CHAPTER 4

ELECTROMAGNETIC INTERFERENCE (EMI) PROTECTION

4-1. Purpose of EMI protection

Interference is any extraneous electrical or electromagnetic (EM) disturbance that tends to interfere with the reception of desired signals or that produces undesirable responses in electronic systems. Interference can be produced by both natural and man-made sources either external or internal to the electronic system. The major objective of interference reduction in modern electronic equipment and facilities is to minimize and, if possible, prevent degradation in the performance of the various electronic systems by the interactions of undesired signals, both internal and external. In systems operating with high level signals, undesired signals with amplitudes on the order of volts may be tolerable, while in low level systems a few microvolts may produce intolerable errors in the response of the system. An important element in the control of unwanted interactions between signals is the proper grounding of the system.

4-2. Typical configuration

An ideal signal system is a simple signal generator-load pair. With no extraneous voltages present within the loop, the simple pair is free of interference. However, when the current return path is non-ideal and sources of noise are present, a voltage difference will exist between the return or low side of the generator and the return or low side of the load. This voltage difference effectively appears in the signal transfer loop in series with the signal generator and produces noise currents in the load.

a. Noise current reduction. Four ways of combating this noise problem are as follows.

(1) Isolate the source-load pair from the noise sources; i.e., float the system and provide the necessary shielding and filtering to prevent coupling by other means.

(2) Connect the return or low side of the generator-load loop to one of the reference planes, but not at both.

(3) Reduce the impedance of the path connecting the two noise sources (the generator and the load).

(4) Reduce the magnitudes of noise voltages through the control of the currents producing them by lowering the impedance through which these currents flow.

b. Common reference plane. Practical electronics circuits typically are a collection of several source-load combinations. These various source-load combinations may be functionally dependent on each other. Hence each individual source-load pair cannot operate in isolation; there must be coupling between pairs. For example, one source may be driving several loads; one load may be receiving signals from several sources; or the load for one signal source may serve as the source for another load. At the circuit level, numerous sources and loads are connected in an interrelated fashion and the use of individual return paths for each source-load pair becomes impractical. It is more realistic to establish a common ground or reference plane that serves as the return path for several signals. The control of undesired network responses, particularly in high gain and/or higher frequency circuits, often requires the establishment of a common signal reference to which functional grouping of components, circuits, and networks can be connected. Ideally, this common reference connection offers zero impedance paths to all signals for which it serves as a reference. The several signal currents within the network can then return to their sources without creating unwanted conductive coupling between circuits.

c. Large common reference planes. At the equipment level, the individual signal reference planes for the various networks must be connected together to prevent personnel shock hazards and to provide as near as possible, the same signal reference for all networks. Thus, the signal reference plane may extend over large distances within a facility. The assumption that this large reference plane provides zero impedance paths is not valid; the series inductance and resistance of the conductors forming the signal reference plane and the shunt capacitance to nearby conductive objects must be considered. Currents flowing in the signal reference plane will develop voltages across this impedance and will produce electric and magnetic fields around the conductors.

4-3. Design considerations

Adherence to the following design considerations should mitigate the effects of any extraneous EM interference in Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) facilities.

a. Equipotential plane. The equipotential plane (described in chapter 3) shall be bonded to the earth electrode subsystem at multiple points. Such an equipotential plane exists in a building with a metal or raised floor or ceiling grid electrically bonded together, or, in a building with a concrete floor with a ground grid imbedded in it, connected to the facility ground. Equipment cabinets are then connected to the equipotential plane. Chassis are connected to the equipment cabinets and all components, signal return leads, etc., are connected to the chassis. The equipotential plane is then terminated to the earth electrode subsystem to assure personnel safety and a low impedance path to ground. Planes are not required in areas of the facility where no communications equipment (CE) equipment is or will be installed.

(1) At high frequencies, the large conducting surface embedded in or on the floor under the equipment to be grounded, presents a much lower characteristic impedance than a single wire, even if both were improperly terminated because the characteristic impedance is a function of L/C. As the capacitance to earth increases, the impedance decreases.

(2) Normally, the capacitance of a metallic sheet to earth is higher than that of wire. If the size of the sheet is increased and allowed to encompass more area, the capacitance increases. Also, the unit length inductance decreases with width, which further decreases Z_o.

(3) If the dimensions of a metallic sheet increase extensively (as in the case of a conducting sub-floor), the characteristic impedance approaches a very low value. In this case, even if the signal equipotential plane were improperly terminated to the earth electrode subsystem, the impedance would be quite low throughout a large portion of the spectrum. This, in turn, would establish an equipotential reference plane for all equipment bonded to it. With this reference plane bonded to earth, the following advantages are obtained.

(a) Any "noisy" cable or conductor connected to the receptor through or along such a ground plane will have its electric field contained between the conductor and the ground plane. The noise field can be "shorted out" by filters and bond straps because the distance between these “transmission line” conductors is very small. Shorting out the noise field has the desirable effect of keeping noise current from flowing over the receptor case and along any antenna input cables.

(b) Filters at the interface terminals of equipment can operate more effectively when both terminals of their equivalent "transmission line" are available. Access to both terminals allows short connections to the equipotential plane from both terminals for filtering of noise generated from either source or load. A large conducting surface makes it possible to contain the field carried by the offending conductor in such a way that it can be more easily prevented from traveling further, and will also tend to shield any rooftop antennas from cable runs below it.

