, operational requirements or equipment locations often preclude direct bonding. When physical separation is necessary between the elements of an equipment complex or between the complex and its reference plane, auxiliary conductors must be incorporated as bonding straps or jumpers. Such straps are commonly used for the bonding of shock mounted equipment to the structural ground reference. They are also used for by-passing structural elements, such as the hinges on distribution box covers or on equipment covers, to eliminate the wideband noise generated by these elements when illuminated by intense radiated fields or when carrying high level currents. Bond straps or cables are also used to prevent static charge buildup and to connect metal objects to lightning down conductors to prevent flashover.

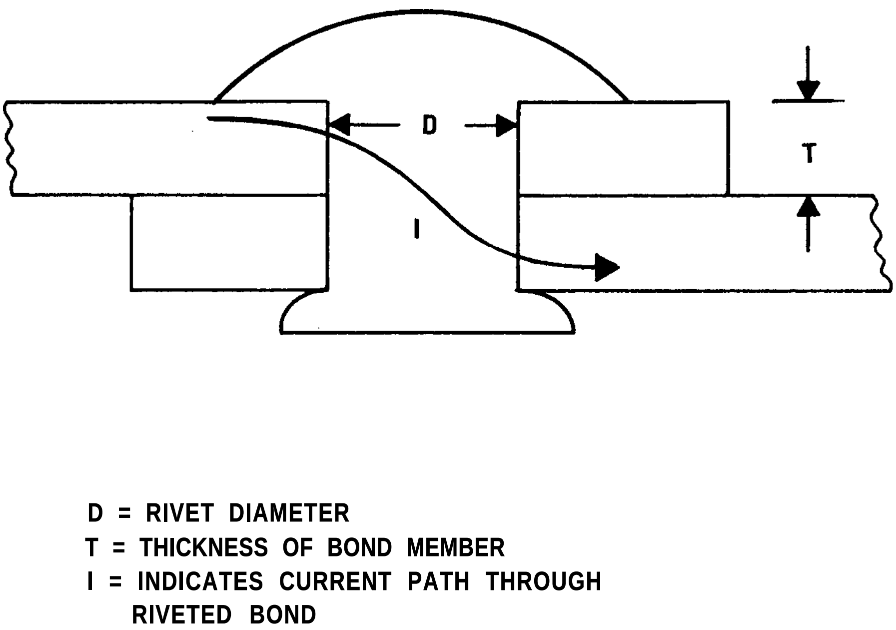


Figure 7-8. Bonding Path Established by Rivets

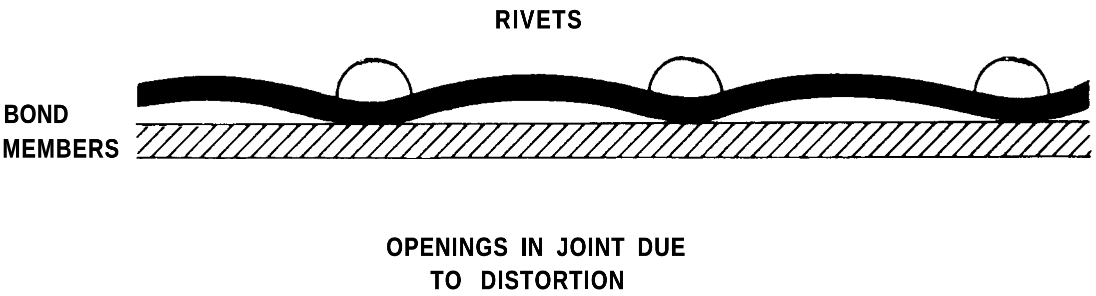


Figure 7-9. An Improperly Riveted Seam

Table 7-2

Ratings of Selected Bonding Techniques*

		Thermal					Chemical	Mechanical							
		Solder	Braze	Gas or Arc Weld	Exo-thermic Weld	Spot Weld	Con-ductive Adhesive	Bolts	Crime	Rivets	Clamps	Screws: Wire	Screws: Terminal	Twisted Wires	Wire Nuts
Electrical Properties	Low Resistance	9	10	10	10	10	3	9	9	9	8	9	9	9	9
	Resistance Stability	10	10	10	10	10	7	8	9	9	5	7	9	5	8
	Voltage Drop	9	10	10	10	10	5	9	9	10	8	8	9	5	8
	Current Capacity	5	10	10	10	9	1	9	9	9	8	9	9	8	9
Mechanical Properties	Pulloff Force	8	10	10	10	10	1	9	9	9	9	3	10	2	8
	Low Creep	9	10	10	10	10	5	9	9	9	8	3	8	2	8
	Strength	6	10	10	10	7	4	9	9	10	8	5	9	4	8
Conductor Applica-bility	Solid Wire	10	10	10	10	10	10	10	10	5	9	10	-	9	10
	Stranded Wire	9	9	8	9	0	9	9	10	2	9	2	-	9	10
	Aluminum Wire	5	2	1	8	0	2	9	8	4	9	4	-	1	6
	Bus Bars and Structures	8	8	8	9	9	6	9	7	10	7	-	10	-	-
Environ-mental	High Tempera-ture	3	9	10	10	10	1	8	9	4	5	7	8	5	7
	Low Temperature	9	10	10	10	10	5	8	9	5	5	8	8	7	7
	Thermal Shock	8	9	10	10	10	7	9	8	4	5	2	8	2	8
	Vibration	6	7	10	10	9	1	7	9	5	4	2	9	1	7
	Corrosive Atmosphere	9	10	10	10	10	5	6	9	8	3	7	9	4	8
	Aging	9	10	10	10	10	5	8	8	8	7	7	8	7	8
Cost Economy	Tooling	7	4	3	4	4	9	8	8	7	10	9	10	10	10
	Process	6	5	5	5	5	8	5	9	8	10	10	10	10	10
Accessi-bility in Assembly	Method Needs Little Space	8	5	4	5	8	8	8	9	8	9	9	9	10	8
	Ease of Repair	8	6	5	5	9	9	9	9	7	9	10	10	10	9

Source: Adapted from Reference (7-8)

7.5.1 Resistance. The resistance of an indirect bond is equal to the sum of the intrinsic resistance of the bonding conductor and the resistances of the metal-to-metal contacts at each end. The resistance of the strap is determined by the resistivity of the material used and the dimensions of the strap. With typical straps, the dc bond resistance is small. For example with a resistivity of 1.72 x 10^{-6} ohm-cm, (6.77 x 10^{-7} ohm-inches), a copper conductor 2.5 cm, (1 inch) wide, 40 mils thick, and 0.3 meters (1 foot) long has a resistance of 0.2 milliohms. To this resistance will be added the sum of the dc resistances of the direct bonds at the ends of the strap. With aluminum, copper, or brass straps, these resistances should be less than 0.1 milliohm with properly made connections. If long straps are required, however, the resistance of the conductor can be significant (see, for example Table 5-1).

