MSFC-HDBK-3697
BASELINE
EFFECTIVE DATE: March 24, 2014

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

ES42

MSFC TECHNICAL STANDARD

ELECTRICAL BONDING DESIGN GUIDE HANDBOOK

Approved for Public Release; Distribution is Unlimited

CHECK THE MASTER LIST—VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE
at https://repository.msfc.nasa.gov/docs/multiprogram/MSFC-HDBK-3697

DOCUMENT HISTORY LOG

Status (Baseline/ Revision/ Canceled)	**Document Revision**	**Effective Date**	**Description**
Baseline	-	3/24/2014	Release was authorized by the MSFC Technical Standards Document Control Board (DCB) through the Multiprogram Document Management System (MPDMS).

FOREWORD

This handbook was written for the designer responsible for designing space vehicles or equipment that will fly on space vehicles. It is intended to aid in determining the electrical bonding requirements that are applicable to specific hardware, understanding those requirements, and preparing drawings to implement the requirements. First and foremost the designer must be aware that electrical bonding is an important aspect of the design.

The NASA Office of Primary Responsibility (OPR) for this document is Marshall Space Flight Center (MSFC), ES42, Electromagnetic Environmental Effects (E3) Team.

Table of Contents

Figures

Tables

1. SCOPE

1.1 PURPOSE

This handbook is intended as an aid to the mechanical designer in implementing electrical bonding requirements when designing space vehicles or equipment that will fly on space vehicles. It is important that the designer knows and understands the requirements and is able to clearly communicate to the Manufacturing organization what needs to be done. The designer does not need to dictate how to perform the electrical bonding tasks, but should have an understanding of what the task entails. If there are options in how the task is performed and there is a preferred way, then the preference should be noted on the design.

1.2 ORGANIZATION

The remainder of the section is devoted to the development and flowdown of requirements in general and bonding requirements specifically. Figure 2 is a bonding design flowchart and road map showing the sections of the handbook that address each step.
Sections 4 and 5 are intended to aid in the understanding of the different bonding classifications and the things to consider for each class.

Section 6 is the “how to” section, meant to illustrate what is required on the design drawings. None of the examples are intended to influence mechanical design for any reason other than electrical bonding.

A bonding design checklist is provided in Section 7.

Appendix A provides definitions of terminology.

Appendix B provides additional information on metal cleaning processes.

Appendix C provides the list of Reference Documents.

1.3 REQUIREMENTS DEVELOPMENT AND FLOWDOWN

Before requirements can be implemented, they must be developed and flowed down to the designer. The following paragraphs are a review of the requirements development and flow-down process, which is depicted in Figure 1. As can be seen from the feedback lines, the process is iterative. As the design progresses and more knowledge is obtained, the requirements may need to be adjusted.

1.3.1 MISSION REQUIREMENTS

Mission requirements are established at the highest level and are closer to objectives (desired achievements) than requirements.

1.3.2 SYSTEM REQUIREMENTS

System requirements are developed at the System Requirements Review (SRR) culminating in the Requirements Baseline.

1.3.3 REQUIREMENTS FOR THE ELEMENT & SUBELEMENT DESIGNER (The Allocated Baseline)

Functional analysis and allocation breaks the higher level system requirements into more detailed technical requirements and constraints for the system elements. The resulting set of technical requirements for each element starts to form the allocated baseline. In addition to those allocated directly from the system level, the allocated baseline includes derived requirements such as interface constraints between elements and equipment as well as requirements provided for producibility, reliability, supportability, and the like. In the design process, these requirements and constraints will lead to the selection and control of parts, materials, and processes. When complete, the allocated baseline defines all design-to requirements for each design team or subcontractor that is responsible for the design and development of each component or other element at the bottom of the physical hierarchy.

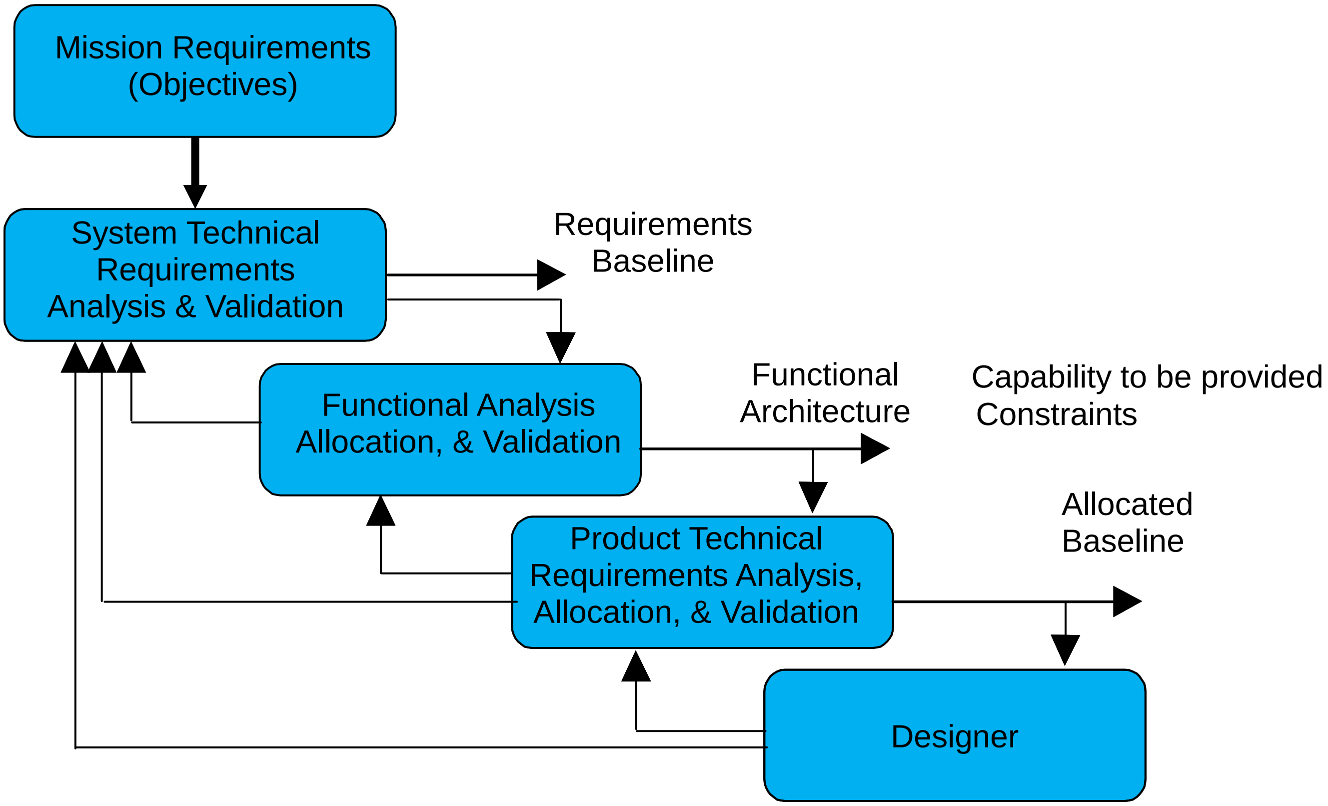


Figure 1. Requirements Development

1.4 REASONS FOR BONDING

Launch vehicles and spacecraft are exposed to a wide variety of electromagnetic environments (EME) from onboard and external sources including the following major items:

a. Electrical power and electronics equipment often require that electric currents flow in the structure, if not by design, at least through equipment faults or short circuits.

b. Lightning strikes result in large currents of short duration. These currents may flow in the structure and in any of the metallic plumbing, control cables, or wiring for the electrical/electronic systems.

c. Antennas and nearby high energy Radio Frequency (RF) sources may cause large RF currents in the structure.

A good current path (structural bond) should be provided around the outside of the vehicle to help protect internal equipment. Vehicle primary structure should be bonded together to provide, as close as possible, an equipotential ground reference for bonding and grounding. Every subassembly should have electrical continuity across mechanical joints, both within the subassembly and between the subassembly and the next higher assembly. This extends to within equipment and between equipment and system structure. Electrical bonding between equipment and structure is essential to:

a. Enable the design objectives of other methods of electromagnetic interference (EMI) suppression, such as shields and filters, to be more nearly achieved.

b. Minimize the build-up of RF voltage differences and ground current loops.

c. Deter the build-up of static charges.

d. Minimize damage which might be caused by lightning strikes.

e. Protect personnel from the shock hazard that could result if primary power were inadvertently shorted to an enclosure.

f. Avoid loss of useful range of RF communications.

g. Prevent accelerated structural metal corrosion.

1.5 GENERAL REQUIREMENTS

The NASA electrical bonding standard is NASA-STD- 4003, however each program or project may have an electrical bonding requirements document. Program/project requirement documents should not conflict with NASA-STD-4003, but they may provide more detail on some areas or omit requirements not applicable to the specific program/project. Figure 2 is a flow diagram for implementing generic bonding requirements. It also provides a road map for where each step is addressed in this document.