(4) The equipotential plane may be a solid sheet or may consist of a wire mesh. A mesh will appear electrically as a solid sheet as long as the mesh openings or spacing of conductors are less than 1/8 wavelength at the highest frequencies of concern. When it is not feasible to include a fine mesh (either overhead or under the equipment) a larger grid may be installed, but even then the mesh size should be made as small as practicable. In all cases, the "design objective" (DO) is to keep the mesh size to less than 1/8 wavelength at the highest frequencies of concern.

$$\lambda = c/f$$

where c = velocity of light in free space = 3×10^8 meters/second

f = frequency in hertz (cycles/second)

(5) Conducting media that can be utilized for ground distribution networks are Q-cell floor (if available) or subfloor of aluminum, copper, or sheet metal laid underneath the floor tile. Since a large solid conducting surface may not be economically feasible for some installations, a ground reference plane, made up of a copper grid, should be considered. Copper-clad steel wire meshes with all crossovers brazed are commercially available. They are obtainable in mesh spacings of from 5 to 61cm (2 to 24 in) squares, in AWG wire sizes Nos. 6, 8, 10, and 12. It is normally furnished in 3.7m (12 foot) rolls, but can be obtained in various widths up to 5.5m (18 feet). Electrically continuous stringers of raised floors may also be used to serve as an equipotential plane. Ground connections can be made to either the grid or stringer by direct bonding or manufactured ground "buses" and give grounding access at the floor surface. Normally, if the grid is embedded in a concrete floor, the latter method provides the easiest grounding source. Equipotential planes for existing facilities may be installed at or near the ceiling above the CE equipment.

b. Grounding and bonding. Intersite or inter-building common-mode noise voltages in the earth contribute to the need for a low resistance of 10 ohms to earth at each facility. Even a resistance to earth of as low as 10 ohms may not, however, alleviate all common mode noise on a data cable connecting two separate locations or buildings.

(1) While a low resistance may help, there will always be potential differences between any two rods in the ground. The use of shielded, balanced twisted pair for all lower frequency equipment interfaces is intended to provide additional common-mode rejection to those unavoidable noise voltages which exist in any facility. This is not to say that the sources of noise in a facility cannot be controlled. In fact, much can be done by equalizing the load between the phases of the alternating current (ac) distribution system; by insuring that the neutral is grounded only at the service disconnecting means; by limiting the quantity of leakage current from power line filter capacitors by using the smallest acceptable value of capacitance; or by sharing common filtered lines with several pieces of equipment.

(2) Bonding provides an electrical union between two metallic surfaces used to provide a low-impedance path between them. Bonding is the procedure by which the conductive surface of a subassembly or component is electrically connected to another. This prevents development of electrical potentials between individual metal surfaces for all frequencies capable of causing interference.

c. Shielding. Groups of equipment or subsystems may be made EM compatible by any combination of three fundamental approaches: the interfering signal level may be reduced, the receptor susceptibility may be reduced, or the attenuation of the path or paths over which interference is transmitted from source to receptor may be increased. Radiated interference signals generated by EM fields may be effectively attenuated by EM shielding, either at the source or at the receptor. Shielding, when properly designed and implemented, offers significant wideband protection against EM radiation, where source and receptor are not sufficiently separated for adequate free space radiation attenuation.

(1) It is relatively easy to obtain 40 decibels (dB) of shielding effectiveness in a frequency range above 100 kHz with a single shield, and values as high as 70 dB can be obtained with careful single-shield construction. Where this is inadequate, double shields are normally used, providing shielding values as high as 120 dB. Radiated energy may still be coupled into a susceptible device through a shield of inadequate thickness, through holes penetrated for ventilation and other purposes, and through imperfectly jointed shielded sections.

(2) Precise calculation of shielding effectiveness, even for perfectly joined solid shields, depends on the form of the shield and the type of field for which the shielding is to be used. Both electric and magnetic coupling can occur. Normally, it is relatively easy to provide electric shielding. Magnetic shielding, however, is more difficult to provide, particularly at frequencies below 100 kHz.

(3) Shielding shall be integrated with other basic interference control measures such as filtering, wire routing, cable and circuit layout, signal processing, spectrum control, and frequency assignment to achieve operational compatibility of the equipment. The degree of shielding shall be determined by the systems engineering process.

(4) Shields shall be constructed from material that provides the required degree of signal suppression without incurring unnecessary expense and weight. The selection of materials shall be based upon: the amplitude and frequency of the signals to be attenuated, the characteristics of the EM field of the signal (i.e., is the signal being coupled via inductive, capacitive, or free space means), configuration, the installation constraints, and the corrosion properties.

(5) Filters on power, control, and signal lines shall be installed in a manner that maintains the integrity of the shield. Power line filters shall be completely shielded with the filter case grounded. Filters on power control and signal lines shall be placed as close as possible to the point of penetration of the case in order to avoid long, unprotected paths inside the equipment.

(6) Several steps can be taken during the design and construction stages of a facility to minimize subsequent common-mode noise problems in instrumentation, equipment, and systems. The recommended steps should be recognized as being appropriate for interference control in general and not limited strictly to common-mode noise.