7.5.2 Frequency Effects.

7.5.2.1 Skin Effect. Because high conductivity materials attenuate radio frequencies rapidly, high frequency currents do not penetrate into conductors very far, i.e., they tend to stay near the surface. At frequencies where this effect becomes significant the ac resistance of the bond strap can differ significantly from its dc value. For a detailed discussion of skin effect, see Section 5.2.2.1.

7.5.2.2 Bond Reactance.

The geometrical configuration of the bonding conductor and the physical relationship between objects being bonded introduce reactive components into the impedance of the bond. The strap itself exhibits an inductance that is related to its dimensions. For a straight, flat strap of nonmagnetic metal, the inductance in microhenries is given by

$$L = 0.002\ell \left(2.303 \log \frac{2\ell}{b + c} + 0.5 + 0.2235 \frac{b + c}{\ell}\right) \mu H \qquad (7\text{-}2)$$

or, for a wire of circular cross section, by

$$L = 0.002\ell \left(2.303 \log \frac{4\ell}{d} - 0.75\right) \mu H \qquad 7\text{-}3$$

where ℓ = length in cm,
b = width of the strap in cm
c = thickness of the strap in cm, and
d = diameter of the wire in cm.

Table 7-3 shows the calculated inductance, using Equation (7-2), of a nonmagnetic rectangular strap, 6 inches (15.2 cm) long. Table 7-4 compares the inductance of 6, 12, and 36 inch lengths of 0.05 inch (1.27 mm) thick straps while Table 7-5 tabulates the inductance of 6, 12, and 36 inch lengths of selected standard size cables from No. 14 AWG to 4/0 AWG. The inductive reactance of the straps tabulated in Tables 7-4 and 7-5 is plotted in Figure 7-10 for frequencies up to 100 MHz.

Table 7-3

Calculated Inductance of a 6 inch (15.2 cm) Rectangular Strap

Width, b (in.)	Thickness, c (in.)	L (μH)
0.5 (12.7 mm)	0.01 (0.25 mm)	0.112
0.5	0.05 (1.27 mm)	0.110
0.5	0.10 (2.54 mm)	0.107
1.0 (25.4 mm)	0.01	0.092
1.0	0.05	0.091
1.0	0.10	0.089
2.0 (50.8 mm)	0.01	0.072
2.0	0.05	0.071
2.0	0.10	0.071

Table 7-4

Calculated Inductance (μH) of 0.05 Inch (1.27 mm) Thick Straps

	Length		
Width (in.)	6 in. (15.2 cm)	12 in. (30.4 cm)	36 in. (91 cm)
0.5 (12.7 mm)	0.110	0.261	0.984
1.0 (25.4 mm)	0.091	0.222	0.866
2.0 (50.8 mm)	0.071	0.183	0.745

Table 7-5

Calculated Inductance (μH) of Standard Size Cable

	Length		
AWG No.	6 in.	12 in.	36 in.
4/0	0.098	0.238	0.914
1/0	0.108	0.259	0.977
2	0.115	0.273	1.020
4	0.122	0.287	1.063
6	0.129	0.301	1.105
10	0.144	0.329	1.189
14	0.158	0.358	1.274

Even at relatively low frequencies, the reactance of the inductive component of the bond impedance becomes much larger than the resistance (7-5), (7-9). Thus, in the application of bonding straps, the inductive properties as well as the resistance of the strap must be considered.

The physical size of the bonding strap is important because of its effect on the rf impedance. As the length, ℓ, of the strap is increased, its impedance increases nonlinearly for a given width; however, as the width, b, increases, there is a nonlinear decrease in strap impedance. Figure 7-11 shows that the relative reactance of a strap decreases significantly as the length to width (ℓ/b) ratio decreases. The curve shows that a strap with an ℓ/b ratio of 5 to 1 has an inductive reactance that is 45 percent that of a thin wire (i.e., very high ratio of ℓ to b); a 3 to 1 ratio decreases this percentage to 38 percent. Because of this reduction in reactance, bonding straps which are expected to provide a path for rf currents are frequently recommended to maintain a length-to-width ratio of 5 to 1 or less, with a ratio of 3 to 1 preferred.

In many applications, braided straps are preferred over solid straps because they offer greater flexibility. Figure 7-12 compares the measured impedance properties of a braided copper strap with those of a solid copper strap and shows that no significant difference exists between the impedance of the braided or solid strap for frequencies up to 10 MHz. Other tests (7-9) confirm that there is no essential difference in the rf impedance properties of braided and solid straps of the same dimensions and made of the same materials. Because the strands are exposed they are more susceptible to corrosion; braided straps may be undesirable for use in some locations for these reasons. Fine braided straps also are generally not recommended because of higher impedances at the higher frequencies as well as lower current carrying capacities.