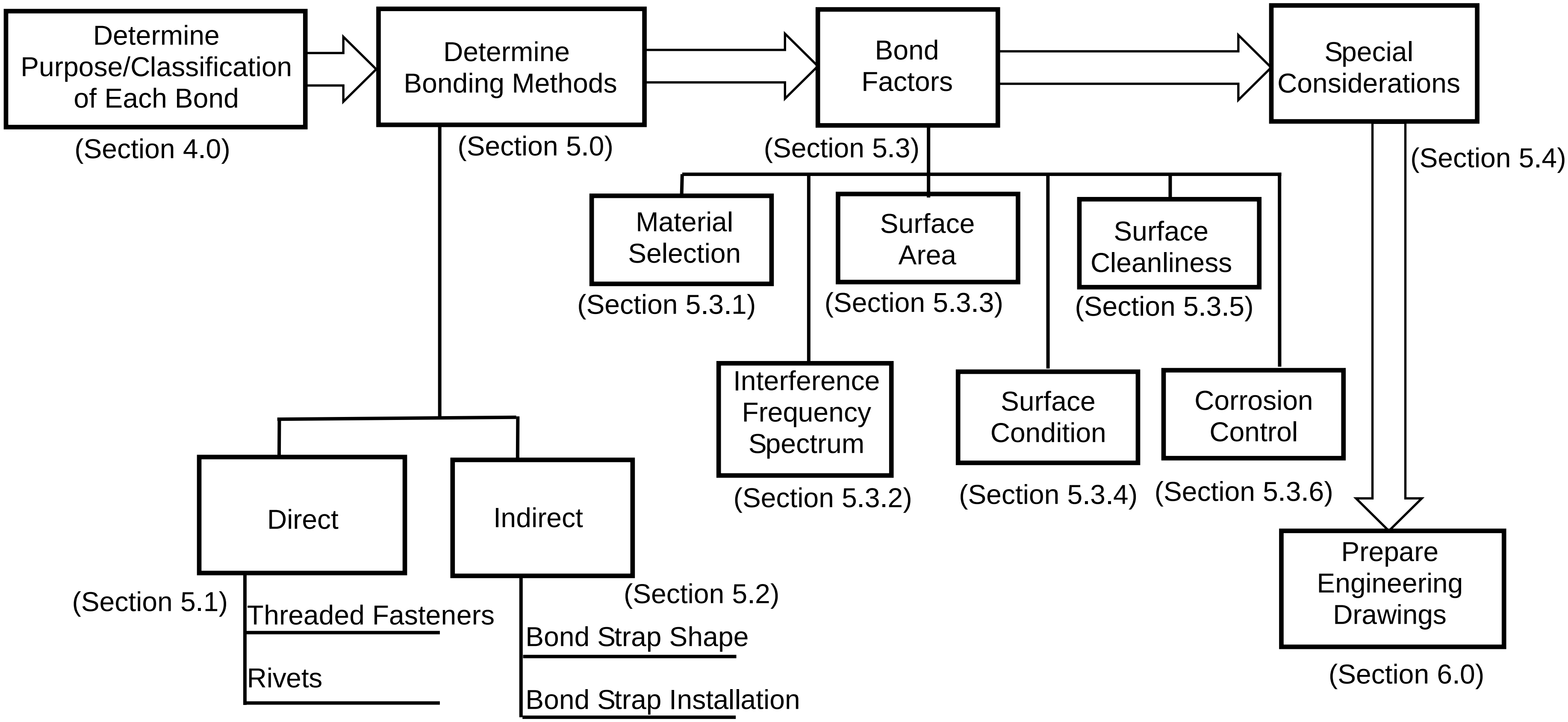


Figure 2. Electrical Bonding Design

2. DOCUMENTS

2.1 APPLICABLE DOCUMENTS

Since this is a handbook, there are no requirements and no applicable documents.

2.2 REFERENCE DOCUMENTS

See Appendix C for Reference Documents.

3. DEFINITIONS

See Appendix A for a *Glossary of Terminology* used in the document.

4. BONDING DESIGN

The first step in designing an electrical bond is to determine its purpose. Table I shows the bonding classifications from NASA-STD-4003 along with their requirements and characteristics. In addition to electrical requirements, the designer must incorporate consideration for the mechanical, thermal, and material requirements. This can sometimes lead to compromises in individual requirements to come up with the best overall design.

Table I. Summary of Electrical Bonding Classes

	Power Return	**Shock Hazard**	**Radio Frequency**	**Lightning**	**Electrostatic Charge**
BOND CLASS	**CLASS "C"**	**CLASS "H"**	**CLASS "R"**	**CLASS "L"**	**CLASS "S"**
PURPOSE OF BOND	Reduces power and voltage losses. Applies to equipment & structure, which are required to return intentional current through structure.	Protects against fire or shock to personnel. Applies to equipment & structure that may be required to carry fault current in case of a short to case or structure.	Applies to equipment that could generate, retransmit, or be susceptible to RF. Includes antenna mounts and cable shield connections. Covers wide frequency range.	Applies to equipment or structure that would carry current resulting from a lightning strike.	Protects against electrostatic discharge. Applies to any item subject to electrostatic charging.
BOND REQT.	Requires low impedance & low voltage across joints to assure adequate power to the user. Jumpers and straps acceptable.	Requires low impedance & low voltage across joints to prevent shock hazard or fire due to short. Jumpers and straps acceptable.	Requires low RF impedance at high frequency. Direct contact preferred. No jumpers. Short, wide strap may be used as last resort.	Requires low impedance at moderate frequency. Bonding components must withstand high current. Straps and jumpers must withstand high magnetic forces.	Allows moderate impedance. Jumpers and straps acceptable.
DC BOND RESISTANCE REQT.	Bonding resistance requirement depends on current.	Bonding resistance requirement, 0.1 ohm or less. Special requirements when near flammable vapors.	Bonding resistance requirement, 2.5 milliohms or less. Low inductance required.	Bonding resistance requirement depends on current. 500 volts or less across any joint. Low inductance required.	Typical bonding resistance requirement, 1.0 ohm or less.
FREQ. REQT.	Low	Low	High	High	Low
CURRENT REQT.	High	High	Low	High	Low
	Low frequency bonds allow use of straps and jumpers. High frequency bonds require low inductance paths. Short straps sometimes acceptable. High current bonds require large cross sectional areas. Low current bonds allow use of small contact areas.				

4.1 POWER CURRENT RETURN PATH (CLASS C) BONDING

Most systems, especially large systems with concerns for EMI, require a dedicated power return. Requirements for controlling system voltage drops due to using structure as a return will not be addressed here. Implementation of Class C bonds will be the same as for other classes except some coordination with power distribution designers may be required to address voltage drops.

The two main criteria for power current return paths are the contact surface area of the bond must be large enough to carry the expected magnitude of current and the system total voltage drop must be controlled. The mechanical designer is only concerned with the contact surface area of the bond interface and the size/length of any bond straps.

4.2. SHOCK AND FAULT PROTECTION (CLASS H) BONDING

The intent of a Class H bond is to prevent the exposed case or chassis of any electrical equipment from becoming a shock hazard and to carry any fault current until the upstream protective device opens. To achieve this, the resistance between the chassis and structure must be low (less than .1 ohm per NASA-STD-4003) and the contact surface area must be large enough to carry the fault current without creating a fire hazard. Additional guidance for Class H bonding can be found in NASA-STD-4003A, A.3.3, and MIL-STD-464C, A.5.11.4.

4.3 RADIO FREQUENCY (RF) (CLASS R) BONDING

The primary purpose of a Class R bond is to allow methods of EMI suppression, such as shields and filters, to perform their function. Historically, the Class R bond has been associated with a 2.5 mohm resistance across each bonding joint. The resistance of a bond joint does not change with frequency. Unfortunately, there are no purely resistive joints in the real world. All circuits, including bonding paths, contain elements of capacitance and inductance that have reactances that vary with frequency. Impedance is the combination of resistance, capacitive reactance, and inductive reactance. (A more detailed description of impedance is provided in Appendix A.) The effectiveness of a bond at radio frequencies cannot be measured in terms of its DC electrical resistance. As frequencies get higher, the capacitance and inductance of the bond come into play. Measuring the DC resistance of a bond is relatively easy with a Micro-Ohmmeter, but it is impractical to measure impedance in the field. Designing for maximum metal-to-metal contact area will ensure minimum DC resistance and RF impedance. Faying surfaces must be free of nonconductive coatings, finishes, corrosion, or foreign matter. Conductive coatings or finishes may be applied for corrosion protection. Measuring less than 2.5 mohms is a good indication of the quality of the mechanical joint. RF bonding by means of metallic straps, braids, or jumpers is not acceptable unless a direct, metal-to-metal RF bond cannot be realistically obtained by any other means (i.e., where shock mounts are necessary). Coordination with the electrical designer and the E3 engineer may be required to determine a system’s frequencies of interest and the equipment that might generate these frequencies or be susceptible to them.

4.4 LIGHTNING PROTECTION (CLASS L) BONDING

When bonding for lightning, the main concern is with resisting the effect of the massive currents of a lightning strike, not controlling electromagnetic interference levels. However, the high currents and fast rise times can produce magnetic and electric fields that can couple into sensitive equipment, if not protected. Lightning current usually enters one extremity of the vehicle and exits at another extremity. Lightning current is high and voltages developed across joints are high enough to arc and jump to an unintended path seeking an exit point. A good current path should be provided around the outside of the vehicle to help protect internal equipment. The majority of the current can be kept external to the vehicle through good electrical bonding of the vehicle skin. Major parts of the vehicle should be bonded to the ground plane so that sparks cannot jump from one metallic structure to another within the vehicle. This is particularly important in areas around fuel or pyrotechnics. Fuel and pyrotechnics should be completely enclosed by a Faraday cage of conductive material bonded to structure to provide an adequate margin against ignition. Wires to pyrotechnics should be shielded and the shields should have 360° terminations to the connector backshell which is in turn bonded to the metal enclosure. Bonds should be capable of carrying several hundred amps steady current and nearly an order of magnitude greater current for shorter periods without heating sufficiently to be an ignition hazard. The rapid rise times of lightning strike currents are similar to those for RF currents. Because of the rapid rise time of the current, bonds must have a low enough series inductance to prevent sparking at the bond discontinuity. (Since impedance of an inductor increases with frequency, a high inductance bond path could quickly develop a very high voltage that could create an arc.) The fact that bonding jumpers have been blown apart because they were not installed properly illustrates the need for low inductance. When bonding with straps. The basic rules for using bonding straps for lightning currents are:

a. Use conductors with sufficient cross-sectional area to carry the lightning current.

b. Keep straps as short as possible, consistent with requirements for flexibility and strain relief.

c. Avoid any bends of more than 45°.

d. Avoid all sharp bends.

e. If two or more straps are used, separate them sufficiently (usually by 30 cm. or more) to minimize magnetic force effects.

f. Do not use soldered terminals. Most crimped connectors are satisfactory. Use jumpers that have been previously qualified or have them tested with simulated lightning currents.