(a) Sensitive data and instrumentation facilities should be located as far as possible from high voltage (66 kV and above) transmission lines.

(b) The routing of data and signal lines should be perpendicular to main power lines wherever possible. Where parallel runs cannot be avoided, maximum separation must be maintained. In many instances, routing of the data and signal cables in ferrous conduit may be necessary.

(c) Distribution feeders to the facility should be routed perpendicularly to high voltage power lines, if possible. In any event, long parallel runs between distribution feeders and the main power line should be avoided.

(d) Where overhead distribution lines are necessary, pre-assembled aerial cable should be used in preference to open wires. Magnetic field is greatly reduced.

(e) All internal distribution power conductors near sensitive test and measurement facilities and carrying more than 5 amperes should be twisted. A suggested rate of twist is one complete twist for each length equal to approximately 25 times the diameter of the insulated power conductor when physically possible.

(7) Metallic enclosures should be used for power conductors wherever possible to take advantage of the shielding they offer. In order of preference, the types of enclosures recommended are:

(a) Rigid steel conduit is the most effective enclosure for power conductors from the standpoint of noise reduction and should be used wherever practical. Electrical metallic tubing (EMT) and rigid aluminum or copper conduit provide effective electrostatic shielding, but their magnetic shielding properties are at least an order-of-magnitude poorer than rigid steel conduit.

(b) Armored cable is sometimes used in lieu of conduit and individual insulated conductors. The armor provides an effective electrostatic shield but is not as effective as rigid steel conduit for magnetic shielding. Steel armor is preferable to aluminum or bronze.

(c) Standard construction grade flexible conduit is a poorer electrostatic shield than either of the above because of its construction and provides considerably less magnetic shielding than rigid steel conduit. It is recommended that the use of flexible conduit be restricted to short lengths and only where required to absorb vibration or to permit position adjustment of the equipment or device served.

(d) Wireways, which are rectangular sheet metal duct-like enclosures and cable trays, are not nearly as effective for electrostatic or magnetic shields as rigid steel conduit. Unless the wireway or cable tray is made of a ferrous metal and all discontinuities are carefully bonded, its use for the shielding of power conductors should be limited.

(8) The effect of RF radiation on living tissue is thought to be primarily thermal in nature. The most vulnerable parts of the human body are nerves, skin, and muscles. However, other parts that can be affected are the brain, the eyes and the testes. The thermal effects can range from mild heating of the skin or organs to fatal damage. To minimize possible hazards from RF radiation, Dept of Defense Instruction 6055.11 (9-4) provides recommendations to prevent possible harmful effects in human beings exposed to radio frequency radiation.

(a) Below 1000 MHz, RF energy penetrates deeply into the body. These frequencies are extremely hazardous since the radiation is not detected by the nerve endings located in the skin. The power absorbed in the body tissues can be as high as 40% of the incident power. The urinary bladder, gall bladder, and parts of the gastro-intestinal tract are particularly vulnerable since they are not cooled by an abundant flow of blood. Also, stainless steel and platinum bone implants and fillings in teeth can increase in temperature when subjected to RF radiation, resulting in burning of tissues.

(b) In the 2-5 GHz region of the RF spectrum, the eyes and the testes are the most vulnerable organs to RF radiation damage. Damage to the eyes is generally irreversible and can result in blindness from cataracts or loss of lens transparency. Animal experiments have shown that damage to the testes from low levels of exposure does not differ from that caused by common forms of heat applied to the testes, and that the reduction in testicular function due to heating appears to be temporary. It is not known if RF radiation produces any genetic damage.

(9) Various organizations and countries have developed exposure standards and guidelines over the past several decades. In North America and most of Europe exposure standards and guidelines have generally been based on exposure levels where effects considered harmful to humans occur. Safety factors are then incorporated to arrive at specific levels of exposure to provide sufficient protection for various segments of the population. The Federal Communications Commission (FCC) Office of Engineering and Technology Bulletin 56 (OET-56) discusses in great detail the recommended human exposure limits to RF radiation for the general public and occupational exposures. The ANSI/IEEE document (ANSI/IEEE C95.3-1992) entitled, "Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields - RF and Microwave," contains practical guidelines, required instrumentation and information for performing RF field measurements.

d. Aperture control. Unnecessary apertures shall be avoided. Only those shield openings needed to achieve proper functioning and operation of the equipment shall be provided.

(1) Controls, switches, and fuse holders shall be mounted such that close metal-to-metal contact is maintained between the cover or housing of the devices and the case.

(2) Where non-conductive control shafts are necessary, a waveguide-below-cutoff metal sleeve (for the highest frequency of concern) shall be peripherally bonded to the case for the shaft.

(3) The cutoff frequency for the waveguide shall be considerably higher than the equipment operating frequency. The length of the sleeve shall be no less than three times its diameter.

(4) Pilot lights shall be filtered or shielded as needed to maintain the required degree of shielding effectiveness.