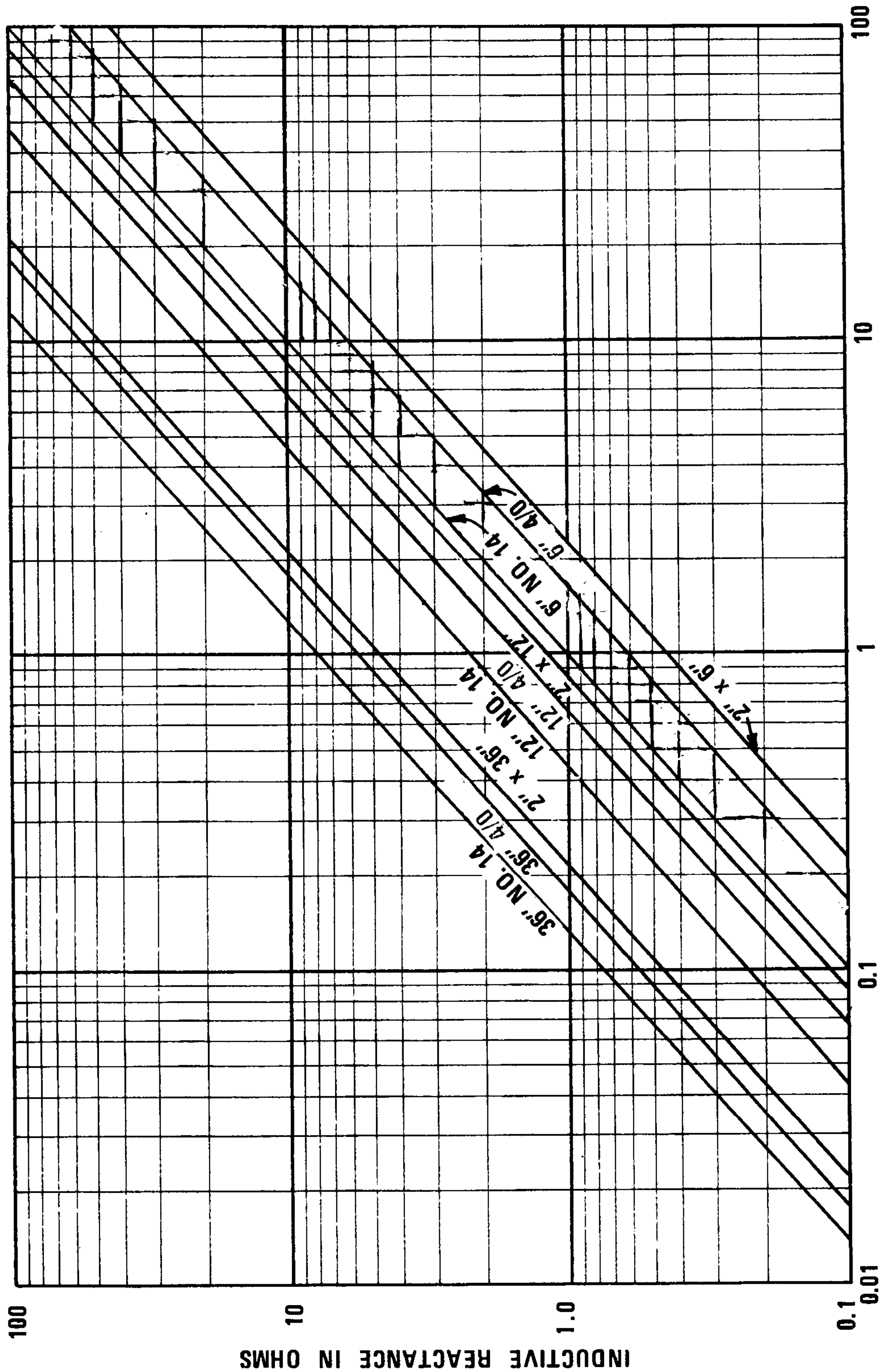


Figure 7-10. Inductive Reactance of Wire and Strap Bond Jumpers

7.5.2.3 Stray Capacitance.

A certain amount of stray capacitance is inherently present between the bonding jumper and the objects being bonded as well as between the bonded objects themselves. Figure 7-13 shows an equivalent circuit for the bonding strap alone. R_S represents the ac resistance of the strap; L_S is the inductance which may be calculated with either Equation 7-2 or 7-3; and C_S is the stray capacitance between the jumper and the two members being bonded. Except for extremely short straps, the magnitude of the inductive reactance of the strap will be significantly larger than the resistance and, at frequencies above approximately 100 kHz, the R_S term can be ignored. Thus, not considering R_S, the equation for the magnitude of impedance, Z_S, of the equivalent circuit is

$$\left| Z_S \right| = \frac{\omega L_S}{1-\omega^2 L_S C_S} \tag{7-4}$$

The equivalent circuit of Figure 7-13 does not take into account the effects of the equipment enclosure or other objects being bonded. Figure 7-14 shows the true equivalent circuit of an indirectly bonded system. The bonding strap parameters are again represented by R_S, C_S, L_S.

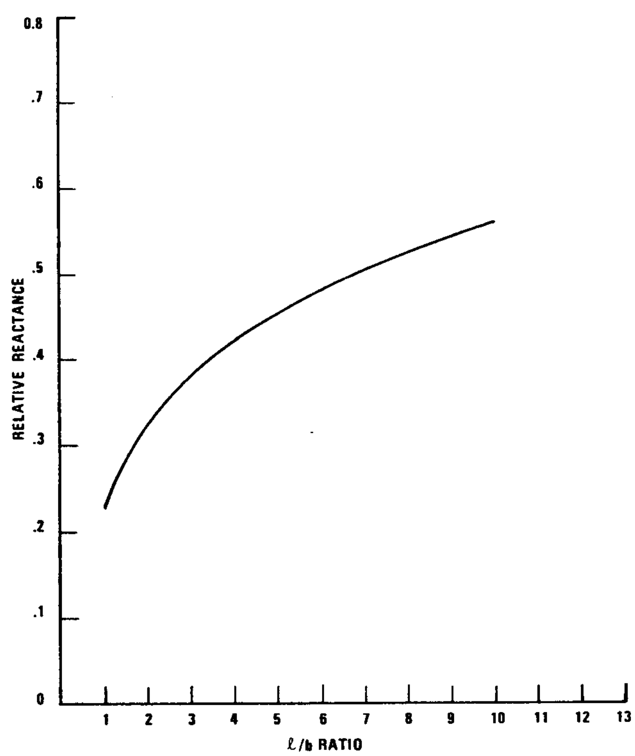


Figure 7-11. Relative Inductive Reactance versus Length-to-Width Ratio of Flat Straps (7-10)

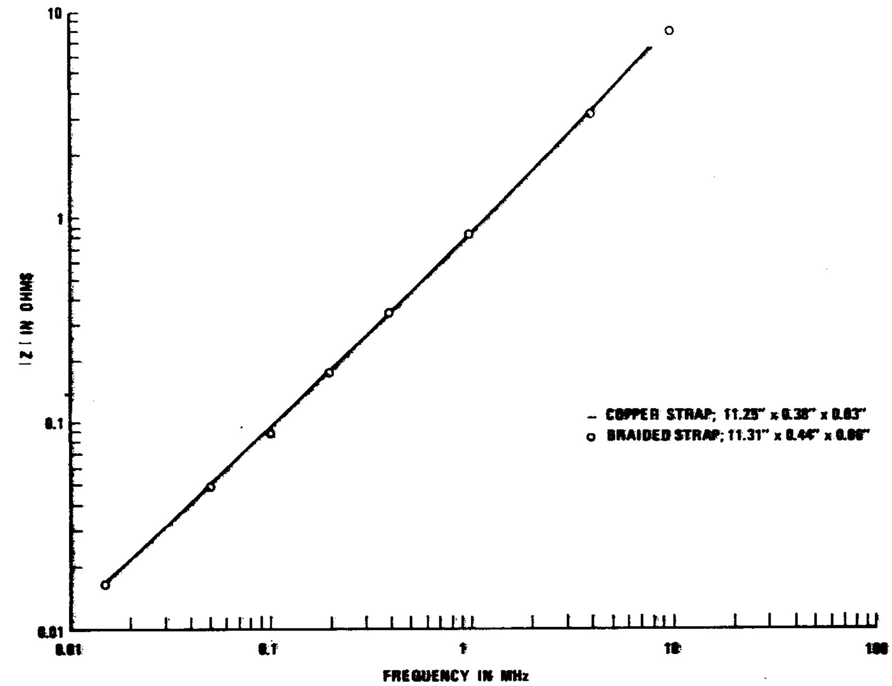


Figure 7-12. Frequency Variation of the Impedance of Simple Conductors (7-5)