Apertures should be kept as small as possible. Joints should be bonded in many places to prevent long slots between bonds. Perforation of panels in the vehicle skin may result if sparking from panel to panel occurs. For lightning protection, bare metal-to-metal connection between surfaces is best. Often vehicle surfaces are painted or sealed before fasteners are installed for corrosion control. Fortunately, insulating films are often broken during installation and the large number of fasteners required to meet mechanical requirements helps to limit current through any one fastener. Joints near flammable liquids or vapors are considered hazardous and must be given special attention.

4.5 ELECTROSTATIC DISCHARGE (ESD) PREVENTION, (CLASS S) BONDING

For ESD to occur, an electrostatic charge imbalance must be present between two surfaces creating a potential difference (voltage) that exceeds the dielectric breakdown threshold of the medium between the surfaces. Providing a low resistance path to ground will prevent the accumulation of charge on a surface. Most bonding requirement specifications require conductive items greater than some size to have a secure mechanical connection to vehicle structure.

NASA-STD-4003 requires conducting items, except active antenna elements, having any linear dimension greater than 7.6 centimeters (cm) to have a connection to structure of 1 ohm or less. A limit of 1 ohm is used as a requirement because it is easily obtained with good contact between conductive surfaces. Static charges can usually be dissipated through less conductive connections. Higher DC resistance values acceptable for Class S electrical bonds may be established through performance of a detailed analysis to determine the amount of stored energy on the item to be bonded as a function of the proposed electrical bond resistance. Additional information on electrostatic discharge control is provided in appendix A.3.6 of NASA-STD-4003A.

5. BONDING METHODS

There are two types of bonding: direct bonding, where there is metal-to-metal contact between the members to be bonded; and indirect bonding through the use of conductive jumpers or straps. Equipment and structure with metal-to-metal joints that are joined by processes that transform the mated surfaces into one piece of metal, such as by welding or brazing, are considered permanent and are inherently bonded. Semi-permanent joints held together by screws, rivets, clamps, etc., are also considered direct bonds.

5.1 DIRECT BONDING

Direct bonding, i.e. faying surface to faying surface, is always preferred. Bonds should have good metal-to-metal contact over the entire mating surfaces of the bond joint. The contact areas should be clean with all non-conductive coatings removed prior to assembly. If possible the primary current path should be established across the metallic interface. When metallic items are directly bolted together, maximum metal-to-metal contact area ensures minimum DC resistance and RF impedance, and allows ground currents to flow over maximum contact area. A small bonding surface with a high contact pressure can produce a very low resistance, but a larger surface area will provide a better RF bond and better current carrying capacity. The larger surface area will require more or larger fasteners to maintain the low resistance. The fastening method must exert sufficient pressure to hold the surfaces in contact in the presence of deforming stresses, shock, and vibrations associated with the equipment and its environments. More fasteners around the periphery of a box lid or vehicle seam will reduce the size of apertures, increasing shielding efficiency. Joints that are press-fitted or joined by self-tapping or sheet metal screws cannot be relied upon to provide a low-impedance bond at high frequencies. A typical installation of a piece of removable electrical equipment is shown in Figure 3.

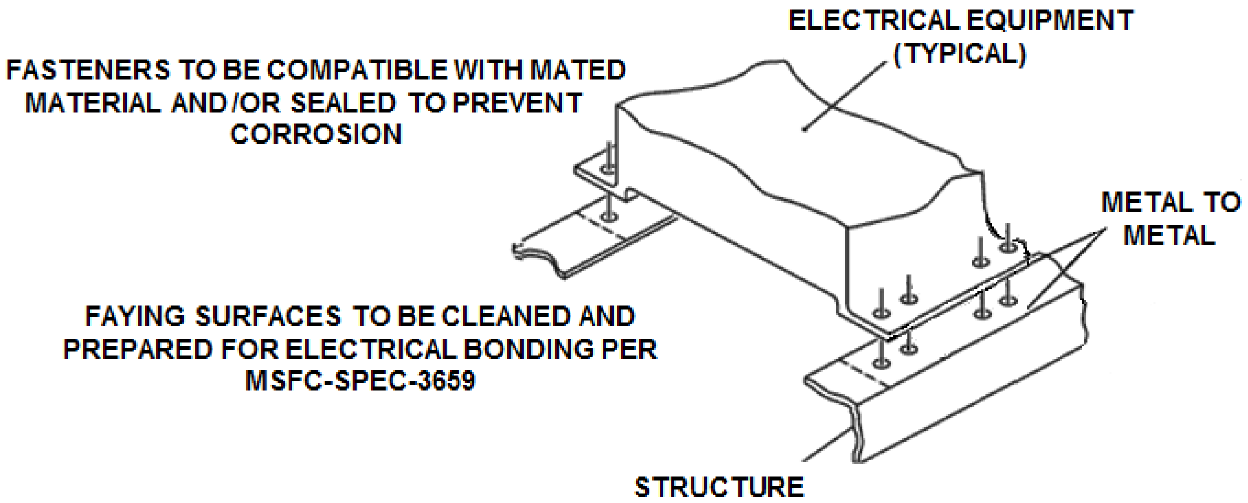


Figure 3. Direct Bonding of Removable Electrical Equipment

5.1.1 THREADED FASTENERS

Fasteners should be primarily used to maintain pressure on faying surfaces. Threads of individual fasteners are not acceptable to fulfill bonding requirements. Single high-strength steel bolts are relatively poor conductors due to their alloying materials. NASA-STD-4003 allows the use of multiple fasteners (e.g., bolts, nuts, or studs) for some applications. One example is large mating flanges, with many fasteners, where the sum of many small contact values is sufficient and can provide a better RF bond path than a strap. Multiple fasteners may perform better than straps for Class L and R applications. The inductance of multiple bolts between otherwise isolated materials may be less than the inductance of a strap between surfaces. The use of bolts as part of the bond path, requires an analysis to be performed showing that the number of bolts used in the path is sufficient to provide a low impedance path. Fasteners should be sealed against moisture and air to prevent corrosion of the threads. Wet installation of fasteners is not required except in applications where condensation or aqueous corrosive environments exist. Because of the poor reliability of screw thread bonds, self-tapping screws are never to be used for bonding purposes. Likewise, Tinnerman spring nuts (speed nuts), because of their tendency to vibrate loose, should not be used for securing screws or bolts intended to perform a bonding function. Mechanical and adhesive locking features are the best options for preload-critical joints but should not be relied upon to maintain preload. Proper joint design is necessary to maintain preload in dynamic environments. A good reference for threaded fasteners is NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware.

5.1.1.1 Washers

Washers are primarily used as a seat to distribute load, but they may also provide spring tension, span oversize holes, insulate, seal, or provide electrical connection. Various kinds include flat, conical, and helical-spring washers, tooth or ribbed lock washers, and special-purpose washers. Tooth or ribbed lock washers (star washers) are generally prohibited from flight applications as they can damage surfaces and allow corrosion to develop or generate foreign object debris (FOD).

Helical-spring (split-ring) washers are allowed on many projects, but their locking properties are questionable, since when flattened, they become equivalent to a flat washer.

When used in electrical bonding applications, washers should:
a. Be conductive,

b. Ensure adequate surface area contact,

c. Prevent corrosion,

d. Provide contact pressure, and

Should not:
a. Be surface treated or coated with non-conductive material,

b. Damage surfaces.

5.1.2 RIVETS

Rivets are acceptable if a minimum of three rivets are used per junction and the holes for the rivets are match-drilled. Rivets expand when set (as opposed to bolts, which neck-down when torqued). They fill their holes tightly -- guaranteeing good surface contact. 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. A number of standard documents are available for the selection, installation, and drawing callout of rivets:

a. Rivet installations are covered by MIL-STD-403. This specification covers pilot holes, deburring, countersinking, dimpling, and corrosion prevention. Other specifications for corrosion prevention of drilled or countersunk surfaces are covered in MIL-STD-171.

b. Design and selection requirements for blind structural rivets are given in NASM33522 (appendix C).

c. Design and selection requirements for blind nonstructural rivets are given in NASM33557.

d. Information on allowable rivet strengths in various materials and thicknesses is given in chapter 8 of Metallic Materials Properties Development and Standardization (MMPDS) - 08, Structural Joints.