(5) If possible, ventilation and drainage holes shall not penetrate radio frequency (RF) compartments. If necessary, such holes shall utilize waveguide-below-cutoff honeycomb or other appropriate screening. Care shall be taken to assure the honeycomb and screens are well bonded to the shield completely around the opening.

e. RED/BLACK equipment. Specific requirements concerning the installation of RED/BLACK equipment is contained in MIL-HDBK-232A, Red/Black Engineering-Installation Guidelines. This manual will provide the general requirements expected to provide interference protection for signals generated from these installations.

(1) Physical barriers should be provided at the perimeter of the facility to ensure that the earth electrodes are not degraded or tapped, or that pickup devices are not introduced into the system.

(2) Each RED/BLACK facility should use a facility entrance plate with all conductors entering the facility passing through this plate. The entrance plate should extend approximately one foot from the nearest conduit or cable penetrations. All signal cables entering the facility should be shielded, with the shield circumferentially bonded to the plate. These cables should be either filtered or isolated and protected by surge arresters or other protective devices. The entrance plate should be bonded to the earth electrode subsystem using two #1/0 AWG cables.

(3) Internally the interference barrier between RED and BLACK equipment consists of physical separation, shielding of cables, and encrypting or filtering signal lines which connect the RED/BLACK equipment. All equipment shields should be grounded to the equipotential plane at every convenient point.

4-4. Typical components and installation details

Typical components and installation details for electromagnetic interference (EMI) protection systems are described below.

a. Shielding. Coupling is defined as the means by which a magnetic or electric field produced by one circuit induces a voltage or current in another circuit. Interference coupling is the stray or unintentional coupling between circuits, which produces an error in the response of one of the circuits. An effective means for the reduction of coupling is the use of shields around the circuits and around interconnecting lines.

(1) To determine the shielding required at a facility, the EM environment at the planned location should first be surveyed. The threat should be compared with the response properties or susceptibilities of the equipment to be located in that environment. If a need for shielding is indicated, then it should be provided either as a part of the facility or the equipment shielding should be upgraded.

(2) Conduct an EM survey at the facility location using the proper equipment and experienced personnel, examine the history of performance of the similar equipment at other sites with comparable environments, and consider the measured EMI characteristics of the equipment.

(3) Determine the amount of shielding necessary. If the measured signal strength is greater than the susceptible level, arrange to provide the extra shielding necessary either as part of the structure or building or require that the equipment's shielding be upgraded. If susceptibility data is not available, make a best estimate of the amount of required shielding from the historical performance of the equipment (or similar types) at other sites.

(4) Before deciding what type or how much supplemental shielding material is necessary, estimate the amount of shielding inherently provided by conventional building materials and techniques. Estimate the shielding provided by normal construction techniques (steel skeleton with brick or concrete block exterior with standard wood, gypsum board, or concrete block interior walls). Reinforced concrete offers additional shielding because of the presence of the rebar. Estimate the shielding effectiveness of single course rebar to low frequency magnetic fields.

(5) Design the shielding to conform to the needs of the system. Consider the relative ease of shielding individual equipment rather than shielding a room or the entire structure.

(6) Assure that the shielding provided is sufficient to meet system needs (both known and predicted) but do not excessively over design.

(7) Use the inherent shielding properties of the structure to maximum advantage. Employ the small amount of shielding (typically 10-20 dB) offered by reinforced concrete. However, do not expect common building materials such as brick, concrete, wood, fiberglass, or plastic to provide any significant shielding to EM signals.

(8) Locate most sensitive and most critical equipment as close to the core of the structure as operational requirements will permit.

(9) To minimize the attenuation requirements on shields, predetermine the location of likely sources of interference such as power substations, engine-generators, and RF transmitters; maximize the separation between such sources and potentially susceptible equipment or systems.

(10) Where a choice exists as to exterior skin materials for the shelter or structure (e.g., fiberglass versus sheet steel or aluminum) choose metals to take advantage of their improved shielding properties. (In order to utilize metal sidings as effective shields, seams must be electrically continuous.)

(11) Insure that shield continuity is maintained at points of entry of signal cables, power conductors, utility lines, and ground conductors.

(12) Make sure that windows, doors, and ventilation ports are shielded along with the walls. Use well bonded screen wire for windows, use metal doors, and apply honeycomb ducts or appropriate screening over ventilation ports.

(13) Equip all power lines supplying shielded areas with power line filters.

(14) Use steel conduit in preference to aluminum conduit to take advantage of the improved magnetic shielding properties of steel.

(15) Use enclosed metal wiring ducts or raceways in preference to open mesh or unenclosed types.

(16) If the only purpose of the shield is to establish a personnel barrier to prevent inadvertent contact with direct current (dc) and power frequency hazardous voltages, consider the use of non-conductive shields which may be less expensive. (If metal shields are used to provide shock protection, they must be well grounded to the power safety ground - the green wire network.)

(17) The selection of a shielding material can be done either by choosing a possible metal of a given thickness and then determining if the shielding effectiveness is equal to or greater than the field attenuation desired, or starting with desired attenuation, determining what thickness of metal sheet or what type of screen is required. Either approach is acceptable.

(a) The first step in the selection of a shield type and material is to determine the nature of the field by determining whether it is an electric field, magnetic field, or a plane wave.

(b) Compute the wavelength, or the incident signal or signals and measure the location of the sources. From this a determination is made of the incident field and the absorption and reflection loss of the material selected for a plane wave.