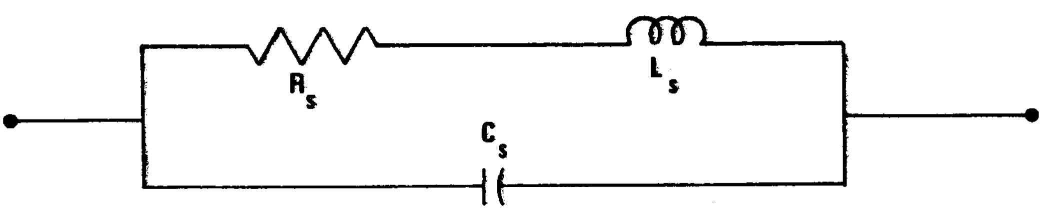


Figure 7-13. Equivalent Circuit for Bonding Strap

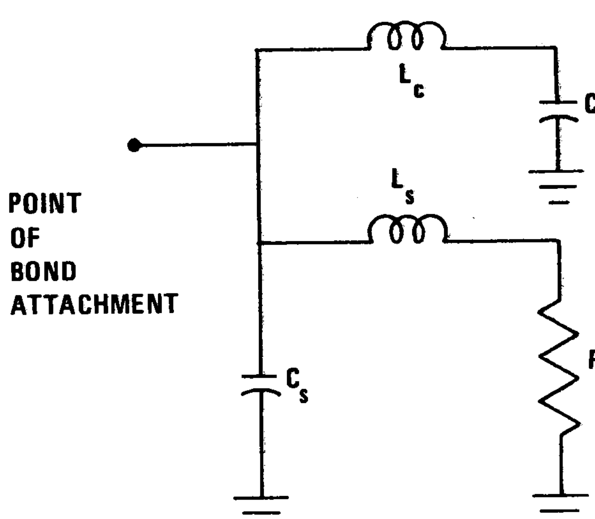


Figure 7-14. True Equivalent Circuit of a Bonded System

The inherent inductance of a bonded object, e.g., an equipment rack or cabinet, is represented by L_C and the capacitance between the bonded members, i.e., between the equipment and its reference plane, is represented by C_c. In most situations , $L_S \gg L_C$, $C_C \gg C_S$, and R_S can again be ignored. Thus, the primary (i.e., the lowest) resonant frequency is given by

$$f_r = \frac{1}{2\pi\sqrt{L_S C_C}} \qquad (7\text{-}5)$$

These resonances can occur at surprisingly low frequencies -- as low as 10 to 15 MHz (7-5) in typical configurations. In the vicinity of these resonances, bonding path impedances of several hundred ohms are common. Because of such high impedances, the strap is not effective. In fact, in these high impedance regions, the bonded system may act as an effective antenna system which increases the pickup of the same signals which bond straps are intended to reduce. Figures 7-15 and 7-16 show the measured effectiveness of two different lengths of bonding straps in the reduction of the voltage induced by a radiated field on an equipment cabinet above a ground plane. The bond effectiveness indicates the amount of voltage reduction achieved by the addition of the bonding strap. Positive values of bonding effectiveness indicate a lowering of the induced voltage. At frequencies near the network resonances, the induced voltages are higher with the bonding straps than without the straps. Figures 7-15 and 7-16 show that:

a. at low frequencies where the reactance of the strap is low, bonding straps will provide effective bonding;

b. at frequencies where parallel resonances exist in the bonding network, straps may severely enhance the pickup of unwanted signals and

c. above the parallel resonant frequency, bonding straps do not contribute to the pickup of radiated signals either positively or negatively.

In conclusion, bonding straps should be designed and used with care with special note taken to ensure that unexpected interference conditions are not generated by the use of such straps.

7.6 SURFACE PREPARATION. To achieve an effective and reliable bond, the mating surfaces must be free of any foreign materials, e.g., dirt, filings, preservatives, etc., and nonconducting films such as paint, anodizing, and oxides and other metallic films. Various mechanical and chemical means can be used to remove the different substances which may be present on the bond surfaces. After cleaning, the bond should be assembled or joined as soon as possible to minimize recontamination of the surfaces. After completion of the joining process, the bond region should be sealed with appropriate protective agents to prevent bond deterioration through corrosion of the mating surfaces.

7.6.1 Solid Materials.

Solid material such as dust, dirt, filings, lint, sawdust and packing materials impede metallic contact by providing mechanical stops between the surfaces. They can affect the reliability of the connection by fostering corrosion. Dust, dirt, and lint will absorb moisture and will tend to retain it on the surface. They may even promote the growth of molds, fungi, and bacteriological organisms which give off corrosive products. Filings of foreign metals can establish tiny electrolytic cells (see Section 7.8) which will greatly accelerate the deterioration of the surfaces.

The bond surface should be cleaned of all such solid materials. Mechanical means such as brushing or wiping are generally sufficient. Care should be exercised to see that all materials in grooves or crevices are removed. If a source of compressed air is available, air blasting is an effective technique for removing solid particles if they are dry enough to be dislodged.

7.6.2 Organic Compounds.

Paints, varnishes, lacquers, and other protective compounds along with oils, greases and other lubricants are nonconductive and, in general, should be removed. Commercial paint removers can be used effectively. Lacquer thinner works well with oil-based paints, varnish, and lacquer. If chemical solvents cannot be used effectively, mechanical removal with scrapers, wire brushes, power sanders, sandpaper, or blasters should be employed. When using mechanical techniques, care should be exercised to avoid removing excess material from the surfaces. Final cleaning should be done with a fine, such as 400-grit, sandpaper or steel wool. After all of the organic material is removed, abrasive grit or steel wool filaments should be brushed or blown away. A final wipe down with denatured alcohol, dry cleaning fluid, or lacquer thinner should be accomplished to remove any remaining oil or moisture films.