5.2 INDIRECT BONDING

Where the direct joining of structural elements, assemblies, and electrical paths is impossible or impractical, bonding straps or jumpers may be used. The strap type of bond connection provides flexibility, sometimes necessary because of vibration, expansion, contraction, hinges, and equipment misalignment arising from normal fabrication and installation tolerances. Bond straps or jumpers may be used to meet class "C", "H", or "S" bonding requirements, and are useful in some cases for class "L". The usefulness of bond straps for class "R" bonds is very limited, and should be used only as a last resort. Resonance between the inductance of the jumper and the capacitance between components will result in a maximum bond impedance at some frequency. The voltage buildup at resonance could result in the generation of arc discharges and strong electric-field interference at that frequency. The RF impedance of the bond, and thus its bonding effectiveness, can be increased by minimizing the case to ground spacing and the length to width ratio of the bond strap. The inductance of the bonding strap can be minimized by selecting a strap whose length is less than 5 times its width. Jumpers should be bonded directly to the basic structure, rather than through an adjacent part. Faying surfaces of bond straps are treated the same as other faying surfaces. Bond straps or wires must be sized to carry any current that may be required to flow through them (fault current). They must be fastened securely to prevent arcing or other means of electrical noise generation with movement of the strap. The jumpers should not be lower in the electro-chemical series than the bonded members.

5.2.1 BOND STRAP SHAPE (Round or Flat)

Even though a round strap would have slightly higher impedance at all frequencies than a flat strap of comparable size, it would be acceptable for most applications (other than Class R). For Class S applications bonding straps may be round or flat and do not have to meet the width-to-length ratio. Standard round strap configurations are detailed in MIL-DTL-83413/8C. Types D, E, and, H (with coupler) should only be used with special permission. Flat straps should comply with MIL-DTL-24749, types III or IV. QQ-B-575 for braid has been superseded by A-A-59569.

5.2.2 BOND STRAP INSTALLATION

Bond straps should be installed using methods that permit inspection, removal and reinstallation or replacement when required. Bonding straps should not impede the performance of the mounting device. They should be installed such that vibration, expansion, contraction, or relative movement incident to normal service will not break or loosen the bond strap connection. When attaching a number of jumpers to structure by means of a single fastener, place the largest terminal nearest structure; with the others stacked in order of decreasing size. Where space permits, fan the terminals. Limit the number of jumpers attached to the same fastener to 4. Do not use any non-conductive coated washers in the conducting path of a bond. Figure 4 shows a typical stackup of hardware for a bond strap installation. Figure 5 shows a typical bond strap connection to structure. Figure 6 shows one application of Belleville washers used to maintain contact pressure on a bond strap. Flat washers are optional depending on need for pressure or galvanic compatibility. When two or more bonding jumpers are terminated at the same point, they should have the same resistance requirement. However, if it is necessary to terminate multiple bonds with different resistance requirements at the same point, the bond with the lowest resistance requirement should be on the bottom of the stack.

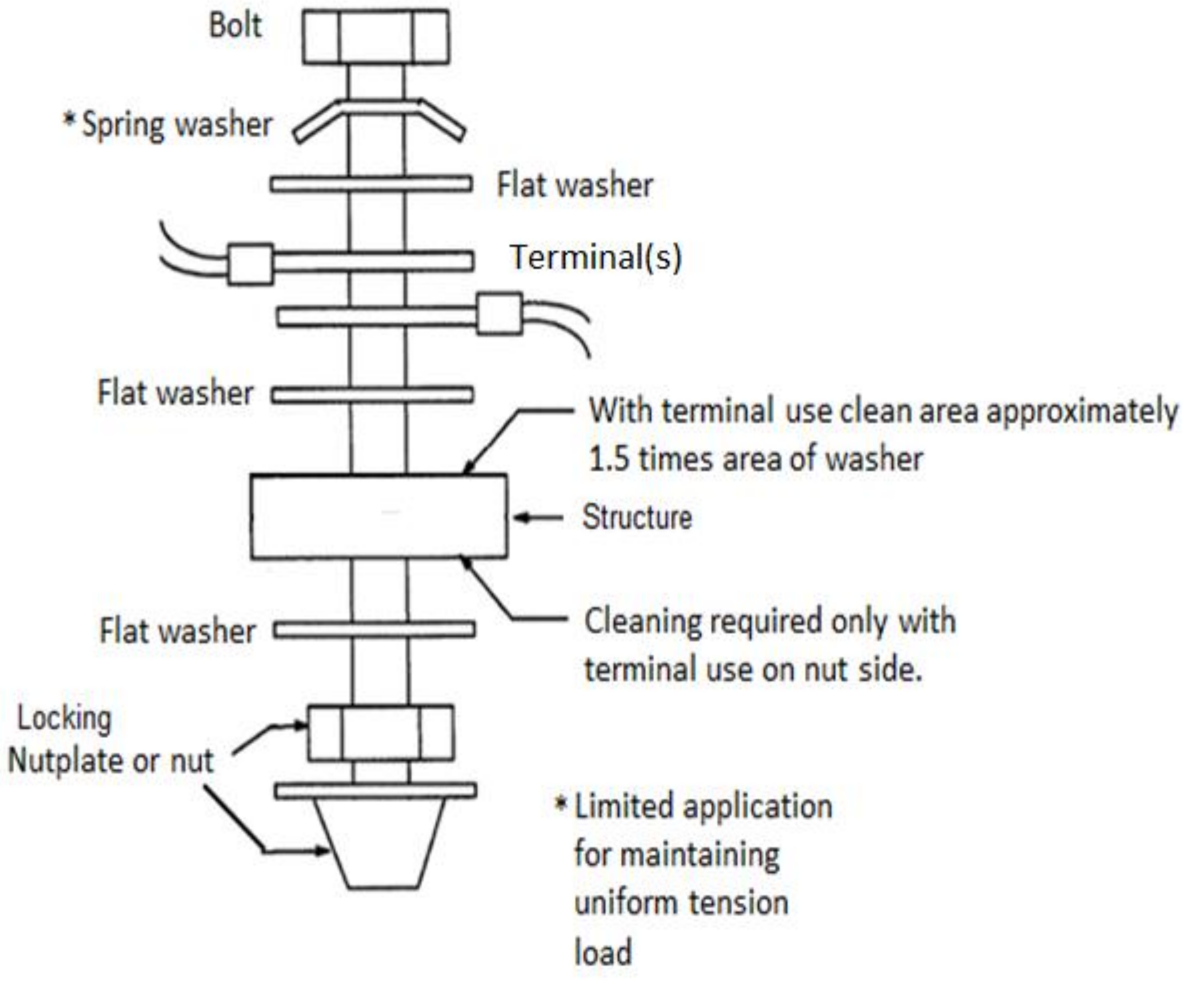
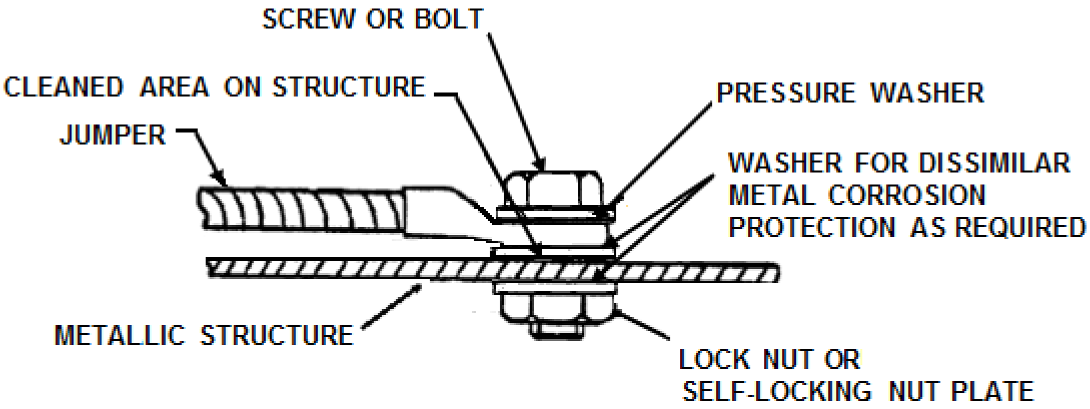


Figure 4. Order of Assembly for Bolted Connections



Surfaces of jumper terminal and mating structure must meet same requirements as direct metal-to-metal interfaces, i.e., they must be clean, galvanically compatible, and protected from corrosion.

Figure 5. Typical Electrical Bond Strap Connection to Structure

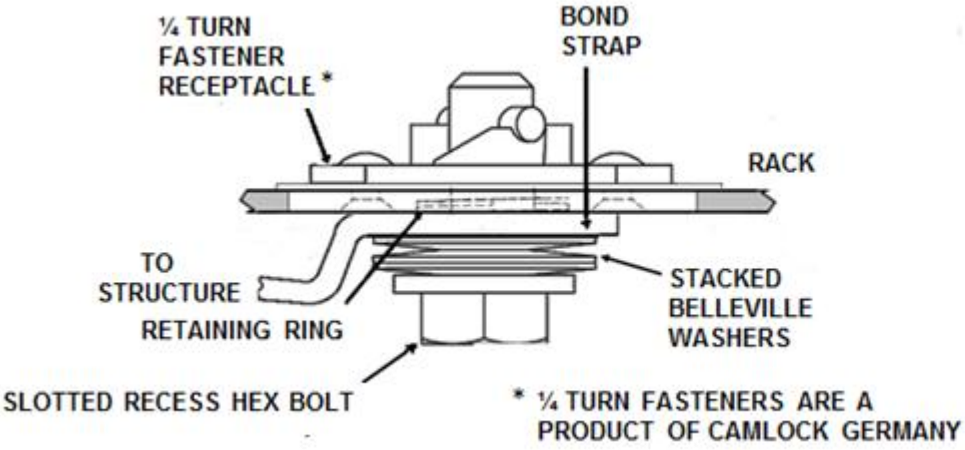


Figure 6. Use of Washers to Maintain Tension

5.3 BOND FACTORS

The effectiveness of an electrical bond for a given purpose depends on the characteristics of its application such as frequency range, magnitude of current passing through it, and environmental conditions such as vibration, temperature, humidity, fungus, and salt content in the ambient. The main factors that must be considered in electrical bonding design are:

1. Material selection

2. Interference frequency spectrum

3. Surface area

4. Surface condition

5. Surface cleanliness

6. Corrosion control

7. Special considerations

5.3.1 MATERIAL SELECTION

Electrical bonding is not generally a prime consideration in the selection of materials for a design. The function and environment in which the material must function are usually the main considerations. When these materials come together to form an assembly, then electrical bonding and corrosion protection must be considered.