(c) The total shielding effectiveness is the sum of the absorption loss and the reflection loss. Consider the use of thin metal foils for shielding high frequency (broadcast frequencies and above) plane and electric fields.

(18) Employ the following installation guidelines when constructing shielded facilities.

(a) Securely ground all metal shields.

(b) All seams and joints must be well bonded. Welded seams are highly desirable in enclosures, which must provide a high degree 80 dB of RF shielding or are intended for EMP protection. Where welding is impractical, solder or knitted wire gaskets should be used to supplement the mechanical fasteners.

(c) Limit openings (windows, doors, ventilation ports) and penetrations (signal lines, power lines, utilities) to the lowest possible number and restrict their dimensions to a minimum.

(d) If holes through the shield are necessary, determine the optimum size and spacing.

(e) Use honeycomb for the shielding of ventilation ports wherever possible.

(f) Peripherally bond metallic utility lines to the shield at the point of entrance. Non-metallic lines entering through waveguide-below-cutoff ducts or tubes may also be used for water, gas, compressed air, etc.

(g) Cover all openings required for visual access with wire screen or conductive glass. Ensure that the screen or glass is carefully bonded to the enclosure around the perimeter of the opening.

(h) Doors should be metal with solid, uniform contact around the edges. Wire mesh gaskets or finger stock should be provided.

(i) For large shielded enclosures where high traffic volume is expected, consider the use of waveguide-below-cutoff hallways.

b. Bonding. Bonding is the process by which a low impedance path for the flow of an electric current is established between two metallic objects. Bonding is concerned with the 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. 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. 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.

(1) A degradation in system performance from high noise levels is frequently traceable to poorly bonded joints in circuit returns and signal referencing networks. 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 equipment are interconnected, the voltage differential represents an unwanted signal within the system.

(2) 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 EM shields is essential to the achievement of a high degree of shielding effectiveness.

(3) Interference reduction components and devices also must be well bonded for optimum performance. 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. Some metal oxides are semiconductors and behave as non-linear devices to provide the mixing action between the incident signals. Interference thus generated can couple into nearby susceptible equipment.

(4) 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. 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.

(a) 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.

(b) 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.

(5) 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.

(a) Properly constructed direct bonds exhibit a low dc resistance and provide 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.

(b) The objective in bonding is to reduce the bond resistance to a value negligible in comparison to the conductor resistance so that the resistance of the conductors primarily determines the total path resistance.

(c) 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.

(d) 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.

(6) In terms of electrical performance, welding is the ideal method of bonding. An effective welding technique for many bonding applications is the exothermic mixture of aluminum, copper oxide, and other powders. The mixture is held in place around the junction by a 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.

(a) The intense heat involved is sufficient to boil away contaminating films and foreign substances. A continuous metallic bridge is formed across the joint, and 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.

(b) 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 that will be inaccessible once construction is completed. Most metals that will be encountered in normal construction can be welded with one of the standard welding techniques

(7) 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.

(8) 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.

(a) 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. For example, it can be used to tin surfaces prior to assembly to assist in corrosion control.

(b) 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.

(9) In many applications, permanent bonds are not desired. For example, equipment must be removed from enclosures or moved to other locations that require ground leads and other connections must be broken. The most common semi-permanent 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. Examples are shown in figure 4-1.