WARNING

> Many paint solvents such as lacquer thinner and acetone are highly flammable and toxic in nature. They should never be used around open flames and adequate ventilation must be present. Inhalation of the fumes must be prevented.

Oils, greases, and other petroleum compounds should be wiped with a cloth or scraped off. Residual films should be dissolved away with an appropriate solvent. Hot soapy water can be used effectively for removing any remaining oil or grease. If water is used, however, the surfaces must be thoroughly dried before completing the bond. For small or intricate parts, vapor degreasing is an effective cleaning method. Parts to be cleaned are exposed to vapors of trichlorethylene, perchlorethylene, or methylene chloride until the surfaces reach the temperature of the vapor. In extreme cases, further cleaning by agitation in a bath of dry chromic acid, 2 lbs per gallon of water, and sulfuric acid, 4 oz per gallon of water, (7-7) may be necessary. The average dip time should be restricted to less than 30 seconds because prolonged submersion of parts in this bath may produce severe etching and cause loss of dimension. This bath must be followed by a thorough rinse with cold water and then a hot water rinse to facilitate drying.

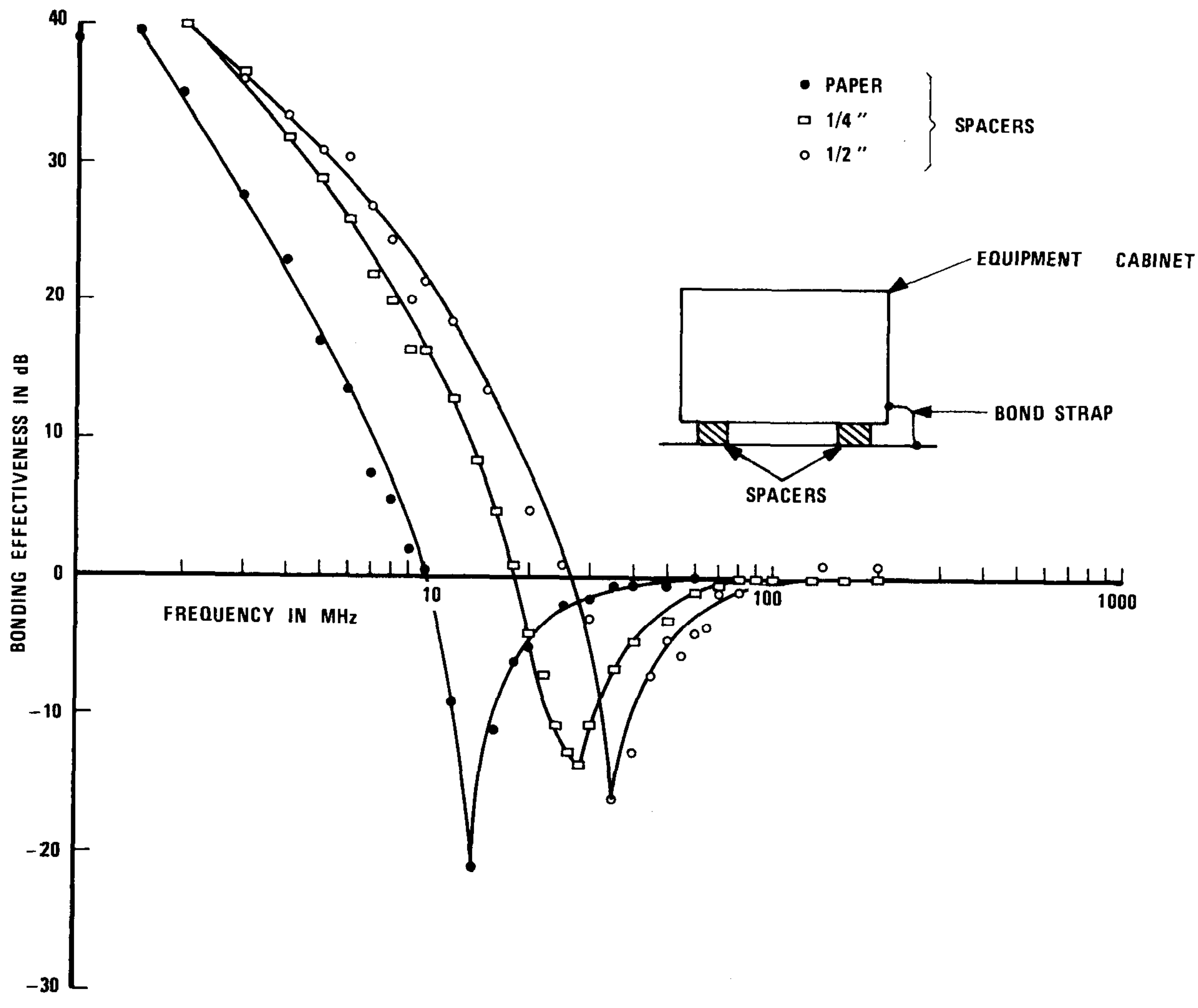


Figure 7-15. Measured Bonding Effectiveness of a 9-1/2 Inch Bonding Strap (7-5)