5.3.2 INTERFERENCE FREQUENCY SPECTRUM

Intentional transmitters are obvious sources of interference, but practically every electronic assembly contains unintentional transmitters. Unintentional transmitters can be active devices like oscillators and amplifiers, switching devices, motors with brushes, or other devices that produce frequencies or fast rise-time pulses. Certain natural occurrences can produce sufficient electromagnetic energy to interfere with normal operation of communications, navigation, and other electronic equipment. As the frequencies get higher, a lower inductance is required to maintain low impedance. The best way to lower inductance is to maximize the surface area of the faying surfaces. It is almost impossible to get a good class R bond with a jumper or strap. The best that can be achieved is to use straps that are as short, wide, and straight as possible.

5.3.3 SURFACE AREA

Large bond mating surface areas provide more points of surface contact, creating a larger path for current flow. This means less heat generated from large currents due to fault conditions or lightning strikes and a lower impedance for higher frequencies.

5.3.4 SURFACE CONDITION

5.3.4.1 Surface Smoothness/Roughness

The real area of contact between mating surfaces is several orders of magnitude smaller than the apparent area of contact. At the microscopic level, surfaces consist of many peaks and valleys. Theoretically, two infinitely hard surfaces would only touch at three points, but, in practice, pressure, elastic deformation, and plasticity allow more points to come into contact.

5.3.4.2 Surface Hardness

Interfaces between two soft metals or between a hard metal and a soft metal will have lower contact resistance than between two hard metals with the same contact pressure.

5.3.4.3 Contact Pressure

Although there are tables that provide minimum torque requirements for bolted bonds, the joining pressure, for mechanical reasons, is usually much greater than what is required for bonding. If the fastening method exerts enough pressure to hold surfaces in contact in the presence of the deforming stresses, shock, and vibrations associated with the equipment and its environment, then it is sufficient for electrical bonding purposes.

5.3.5 SURFACE CLEANLINESS

One of the most important factors in electrical bonding is the faying surfaces must be free from any nonconductive contaminants. Finishing processes depend on a clean surface as a foundation. In selecting a cleaning operation, the process to be performed as well as the type of metal and contaminant are important considerations. All mating surfaces which comprise both direct and indirect bonding connections should be chemically and/or mechanically cleaned before joining to remove dust, grease, oil, moisture, nonconductive protective finishes, and corrosion products. There are many cleaning methods available. Any approved method or methods that remove all nonconductive material from the mating surface is acceptable for electrical bonding. The mildest form of cleaning that will accomplish the task should always be selected. The cleaning process for electrical bonding should meet the requirements of MSFC-SPEC-3659. Descriptions of some of the more common cleaning methods are provided in Appendix B.

5.3.5.1 Cleaning Precautions

The selection of a cleaning process must be based on the metal being cleaned as well as the non-conductive material to be removed. Metals such as aluminum and magnesium require special consideration because of their sensitivity to chemicals. Aluminum is dissolved rapidly by both alkalis and acids. Magnesium is resistant to alkaline solutions with pH values up to 11, but is attacked by many acids. Copper is merely stained by alkalis, yet severely damaged by oxidizing acids (such as nitric acid) and only slightly by others. Zinc and cadmium are damaged by both acids and alkalis. Steels are highly resistant to alkalis and damaged by essentially all acidic material. Corrosion-resistant steels (stainless steels) have a high resistance to both acids and alkalis, but the degree of resistance depends on the alloying elements. Titanium and zirconium have come into common use because of their excellent chemical resistance. These two metals are highly resistant to both alkalis and acids with the exception of acid fluorides which damage them rapidly and severely. Chlorinated solvents should not be used to clean titanium surfaces. (Trichlorotrifluoroethane per MIL-C-81302 is not considered a chlorinated solvent for cleaning titanium.) Cleaning methods or solutions should be used only long enough to remove the finish and not abrade the underlying metal surface. Speed of removal is not the most important factor. Removal without damage to the surface or creating a condition which can lead to future corrosion damage and providing a surface suitable for finish reapplication are the most important factors. Where there is significant time between cleaning and finishing or between various finishing steps, suitable precautions to maintain cleanliness and prevent corrosion should be observed. Approved cleaning and surface preparation processes should be documented in the project's Corrosion Prevention and Control Plan. If this is not the case, then proposed cleaning processes should be coordinated with the Materials and Processes representative.

5.3.5.2 Chemical Cleaners and Solvents

All cleaning fluids and other chemicals must be compatible with the hardware being cleaned. Practically all chemical removers are toxic to skin, eyes, and respiratory tract. Precautions must be taken to protect worker's skin and eyes and nearby hardware from damage.

5.3.5.3 Metal Particles

Fabrication and assembly procedures should be established which preclude the retention of metal particles or pieces such as chips, slivers, rivets, bolts, tools and filings in structures for which no access exists or is afforded to the manufacturer for their removal. A vacuum cleaner providing strong suction should be employed for frequent cleaning operations in relatively inaccessible areas. Metal cutting or filing should not be performed on any assembly after it has been accepted, without specific documented approval of the cognizant authority.

5.3.5.4 Metallic Wool

Metallic wool selected for use on a particular material surface should be galvanically compatible with the material. The use of steel and aluminum wools is not recommended per NASA-STD-6012.

5.3.5.5 Wire Brushes

In general, the use of wire brushes is restricted to the same alloy type, e.g., carbon steel brushes on carbon or low-alloy steel structures. CRES brushes may be used on other alloy classes, provided that use of that brush is restricted to a single alloy or is appropriately cleaned, rinsed, and dried before use on a different alloy.

5.3.5.6 Other Abrasive Materials

Aluminum and fiber wool or bristles, fine grain aluminum oxide abrasive paper, cloth or pads or other non–metallic abrasives may be used for localized cleaning provided that any given abrasive is restricted for use on a single basic alloy. Dry abrasive blasting, motor-driven wire brush, or motor-driven abrasive disc finish system removal on steel and titanium alloy surfaces may cause sparking. Abrasive cleaning tools are not authorized on components where ESD sensitive devices are installed.

5.3.6 CORROSION CONTROL

Controlling corrosion is important because, not only does it degrade electrical bonds, it impacts the structural integrity of the vehicle. All parts, assemblies, and equipment, including spares, should be finished to provide protection from corrosion in accordance with the requirements of NASA-STD-6012, Corrosion Protection for Space Flight Hardware. Design for corrosion control must include consideration of proper material selection, finish selection, drainage, application of sealants and corrosion-inhibiting compounds, and environmental issues. Selection of materials to avoid dissimilar metal contact cannot always be accomplished due to weight, cost, and functional issues. Controlling the presence of moisture is usually the most effective means of preventing corrosion. Applying protective surface treatments is another. Unfortunately, all protective surface treatments are not conductive and some should not be used where electrical bonding is required. In case of conflict between corrosion control and electrical bonding requirements, it is imperative that the conflict be resolved as early in the design process as practical. In the event of a compromise, continuing maintenance instructions should be written to ensure any necessary periodic inspection and service or treatment of the affected bond(s).

5.3.6.1 Galvanic Corrosion

When two dissimilar metals make contact in the presence of an electrolyte (usually water) an electrochemical difference is created which causes electrons to flow and ions to be created. These ions combine with oxygen or other elements to create corrosion products. All metals have a particular potential (when measured in the same electrolyte, usually sea water) and there are many galvanic series charts available that rank metals from the most passive (Most cathodic, noble, or resistant to corrosion), to the most active (most anodic, less noble, easily corroded). The safest action for the designer is to consult with M&P on the compatibility of materials where there is a lack of experience and knowledge gained of the behavior of dissimilar metal combinations in field service. Galvanic couples for material combinations should not exceed 0.25 volts. For more information concerning corrosion control of dissimilar metals, consult MIL-STD-889 or NASA-STD-6012. There is a table in NASA-STD-6012, and other tables may be cited in Program/Project specific requirements. Galvanic coupling is a consideration for carbon-fiber reinforced composites when they are attached to metals or have a metal coating. In galvanic couples, carbon-fiber composites usually behave as the cathode causing the metal or coating (often a metal) to corrode. A potential difference over one volt can be expected between carbon and aluminum. Aluminum or other metal high in the galvanic series will corrode when in direct contact with graphite filament reinforced plastic (GFRP) in the presence of moisture. A dielectric coating between materials prevents corrosion but also prevents electrical contact. A metal that is nearer the more active metal in the galvanic series should be used as a conductive coating on the GFRP mating surface. Coat both the GFRP and the more active metal or just the GFRP. Never coat just the more active metal because any contact through a small break in the coating will cause corrosion more severe than through a large contact area. Tin plating or shims between aluminum and GFRP should be satisfactory. Nickel may be used for moderately long term installations if a water tight coating is applied after assembling the joint. Permanent installations with nickel to aluminum may eventually corrode. Contacts between graphite-based composites and metallic materials should be treated as dissimilar metal couples and sealed per NASA-STD-6012. Where contact between dissimilar metals cannot be avoided the following steps should be considered.