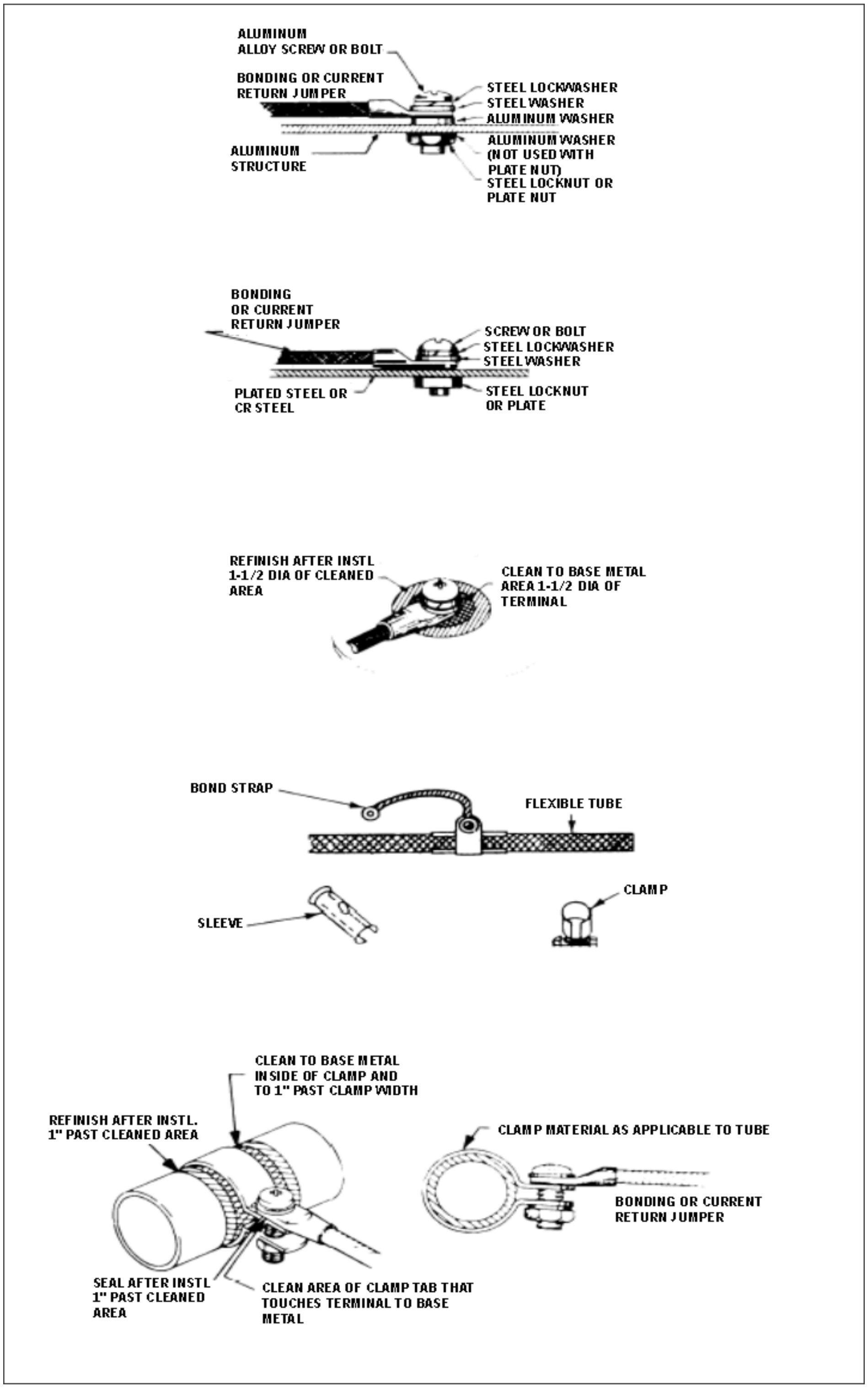

Figure 4-1. Connection of bonding jumpers to flat surface

(10) 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. Examples of riveted bonds are shown in figure 4-2.

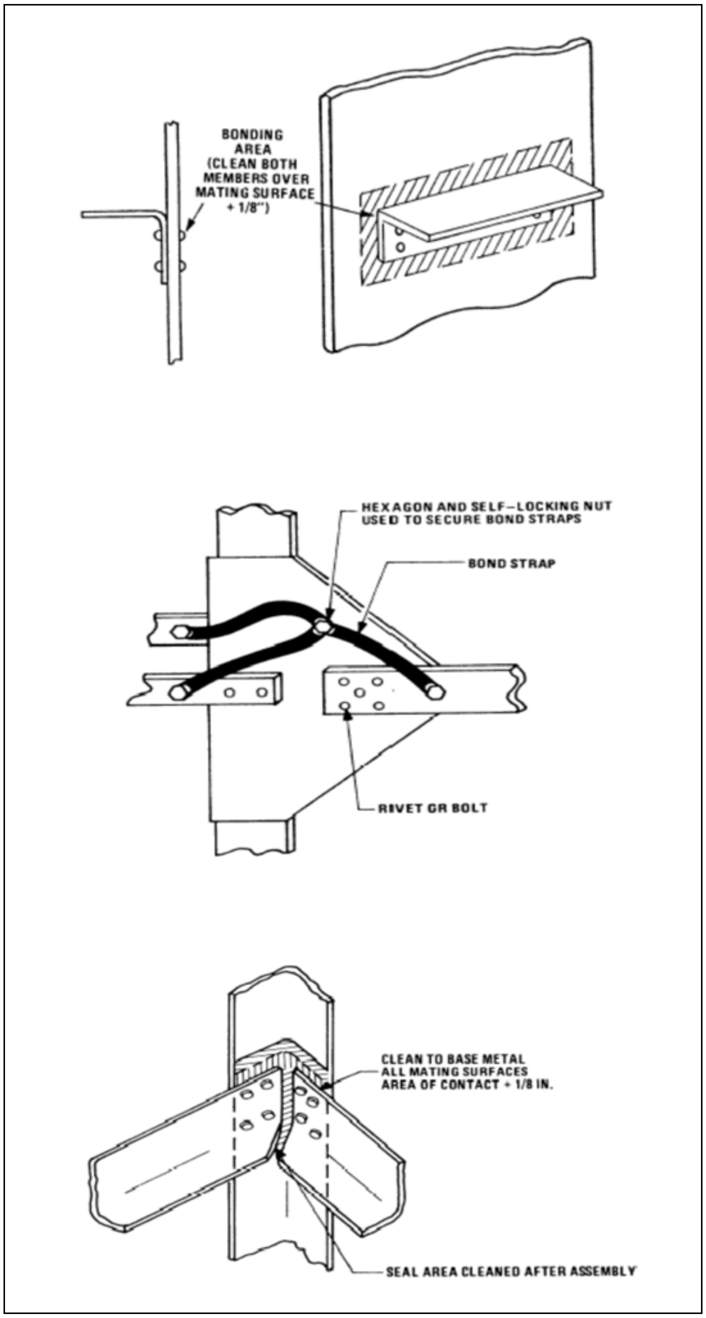

Figure 4-2. Examples of bonding

(a) 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.