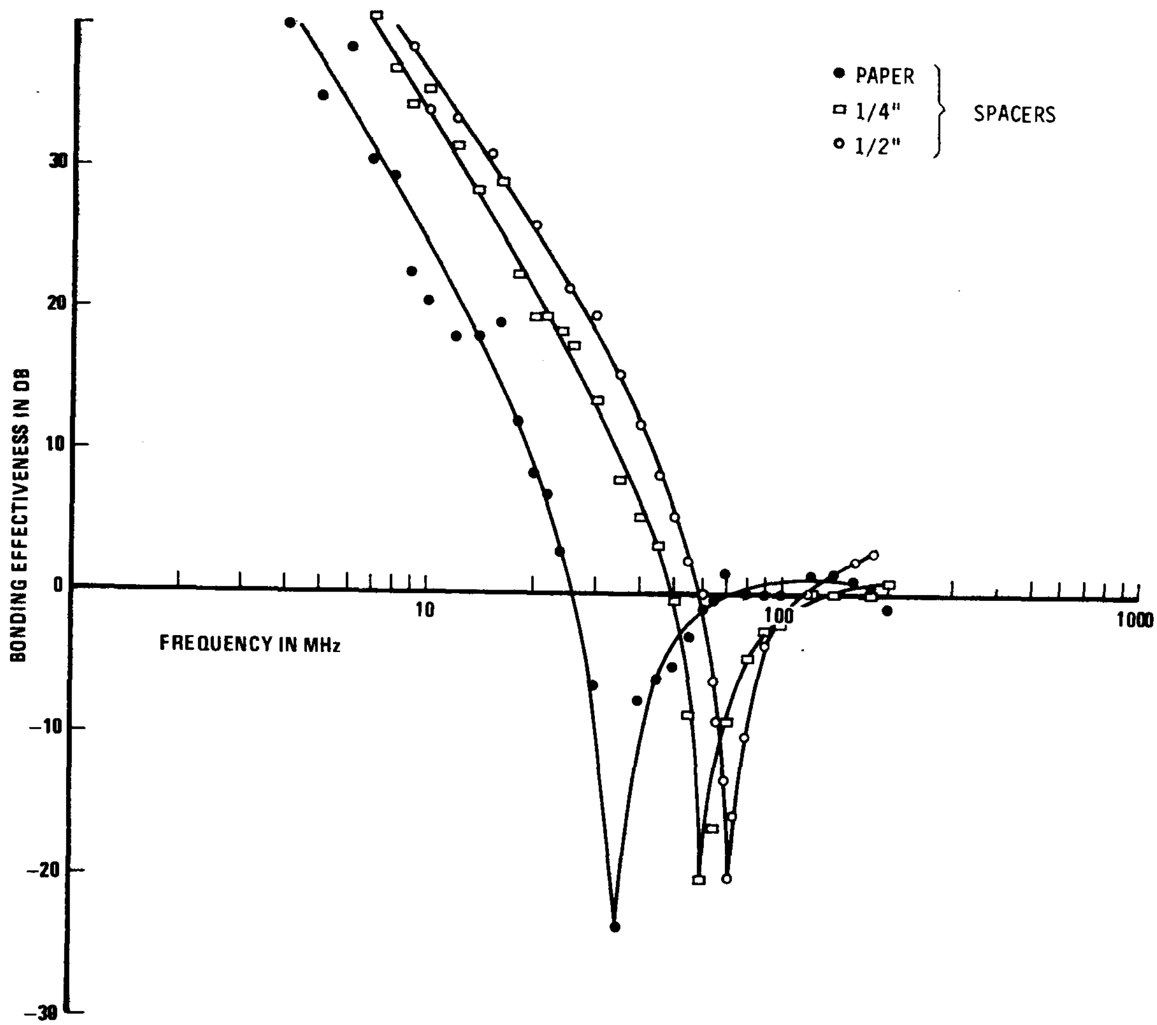


Figure 7-16. Measured Bonding Effectiveness of a 2-3/8 Inch Bonding Strap (7-5)

7.6.3 Platings and Inorganic Finishes.

Many metals are plated or coated with other metals or are treated to produce surface films to achieve improved wearability or provide corrosion resistance. Metal platings such as gold, silver, nickel, cadmium, tin, and rhodium should have all foreign solid materials removed by brushing or scraping and all organic materials removed with an appropriate solvent. Since such platings are usually very thin, acids and other strong etchants should not be used. Once the foreign substances are removed, the bond surfaces should be burnished to a bright shiny condition with fine steel wool or fine grit sandpaper. Care must be exercised to see that excessive metal is not removed. Finally, the surfaces should be wiped with a cloth dampened in a denatured alcohol or dry cleaning solvent and allowed to dry before completing the bond.

Chromate coatings such as iridite 14, iridite 18P, oadkite 36, and alodine 1000 offer low resistance as well as provide corrosion resistance. These coatings should not be removed. In general, any chromate coatings meeting the requirements of MIL-C-5541 (7-11) should be left in place.

Many aluminum products are anodized for appearance and corrosion resistance. Since these anodic films are excellent insulators, they must be removed prior to bonding. Those aluminum parts to be electrically bonded either should not be anodized or the anodic coating must be removed from the bond area.

7.6.4 Corrosion By-Products. Oxides, sulfides, sulfates, and other corrosion by-products must be removed because they restrict or prevent metallic contact. Soft products such as iron oxide and copper sulfate can be removed with a stiff wire brush, steel wool, or other abrasives. Removal down to a bright metal finish is generally adequate. When pitting has occurred, refinishing of the surface by grinding or milling may be necessary to achieve a smooth, even contact surface. Some sulfides are difficult to remove mechanically and chemical cleaning and polishing may be necessary. Oxides of aluminum are clear and thus the appearance of the surface cannot be relied upon as an indication of the need for cleaning. Although the oxides are hard, they are brittle and roughening of the surface with a file or coarse abrasive is an effective way to prepare aluminum surfaces for bonding.

7.7 COMPLETION OF THE BOND.

After cleaning of the mating surfaces, the bond members should be assembled or attached as soon as possible. Assembly should be completed within 30 minutes if at all possible. If more than 2 hours is required between cleaning and assembly, a temporary protective coating must be applied. Of course, this coating must also be removed before completing the bond.

The bond surfaces must be kept free of moisture before assembly and the completed bond must be sealed against the entrance of moisture into the mating region. Acceptable sealants are paint, silicone rubber, grease, and polysulfates. Where paint has been removed prior to bonding, the completed bond should be repainted to match the original finish. Excessively thinned paint should be avoided; otherwise, the paint may seep under the edges of the bonded components and impair the quality of the connection. Compression bonds between copper conductors or between compatible aluminum alloys located in readily accessible areas not subject to weather exposure, corrosive fumes, or excessive dust do not require sealing. This is subject to the approval of the responsible civil engineer or the local authorized approval representative.

7.8 BOND CORROSION. Corrosion is the deterioration of a substance (usually a metal) because of a reaction with its environment. Most environments are corrosive to some degree. Those containing salt sprays and industrial contaminants are particularly destructive. Bonds exposed to these and other environments must be protected to prevent deterioration of the bonding surfaces to the point where the required low resistance connection is destroyed.

7.8.1 Chemical Basis of Corrosion.

The basic diagram of the corrosion process for metals is shown in Figure 7-17. The requirements for this process to take place are that (1) an anode and a cathode must be present to form an electrochemical cell and (2) a complete path for the flow of direct current must exist. These conditions occur readily in many environments. On the surface of a single piece of metal, anodic and cathodic regions are present because of impurities, grain boundaries and grain orientations, or localized stresses. These anodic and cathodic regions are in electrical contact through the body of metal. The presence of an electrolyte or conducting fluid completes the circuit and allows the current to flow from the anode to the cathode of the cell.