1. It is best to protect both components.

2. The most active of the metals should be replaceable.

3. Where parts are not replaceable, the electrolyte contact area of the most active metal should be larger than that of the least active metal (cathode).

    a. Because the anode is being dissolved by the electrolyte, uniform corrosion takes place over a relatively large area at a relatively slower rate, thus increasing the service life of the anode, and

    b. The small cathode areas tend to become polarized, thereby slowing or stopping the reaction.

4. Select small parts such as bolts and nuts of material compatible with the least active metal.

5. An intermediate metal can be placed between two metals that are far apart in the galvanic series.

6. If for any reason corrosion must be tolerated, the design should be such that only replaceable hardware items (such as jumpers, bolts, nuts, washers or separators, which are not part of the basic structure) are affected.

7. Preclude moisture from the joint

5.3.6.2 Surface Treatment

Both direct and indirect bonding connections require metal-to-metal contact of bare surfaces. It is frequently necessary to remove protective coatings from metals to provide a satisfactory bond. Protective coatings should be removed from an area slightly larger than the area to be bonded. Ridges of paint around the periphery of the bonding area can prevent good metal-to-metal contact. Washers or fittings must fit inside the cleaned area. Immediately prior to bonding, all chips, paint, grease, or other foreign matter must be removed with a proper cleaning solution. Removable components must be provided with a suitable conductive coating. The most common metals used in aerospace applications are aluminum alloys, steels, high-strength steels and alloys, titanium alloys, and magnesium alloys. Surface treatments for surfaces of commonly used galvanically compatible metals are described in Table II and surface treatments for dissimilar metals are described in Table III. The designer needs only to specify that non-conductive coatings are to be removed to accommodate electrical bonding, and what finish to apply to exposed areas after assembly. Manufacturing procedures should address how much finish to remove and methods for removing the finish.

Table II. Surface Treatments for Mating Surfaces of Similar Metals

METAL	FINISH	SPECIFICATION	FINISH CHARACTERISTICS
Clad and corrosion resistant aluminum	Clean and deoxidize		Mating surfaces free from non-conductive material.
Non-corrosion resistant aluminum	Chemical Conversion Coating	MIL-DTL-5541 MIL-DTL-81706 SAE AMS-2477	Good resistance to corrosion. Good electrical conductivity (Hexavalent chromium conversion coated parts shall not be exposed to temperatures exceeding 60 °C (140 °F)).
Stainless Steel	Passivation	SAE AMS2700 ASTM A 380	Passivation is not an electrical bonding requirement. It improves the corrosion resistance of the steel.
Steel, Iron	Tin Plating	ASTM B545. SAE AMS 2451/12 SAE AMS 2408 Caution: Tin plating per ASTM B 545, shall not be used where electrical or electronic currents are involved, unless the plating is reflowed.	If entire part is finished, plate with tin per ASTM B545. If only faying surface is finished, plate with tin using brush plating method per AMS 2451/12. Only use tin that is alloyed with at least 3 percent lead to prevent tin whisker growth.
titanium alloys, nickel alloys, or cobalt alloys	Clean, no protection required		Mating surfaces must be clean and free from non-conductive material.
Magnesium alloys	Chemical Conversion Coating	MIL-M-3171, Type I	Because of magnesium's poor resistance to corrosion, it should be avoided in the bond path if possible. Not suitable for close tolerance surfaces.

Contacting similar metals in exterior (vacuum exposure) applications on secondary structures do not require protection if adequate environmental control is provided to preclude corrosion prior to launch.

Table III. Surface Treatments for Mating Surfaces of Dissimilar Metals

METAL		Surface Treatment
Clad, corrosion resistant , and non-corrosion resistant aluminum (See Note 2)		Chemically treat per MIL-DTL-5541, Class 3, or electroless nickel plate per AMS2404 (See Notes 1 & 2)
mated with	Low alloy steel (See Note 3)	If entire part is finished, plate with tin per ASTM B545. If only faying surface is finished, plate with tin using brush plating method per AMS 2451/12. Only use tin that is alloyed with at least 3 percent lead to prevent tin whisker growth. (Coating the steel is usually more effective than coating the aluminum to prevent galvanic corrosion between aluminum and steel.)
	Corrosion-resistance steel alloys	Passivate per AMS2700.
	Titanium and its alloys	Protective coatings not normally needed for corrosion protection.
	Copper and copper alloys	If entire part is finished, plate with tin per ASTM B545. If only faying surface is finished, plate with tin using brush plating method per AMS 2451/12. Only use tin that is alloyed with at least 3 percent lead to prevent tin whisker growth.
Low alloy steel (See Note 3)		If entire part is finished, plate with tin per ASTM B545. If only faying surface is finished, plate with tin using brush plating method per AMS 2451/12. Only use tin that is alloyed with at least 3 percent lead to prevent tin whisker growth.
mated with	Corrosion-resistance steel alloys	Passivate per AMS2700.
	Titanium and its alloys	Protective coatings not normally needed for corrosion protection.
	Copper and copper alloys	If entire part is finished, plate with tin per ASTM B545. If only faying surface is finished, plate with tin using brush plating method per AMS 2451/12. Only use tin that is alloyed with at least 3 percent lead to prevent tin whisker growth.
Corrosion-resistance steel alloys (See Note 3)		Passivate per AMS2700.
mated with	Titanium and its alloys	Protective coatings not normally needed for corrosion protection.
	Copper and copper alloys	No protection required for stainless steel coupling.

Notes:

1. Chemical conversion coatings are typically only used between mechanical assemblies that require infrequent disassembly. Mechanical assemblies with removable bonding surfaces should have a more durable finish, such as nickel plate.
2. Corrosion resistant aluminum alloys include aluminum alloys 1100, 3003, 5052, 5056, 5086, 5356, 5456, 6053, 6061, and all clad alloys. All other aluminum alloys are considered non–corrosion resistant aluminum alloys.
3. Steels having 12 percent or more effective chromium are considered to be corrosion resistant steels. Steels having less than 12 percent effective chromium are considered to be non–corrosion resistant steels.

Effective chromium equals total percent chromium minus (11 times percent carbon).

$$\text{Effective Cr} = [\%\text{Cr} - 11(\%\text{c})]$$

Do not use any conductive paints to establish an electrical or RF bond. Such methods are prone to disruption, disturbance and damage during routine or special maintenance. The requirements for, and the application of, protective finishes, including cleaning prior-to application, should be in accordance with NASA-STD-6012, with the exception of zinc, cadmium, and pure tin finishes which are prohibited.

Due to recent concerns about the health impact of hexavalent chromium compounds used in the chemical conversion coating of MIL-DTL-5541, alternative coatings have been developed and approved. New non-hexavalent chromium based processes are currently being evaluated. Table IV lists some of the recently approved alternatives to hexavalent chromium chemical conversion coatings.

Table IV. Hexavalent Chromium Alternatives

Alternative Coating	Description
Alodine T 5900	Non-hexavalent chrome complex conversion coating. The treated metal surfaces will possess a blue to blue iridescent or blue to gold iridescent coating color.
Iridite NCP	Does not contain Lead, Cadmium, Chromium (hexavalent or trivalent), Mercury PBB or PBDE compounds.
Metalast TCP-HF	Trivalent chromium chemical conversion coating light colors; passed all QPL testing to MIL-DTL-81706-B for immersion applications.
Metalast TCP-HF EPA	EPA (Extended Protection Additive) An anti-corrosion and paint adhesion to metal agent.
SurTec 650 ChromitAL	Trivalent chromium chemical conversion coating. Produces an iridescent, faintly blue to tan and visible layer
OXSILAN AL-0500	Conversion coating free of both hexavalent and trivalent chromate ions

5.3.6.3 Sealing of Bond Joints

In lieu of coating with a primer, permanent dissimilar metal joints may use wet faying surface sealing with epoxy primer to obtain a corrosion resistant joint and electrical bonding. An unbroken (perfect) coating on the surface of the metal will prevent the electrolyte from connecting the cathode and anode so that no corrosion will occur as long as the coating is unbroken. For equipment with neither hermetic sealing nor pressurization, protection from fluid intrusion is achieved by the application of a polysulfide or a Room Temperature Vulcanizing (RTV) sealant. Polysulfide is most resistant to fluid attack, but one part noncorrosive RTV per MIL-A-46146 is easier to apply and remove while still providing fairly good sealing of small areas. Clear types of RTV allow visual inspection of the sealed surface; however, they are not as resistant to temperature and operational fluids. Two-part RTVs generally are used in deep cure applications (potting and encapsulating).

Because of the bimetallic couples that are inherent with the use of straps, it is essential that a sealant be applied over each junction. If the junction is frequently disassembled, corrosion preventive compound, MIL-C-16173, Grade 4, provides easily applied protection. For longer term sealing or in an area subject to abrasion, erosion or external weather conditions, a polysulfide sealant such as MIL-PRF-81733 or SAE-AMS-S-8802 is appropriate.

Appropriate sealants must be used where bonds are exposed to fuel or other solvents and chemicals, such as SAE AMS 3266. Compression bonds between compatible materials located in readily accessible areas, not subject to weather exposure, corrosive fumes or excessive dust, do not require sealing. Other materials for EMI and corrosion control, enhanced system operation and maintainability, and personnel safety may become available as the state-of-the-art advances.

If the bonding of dissimilar metals is unavoidable, the joint area should be coated after bonding with a protective sealant such as polysulfide, silicone RTV, or equivalent.
Sealing is not required for compression bonds between compatible conductors locqated in readily accessible areas that are not exposed to moisture, corrosive fumes , or excessive dust. Connections on surfaces that are and will remain unpainted may be sealed with clear lacquer.