(b) For riveted joints in shields, the maximum spacing between rivets is recommended to be approximately 2 cm (3/4 inch) or less. In relatively thin sheet metal, rivets can cause bowing of the stock between the rivets. In the bowed or warped regions, metal-to-metal contact may be slight or non-existent.

(c) 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.

(11) 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.

(12) 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.

(a) Bond straps or cables are also used for bypassing 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. They may also be used to prevent static charge buildup and to connect metal objects to lightning down conductors to prevent flashover.

(b) 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. 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.

(c) Because high conductivity materials attenuate RF rapidly, high frequency currents do not penetrate into conductors very far, i.e., they tend to stay near the surface. At frequencies where this “skin effect” becomes significant, the ac resistance of the bond strap can differ significantly from its dc value.

(d) 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. Even at relatively low frequencies, the reactance of the inductive component of the bond impedance becomes much larger than the resistance. 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 of the strap is increased, its impedance increases non-linearly for a given width; however, as the width increases, there is a non-linear decrease in strap impedance. In many applications, braided straps are preferred over solid straps because they offer greater flexibility. There is no significant difference between the impedance of the braided or solid strap for frequencies up to 10 MHz. 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.

(e) 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. At low frequencies where the reactance of the strap is low, bonding straps will provide effective bonding. At frequencies where parallel resonance exists in the bonding network, straps may severely enhance the pickup of unwanted signal. 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.

(13) To achieve an effective and reliable bond, the mating surfaces must be free of any foreign materials, e.g., dirt, filings, preservatives, etc., and non-conducting 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.

(a) 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 that give off corrosive products. Filings of foreign metals can establish tiny electrolytic cells that will greatly accelerate the deterioration of the surfaces.

(b) 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.

(c) Paints, varnishes, lacquers, and other protective compounds along with oils, greases, and other lubricants are non-conductive and in general, should be removed. Commercial paint removers can be used effectively.

(d) 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.

(e) 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 plating 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.

(f) 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.

(g) 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.

(h) Corrosion by-products such as oxides, sulfides, and sulfates 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.

(14) 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.

(a) 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.

(*b)* Corrosion is the deterioration of a substance (usually a metal) because of a reaction to 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.

(c) 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. 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.

c. Entry plates. All metallic penetrations of the facility shielding should enter at a common location, and all shielded cables, conduits, and pipes should be bonded to an entry plate. This plate should be large enough so that no penetrations will occur within 1 foot of the nearest edge. The entrance plate should be continuously welded around its perimeter to the building shield. The entry plate should be connected to the earth electrode subsystem with a 1/0 AWG (minimum) insulated copper cable. The cable should be bonded to the entry plate and the earth electrode subsystem with exothermic welds. The conduit should be of steel with threaded or welded couplings. Conduit runs should be as short as practical with joints held to a minimum.

(1) Effective transient protection can be provided by peripherally bonding each RF coaxial cable to a metal bulkhead connector that in turn is peripherally bonded to the building entry plate and grounded to the earth electrode subsystem. This scheme will route transient currents from cable shields to earth ground instead of through terminating equipment to ground. Also, transient surge currents will be shunted to ground before transient energy is cross-coupled to other equipment lines in the facility. The entry plate must contain the required number of appropriate coaxial feed through connectors to terminate all applicable incoming lines. The connectors must also provide a path to ground for connected cable shields. If external and internal coaxial cables are of a different physical size, the changeover in connector size should be accomplished by the feed through connectors of the entry plate.

(2) The shields of all telephone cables entering a CE facility must be bonded to each other and to the earth electrode subsystem through the steel entry plate. This measure eliminates harmful differences of potential between the various telephone cables entering the facility. It is important that electrical continuity of all cable shields is maintained. Care must be taken to ensure that shields of aerial telephone cables are bonded to any connecting buried or underground cable shields. This provides a path to ground for lightning and power currents and provides an effective noise shield.

(3) Configuration control must be considered during the design phase. Conducting penetrations must be bonded carefully around the penetration perimeter (360 degrees) to the shield entry plate to prevent aperture coupling to the facility interior or to inner conductors of shielded cables. Non-conducting penetrations must be treated as apertures in the shield.

d. Filters. The majority of interfering signals, even if they are free-space coupled to the signal and power lines, are conductively coupled into the susceptible circuit. The proper application of filters to both the signal and power lines can reduce this coupling.

(1) It is essential to avoid signal penetration via power and signal wiring. This demands that filters achieving adequate insertion loss be installed in all incoming cables; it is fairly normal to have three-phase power circuits and several hundred signal lines going into a large enclosure. It is essential that the filters provide the specified attenuation under full-load conditions at all frequencies. Unless the filter attenuation is maintained at all frequencies and load currents, the overall shield attenuation will be degraded by the signal penetration via the filters. Shield penetrations may also be provided for air, gas, and water lines; these can be achieved either by the use of waveguide-below-cutoff tubes carrying insulating piping or by welding metal pipe to the shield. It is essential that all input circuits and penetrations occur in a localized area.