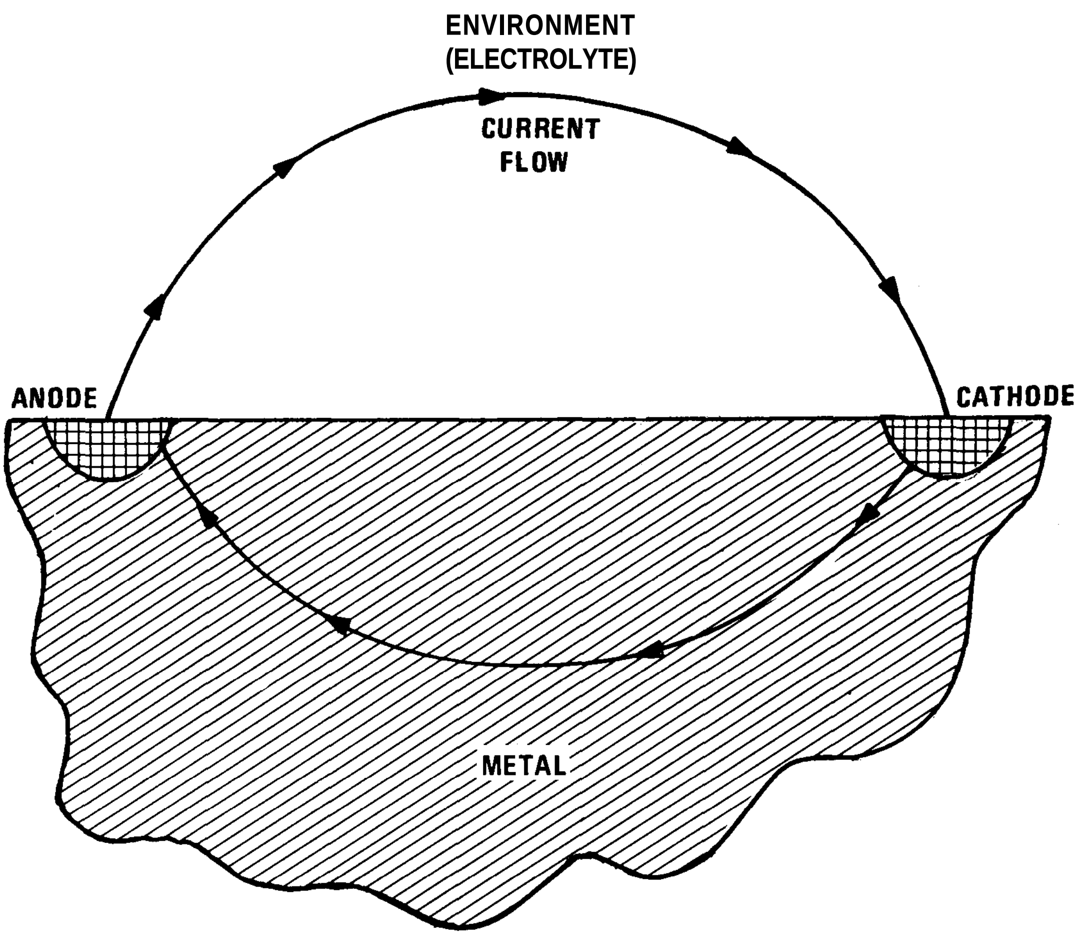


Figure 7-17. Basic Diagram of the Corrosion Process

Anything that prevents the existence of either of the above conditions will prevent corrosion. For example, in pure water, hydrogen gas will accumulate on the cathode to provide an insulating blanket to stop current flow. Most water, however, contains dissolved oxygen which combines with the hydrogen to form additional molecules of water. The removal of the hydrogen permits corrosion to proceed. This principle of insulation is employed in the use of paint as a corrosion preventive. Paint prevents moisture from reaching the metal and thus prevents the necessary electrolytic path from being established.

7.8.1.1 Electrochemical Series. The oxidation of metal involves the transfer of electrons from the metal to the oxidizing agent, In this process of oxidation, an electromotive force (EMF) is established between the metal and the solution containing the oxidizing agent. A metal in contact with an oxidizing solution containing its own metal ions establishes a fixed potential difference with respect to every other metal in the same condition. The set of potentials determined under a standardized set of conditions, including temperature and ion concentration in the solution, is known as the EMF (or electrochemical) series. The EMF series (with hydrogen as the referenced potential of 0 volts) for the more common metals is given in Table 7-6. The importance of the EMF series is that it shows the relative tendencies of metals to corrode. Metals high in the series react more readily and are thus more prone to corrosion. The series also indicates the magnitude of the potential established when two metals are coupled to form a cell. The farther apart the metals are in the series, the higher the voltage between them. The metal higher in the series will act as the anode and the one lower will act as the cathode. When the two metals are in contact, loss of metal at the anode will occur through oxidation to supply the electrons to support current flow. This type of corrosion is defined as galvanic corrosion. The greater the potential difference of the cell, i.e., the greater the dissimilarity of the metals, the greater the rate of corrosion of the anode.

7.8.1.2 Galvanic Series.

The EMF series is based on metals in their pure state -- free of oxides and other films -- in contact with a standardized solution. Of greater interest in practice, however, is the relative ranking of metals in a typical environment with the effects of surface films included. This ranking is referred to as the galvanic series. The most commonly referenced galvanic series is listed in Table 7-7. This series is based on tests performed in sea water and should be used only as an indicator where other environments are of concern.

Galvanic corrosion in the atmosphere is dependent largely on the type and amount of moisture present. For example, corrosion will be more severe near the seashore and in polluted industrial environments than in dry rural settings. Condensate near the seashore or in industrial environments is more conductive even under equal humidity and temperature conditions due to increased concentration of sulfur and chlorine compounds. The higher conductivity means that the rate of corrosion is increased.

Table 7-6

Standard Electromotive Series (7-12)

Metal	Electrode Potential* (volts)
Magnesium	2.37
Aluminum	1.66
Zinc	0.763
Iron	0.440
Cadmium	0.403
Nickel	0.250
Tin	0.136
Lead	0.126
Copper	-0.337
Silver	-0.799
Palladium	-0.987
Gold	-1.50

NOTE: *Signs of potential are those employed by the American Chemical Society.