5.3.6.4 Plated Metallic Finishes

Plated metallic finishes may be used as required for protection, or to provide special surfaces to obtain a different surface hardness, to improve corrosion resistance, to change galvanic potential, to improve electrical contact, to change heat transfer properties, or to change appearance. Prior to the application of any plating, the surfaces to be finished should be clean, and free of flaws or defects that would be detrimental to the performance or appearance of the applied plating. Some common metallic finishes are provided in Table V.

Since the intent of this document is to be a bonding handbook and not a metallurgy handbook, specifications, processes and requirements of metal plating is not addressed to any great depth. References for additional information will be provided.

Table V. Common Metal Finishes

FINISH	THICKNESS BUILDUP	SPECIFICATION	APPEARANCE	FINISH CHARACTERISTICS
Tin Plating	.0002"- .0006"	ASTM B545 and/or ASTM B339. SAE AMS 2451/12 SAE AMS 2408 Caution: Tin plating per ASTM B 545, shall not be used where electrical or electronic currents are involved, unless the plating is reflowed.	Matte	If entire part is finished, plate with tin per ASTM B545. If only faying surface is finished, plate with tin using brush plating method per AMS 2451/12. Only use tin that is alloyed with at least 3 percent lead to prevent tin whisker growth.
Nickel Plating (Electroless)	.0002"- .0016"	SAE AMS 2404 ASTM B733	Dull to bright , free from frosty areas, pin holes, porosity, blisters, nodules, pits, and other imperfections	Minimizes effects of dissimilar metal contacts, such as mild steel with unplated CRES or stainless steel in contact with other stainless steel. Not recommended for non-heat treatable metals.
Nickel Plating (Electro deposited)	.0002"- .0016"	SAE AMS 2403		
Chromium Plating		SAE AMS 2460	Bright, lustrous	High hardness Low coefficient of friction Excellent wear resistance Excellent corrosion resistance
Gold Plating (Electro deposited)	.00002"- .00150"	MIL-DTL-45204 ASTM B488 MIL-HDBK-1250 may be used as guidance to determine further precautions on gold plating for electrical use.	Yellow	Good resistance to tarnishing, chemicals and high temperature oxidation, good ductility, thermal reflectivity and electrical conductivity.
Silver Plating (Electro deposited)	.0005" min	ASTM B 700	Dull to bright	Silver plating is susceptible to attack by atomic oxygen in low Earth orbit applications, and to forming dendrites when exposed to sulfur-/sulfide-containing environments. Excellent electrical conductivity and high seizure resistance.
Copper Plating	.0001"- .0010"	SAE AMS 2418	Pink or reddish	Good resistance to corrosion. Nice appearance. High electrical and thermal conductivity. Used as an undercoat for chromium and nickel plating.
Aluminum (Ion Vapor Deposited) (IVD)	.0003” - .0010”	MIL-DTL-83488D		Corrosion protection for ferrous and aluminum alloy parts. Can be applied to copper, titanium, and stainless steel alloys to provide corrosion compatibility with aluminum structure.

5.3.6.5 Removal of Nonconductive Films or Finishes

Any nonconductive films or finishes should be removed from faying surfaces by the least invasive means possible. Any abrasive material or scraping used to remove protective finishes should produce a smooth surface without removing excessive material under the protective finish. Refer to Table VI for the nonconductive finishes that can be removed and to Table VII for conductive finishes that should not be removed.

Table VI. Nonconductive Finishes that Should be Removed

FINISH	BASE METAL	COLOR
Primers	All	Yellow or green
Topcoats	All	As specified
Anodic coating	Aluminum	Clear to black
Phosphate	Steel	Dull grey
Stains and dyes	All	Full range of colors

Table VII. Conductive Finishes That Should Not be Removed

FINISH	BASE METAL	COLOR
Alodine 600, 1200	Aluminum	Iridescent gold or brown
Alodine 1000	Aluminum	Without color
Clear Iridite	Aluminum	Without color
Nickel plate	Steel	Satin chrome bright metallic
Tin plate	Copper or steel	Bright metallic

5.3.6.6 Refinishing

After completion of the bonding and inspection requirements, when it has been necessary to remove any protective coating (e.g., anodic films, grease, oil, paint, lacquer or other high resistance coatings) on metallic surfaces, the area from which the coating has been removed should be refinished with its original finish or other suitable protective finish within 24 hours. On surfaces not requiring paint or other special finishes, a clear finish such as A-A-3165 may be used to facilitate subsequent inspection. Conductive metal platings are satisfactory without additional protection or treatment other than buffing or cleaning. If the original finish is a thin paint, measures must be taken to ensure the paint doesn't seep under the edges of bonded components and impair the quality of the bond.

5.4 SPECIAL CONSIDERATIONS

5.4.1 BONDING FOR ENCLOSURE SHIELDING INTEGRITY

Unbonded enclosure joints and seams are apertures for RF signals. Intimate contact must be maintained at joints and seams to prevent the entrance and exit of unwanted RF signals. This can be achieved through the use of closely spaced screws or bolts, or by the use of resilient conductive gaskets, or both. Conductive gaskets should be considered in the following cases:

a. Total enclosure shielding requirement >40 dB.

b. Threat/emission frequencies exceed 100 MHz.

c. Dissimilar materials used on mating surfaces of seam.

d. Machined mating surfaces are impractical.

e. Environmental (i.e., dust/vapor) seals are necessary.

The ideal gasket will bridge irregularities within its compression-deflection capabilities without losing its properties of resiliency, stability or conductivity. The surfaces of contact with the gasket should be smooth and free of oily films, corrosion, moisture, and paint. The gasket should be firmly affixed to one of the bond surfaces by screws, conductive cement, or other means, which do not interfere with the effectiveness of the gasket. The gaskets may be placed in a milled slot to prevent lateral movement when the bond is disassembled. Gaskets should be a minimum of 3mm (1/8 in) wide. Four important properties of an EMI gasket which must be considered before it is incorporated into an enclosure are: compression (or deflection), compression set, shielding effectiveness and environmental seal. It is important to understand the various types of joints in order to determine which gasket properties are most important to a particular design.

Types of Joints: There are traditionally three types of joints classified by usage:

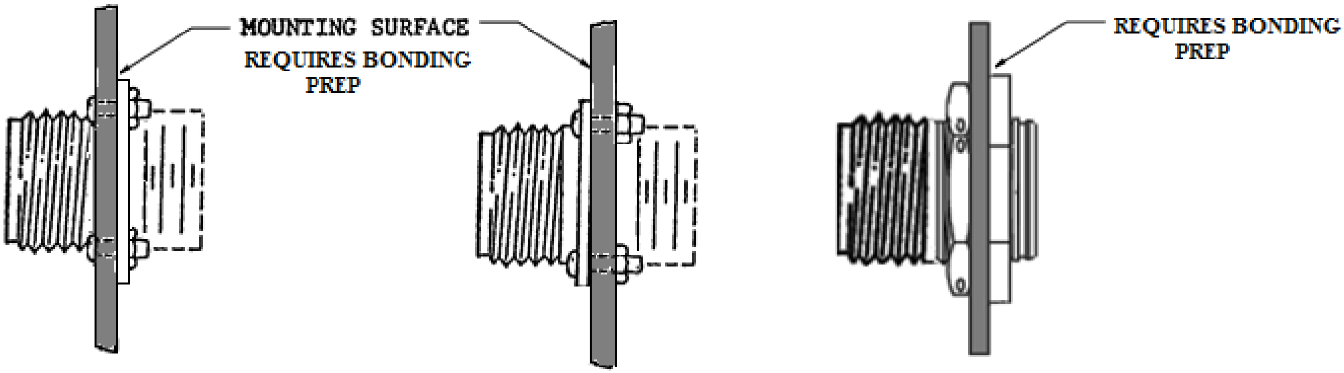
Type I Permanently mounted cover plates or assemblies. Generally compression set is not of concern in these applications even though high pressures may be encountered. The best gasket for this application is a knitted wire mesh gasket pressed to the desired gasket shape.

Type II Access cover plate with high joint unevenness which is opened frequently but always closes on the same portion of the gasket. A hinged door is an example of a Type II joint. Most of the elastomeric gaskets are suitable for this type of application where the closure pressures are under 100 psi. In the lowest closure pressures, the hollow-shaped elastomers are most suitable.

Type III Removable cover plate with a symmetrical mounting pattern which is replaceable but not necessarily in the original orientation. Gaskets for this type of application are removable and reusable. Gasket materials which exhibit low closure force and low compression set would be suitable in most applications.