(2) All power line filter cases shall be directly bonded to the equipment case or enclosure. Filters shall be bonded to any subassembly enclosure used to maintain shield effectiveness.

(3) Filters on power, control, and signal lines shall be installed in a manner that maintains the integrity of the shield. Power line filters shall be completely shielded with the filter case. Filters on power control and signal lines shall be placed as close as possible to the point of penetration of the case in order to avoid long, unprotected paths inside the equipment. Mount filters for power and control cables inside the shield and extend the filter input terminals through the shield.

(4) DC power equipment has been found to be a significant electrical noise source that can be minimized through proper configuration of the facility, the physical and electrical isolation of the dc power equipment from communications equipment, and filtering of the output. Certain communications equipment with inverter or switching type power supplies also cause electrical noise on the dc supply leads and the ac input power leads. This noise can be minimized by the use of decentralizing filters at or in the equipment. The location, number, and termination of the dc reference ground leads are also important elements in providing adequate protection for dc systems and, at the same time, minimizing electrical noise and dc currents in the ground system.

(5) AC line filters can cause ac currents in the ground system when distributed in various areas of the facility. This is due to ac current passing through capacitors in the ac line filters when the lines are filtered to ground. Power line filters should not induce more than 30 milliamperes of current to the fault protection subsystem.

(6) Linear filters may also be used as barrier elements on penetrating wires, but at the outer (facility-level) barrier, filters are always used in combination with surge arresters. On power lines, for example, the line filter usually cannot tolerate the peak voltages, so a spark-gap surge arrester is used to limit the voltage, and the filter isolates the interior circuits from the negative dynamic resistance and shock excitation of the spark-gap discharge. The shunt input capacitance of the filter may also be used to reduce the rate-of-rise of the voltage, so that the firing voltage of the surge arrester will be lower. A variety of low-pass, bandpass, and high-pass filters are available for power and signal line protection.

4-5. Interfaces with other grounding and bonding subsystems

The grounding required for EMI protection is a part of the total facility grounding network. The ultimate path to ground is the earth electrode subsystem. Protection against EMI is imperative for sensitive electronic equipment to ensure a workable and secure system. Grounding for this protection interfaces with each of the major subsystems. The main interface is the earth electrode subsystem which in turn ties in with the fault protection subsystem, the lightning protection subsystem, and the signal reference subsystem.

4-6. Inspections and testing

Thorough inspection and testing programs are imperative to assess the effectiveness of the EMI protection measures utilized.

a. Inspections. Inspect the facility for the following.

(1) Verify that the EM survey at the facility has been properly performed and documented.

(2) Verify that shielding provided is sufficient to meet system needs (both known and predicted).

(3) Verify that shield continuity is maintained at points of entry of signal cables, power conductors, utility lines, and ground conductors.

(4) Verify that windows, doors, and ventilation ports are shielded along with the walls.

(5) Verify that all power lines supplying the shielded areas are protected with power line filters.

(6) Verify that all electrical conduit is steel inside the shielded areas.

(7) Verify that any wiring ducts are totally enclosed.

(8) Verify that all metal shields are grounded.

(9) Verify that all seams and joints are well bonded by welding, solder, or knitted wire gaskets.

(10) Verify that all metallic utility lines are bonded to the shield at the point of entrance.

(11) Verify that all openings required for visual access are covered with wire screen or conductive glass and that the screen or glass is carefully bonded to the enclosure around the perimeter of the opening.

(12) Verify that all doors are metal with solid, uniform contact around the edges.

(13) Verify that all bonds are of the type that will provide the least resistance possible for the application, preferably direct bonding with no intervening conductor.

(14) Verify that the bonding surfaces are cleaned of all such solid materials and moisture.

(15) After bonding, verify that the completed bond is sealed against the entrance of moisture into the mating region.

(16) Verify that all metallic penetrations and shielded cables through the facility shield are bonded to the entry plate.

(17) Verify that each RF coaxial cable is bonded to the entry plate with a metal bulkhead connector, which is bonded to the building entry plate and grounded to the earth electrode subsystem.

(18) Verify that the shields of all telephone cables entering the facility are bonded to each other and to the earth electrode subsystem through the steel entry plate.

(19) Verify filters specified in the design are installed as shown on the engineering drawings.

(20) Verify all power line filter cases are directly bonded to the equipment case or enclosure.

(21) Verify filters are bonded to any subassembly enclosure used to maintain shield effectiveness.

(22) Verify filters on power, control, and signal lines are installed in a manner that maintains the integrity of the shield.

(23) Verify that the power line filters are completely shielded with the filter case.

(24) Verify that filters on power control and signal lines are placed as close as possible to the point of penetration of the case.

b. Testing. Measure the bonding resistance of each bond. One milliohm or less should be the acceptable value of the resistance measured.

c. Inspection and test records. Inspection and test records shall be maintained for the facility with the periodic maintenance records and shall be used as the baseline for determining any corrective actions that be necessary as a result of unacceptable conditions found during normal routine maintenance activities.

4-7. Baseline configuration documentation

Baseline documentation shall be maintained as part of the facility records for the life of the facility. Changes to the baseline configuration shall be documented and approved by the responsible engineer. Modifications and additions to the facility shall have the same requirements for maintaining an acceptable EMI grounding configuration as the original installation.