Table 7-7
Galvanic Series of Common Metals and Alloys in Seawater (7-13)

(ANODIC OR ACTIVE END)
Magnesium
Magnesium Alloys
Zinc
Galvanized Steel or Iron
1100 Aluminum
Cadmium
2024 Aluminum
Mid Steel or Wrought Iron
Cast Iron
Chromium Steel (active)
Ni-Resist (high-Ni cast iron)
18-8 Stainless Steel (active)
18-8 Mo Stainless Steel (active)
Lead-tin Solders
Lead
Tin
Nickel (active)
Inconel (active)
Hastelloy B
Manganese Bronze
Brasses
Aluminum Bronze
Copper
Silicon Bronze
Monel
Silver Solder
Nickel
Inconel
Chromium Steel
18-8 Stainless Steel
18-8 MO Stainless Steel
Hastelloy C
Chlorimet 3
Silver
Titanium
Graphite
Gold
Platinum
(CATHODIC OR MOST NOBLE END)

7.8.2 Relative Area of Anodic Member. When joints between dissimilar metals are unavoidable, the anodic member of the pair should be the largest of the two. For a given current flow in a galvanic cell, the current density is greater for a small electrode than for a larger one. The greater the current density of the current leaving an anode, the greater is the rate of corrosion as illustrated by Figure 7-18. As an example, if a copper strap or cable is bonded to a steel column, the rate of corrosion of the steel will be low because of the large anodic area. On the other hand, a steel strap or bolt fastener in contact with a copper plate will corrode rapidly because of the relatively small area of the anode of the cell.

7.8.3 Protective Coatings. Paint or metallic platings used for the purpose of excluding moisture or to provide a third metal compatible with both bond members should be applied with caution. When they are used, both members must be covered as illustrated in Figure 7-19. Covering the anode alone must be avoided. If only the anode is covered then at imperfections and breaks in the coating, corrosion will be severe because of the relatively small anode area. All such coatings must be maintained in good condition.

7.9 WORKMANSHIP.

Whichever bonding method is determined to be the best for a given situation, the mating surfaces must be cleaned of all foreign material and substances which would preclude the establishment of a low resistance connection. Next, the bond members must be carefully joined employing techniques appropriate to the specific method of bonding. Finally the joint must be finished with a protective coating to ensure continued integrity of the bond. The quality of the junction depends upon the thoroughness and care with which these three steps are performed. In other words, the effectiveness of the bond is influenced greatly by the skill and conscientiousness of the individual making the connection. Therefore, this individual must be aware of the importance of electrical bonds and must have the necessary expertise to correctly implement the method of bonding chosen for the job.

Those individuals charged with making bonds must be carefully trained in the techniques and procedures required. Where bonds are to be welded, for example, work should be performed only by qualified welders. No additional training should be necessary because standard welding techniques appropriate for construction purposes are generally sufficient for establishing electrical bonds. Qualified welders should also be used where brazed connections are to be made.

Exothermic welding can be effectively accomplished by personnel not specifically trained as welders. Every individual doing exothermic welding should become familiar with the procedural details and with the precautions required with these processes. Contact the manufacturers of the materials for such processes for assistance in their use. By taking reasonable care to see that the bond areas are clean and free of water and that the molds are dry and properly positioned, reliable low resistance connections can be readily achieved.

Pressure bonds utilizing bolts, screws, or clamps must be given special attention. Usual construction practices do not require the surface preparation and bolt tightening necessary for an effective and reliable electrical bond. Therefore, emphasis beyond what would be required for strictly mechanical strength is necessary. Bonds of this type must be checked rigorously to see that the mating surfaces are carefully cleaned, that the bond members are properly joined, and that the completed bond is adequately protected against corrosion.

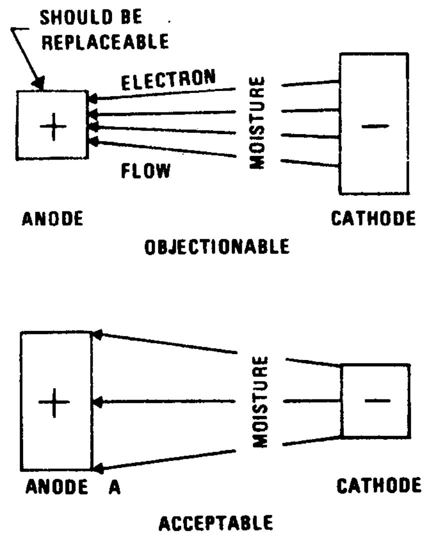


Figure 7-18. Anode-to-Cathode Size at Dissimilar Junctions

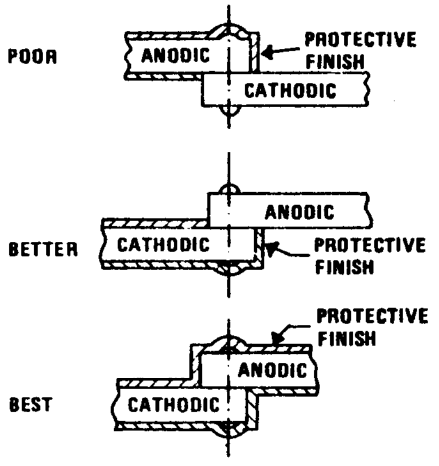


Figure 7-19. Techniques for Protecting Bonds Between Dissimilar Metals

7.10 SUMMARY OF GUIDELINES.

- Bonds must be designed into the system. Specific attention should be directed to the interconnections not only in power lines and signal lines, but also between conductors of signal ground bus networks, between equipments and the ground bus networks, between both cable and component or compartment shields and the ground reference plane, between structural members, and between elements of the lightning protection network. In the design and construction of a facility, signal path, personnel safety, and lightning protection bonding requirements must be considered along with mechanical and operational needs.

- Bonding must achieve and maintain intimate contact between metal surfaces. The surfaces must be smooth and clean and free of nonconductive finishes. Fasteners must exert sufficient pressure to hold the surfaces in contact in the presence of the deforming stresses, shocks, and vibrations associated with the equipment and its environment.

- The effectiveness of the bond depends upon its construction, the frequency and magnitude of the currents flowing through it, and the environmental conditions to which it is subjected.

- Bonding jumpers are only a substitute for direct bonds. If the jumpers are kept as short as possible, have a low resistance and low ℓ/w ratio, and are not higher in the electrochemical series than the bonded members, they can be considered a reasonable substitute.

- Bonds are always best made by joining similar metals. If this is not possible, special attention must be paid to the control of bond corrosion through the choice of the materials to be bonded, the selection of supplementary components (such as washers) to assure that corrosion will affect replaceable elements only, and the use of protective finishes.

- Protection of the bond from moisture and other corrosive elements must be provided.

- Finally, throughout the lifetime of the equipment, system, or facility, the bonds must be inspected, tested, and maintained to assure that they continue to perform as required.

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