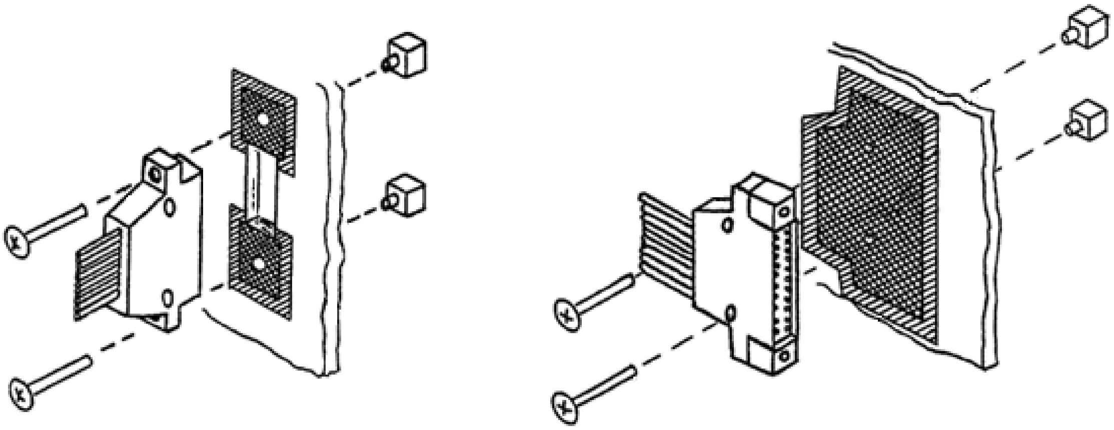
5.4.2 CONNECTORS

The connector shell should have a conductive finish and be compatible with the mounting surface. Cadmium is a common connector finish that is generally not acceptable for flight hardware, but may be acceptable for some ground applications. Connectors should be mounted so that intimate metallic contact is maintained with the surfaces on which mounted. Both the connector flange surface and the mating surface should be cleaned and prepared for bonding. After mounting of the connector, the exposed area of the mating surface should be repainted or otherwise protected from corrosion. A good (low impedance) electrical connection between the connector and the chassis or panel is essential for termination of cable shields. Figure 7 shows some commonly used connectors designating the areas that need to be prepped for electrical bonding.



FLANGE MOUNT RECEPTACLES

JAM NUT RECEPTACLE



END MOUNTED
D TYPE
CONNECTOR

SIDE MOUNTED
D TYPE
CONNECTOR

Figure 7. Mounting of Commonly Used Connectors

5.4.3 TUBES AND HOSES

With plumbing, the primary concern is with static electricity. Fluid flow is a charge generating mechanism. A nonconductive fluid flowing through a conductive pipe can impart a charge on the pipe. To prevent this, metal tubes and hoses that carry fluids must have a connection to structure of 1 ohm or less (Class S). Nonconductive fluids flowing in nonconductive tubing may transfer a charge to conductive items in the line or, if enough potential develops, a discharge may occur arcing from the fluid through the tubing to a metal sheath or other conductive item outside the tubing. This arc is capable of producing small holes in the tubing. To prevent this, use tubing with a resistivity of less than one megohm per meter of length. If the fluid in the tubing has a volume resistivity less than 10^7 ohm-meters, it is conductive enough to prevent charge buildup. In summary, all metallic tubing must be bonded, but nonmetallic tubing only requires bonding if the contained fluid is nonconductive. Conductive tubes and hoses that are in the bond path for devices that require a Class L, R, or H bond must meet those bonding requirements. Bonding in series is permitted for plumbing lines. If the plumbing line has non-conducting joints, bond each section to the structure or to the adjacent plumbing lines. Conductive tube connectors are available. Examples of bonding tubular structures are shown in Figure 8.

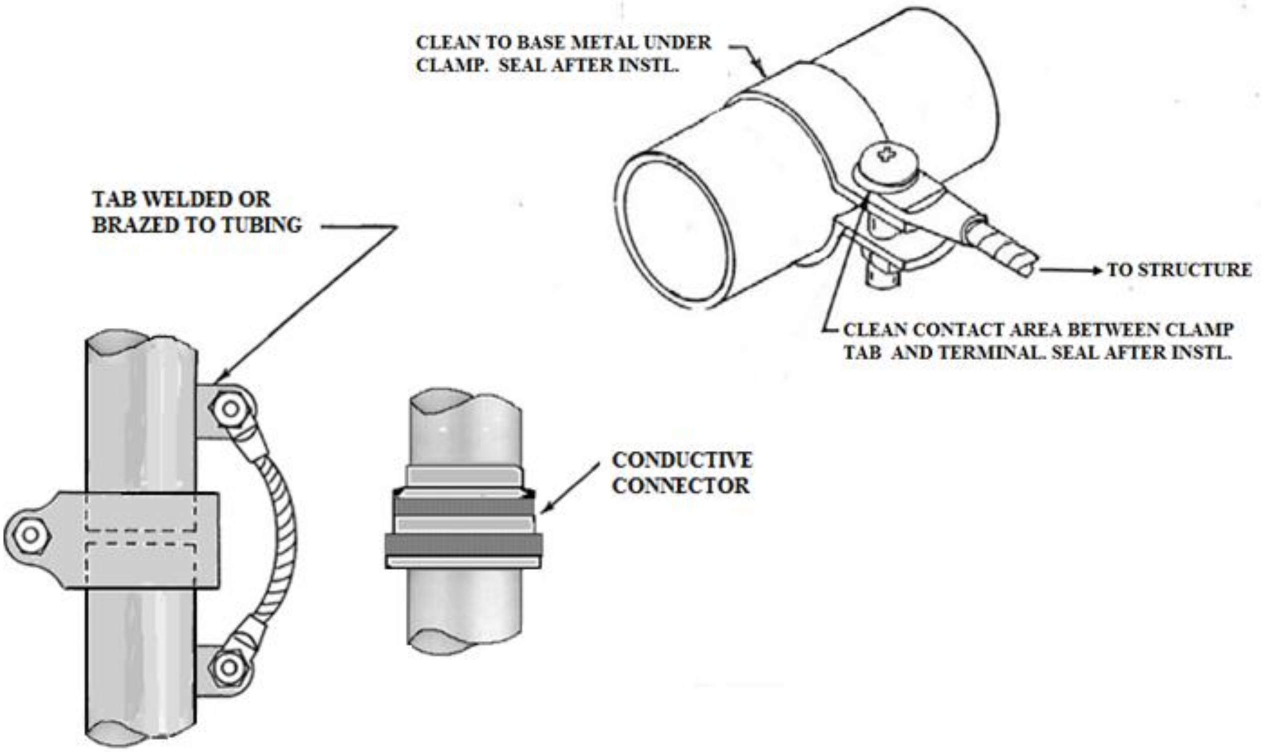


Figure 8. Methods of Bonding Tubular Sections to Each Other and to Structure

5.4.4 BONDING CLAMPS

Electrical bonding clamps should be installed such that the conduit or hose is not crimped or damaged, and that vibration, expansion, or contraction (movement that occurs during usual service) does not break or loosen the connection and change the resistance. The conduit or tubing, to which bonding clamps are attached, should be free from paint and foreign material over the entire area covered by the clamps. All insulating finishes should be removed from the contact area before assembly, and only conductive screws, nuts, and washers should be used to attach contacting parts. The clamp must make metal-to-metal contact with the piping. Clamps used for electrical bonding of pipes and tubing should be the plain type conforming to SAE AS7351 or SAE AS14244 (metric). Do not use cushion clamps, such as MIL-C-8603B and AN742 for electrical bonding. Figure 9 shows two methods of bonding clamps to structure and one method of bonding via a jumper.

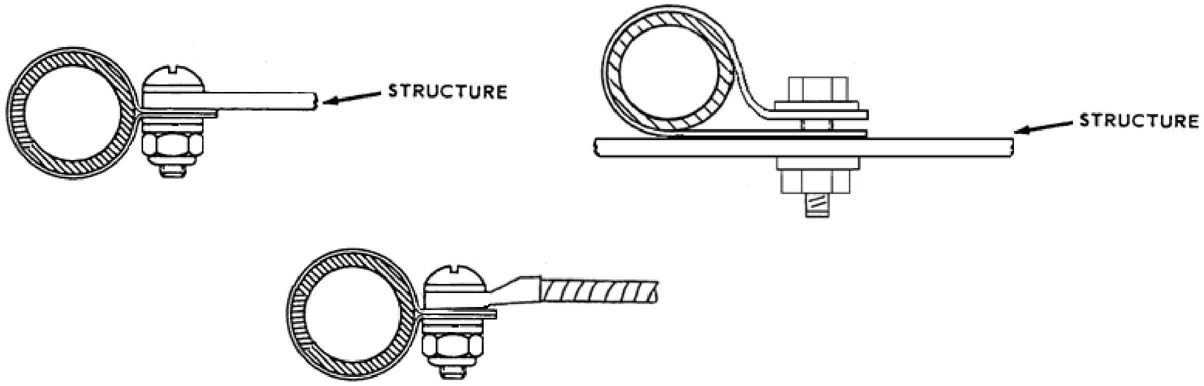


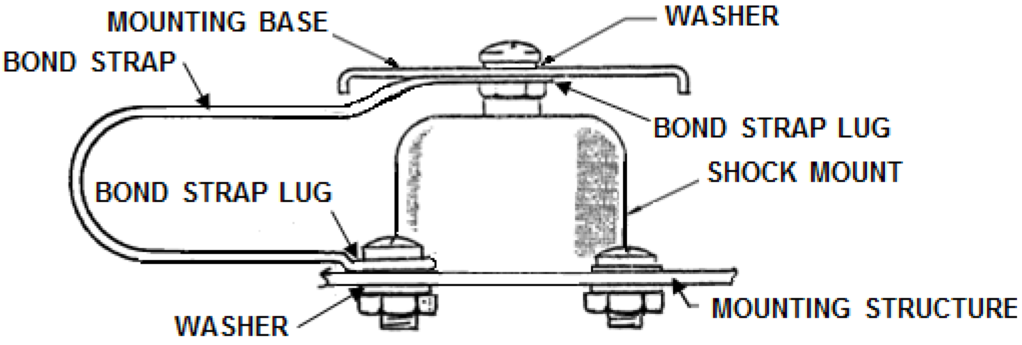
Figure 9. Three Common Methods of Bonding Tubular Clamps

5.4.5 ROTATING JOINTS

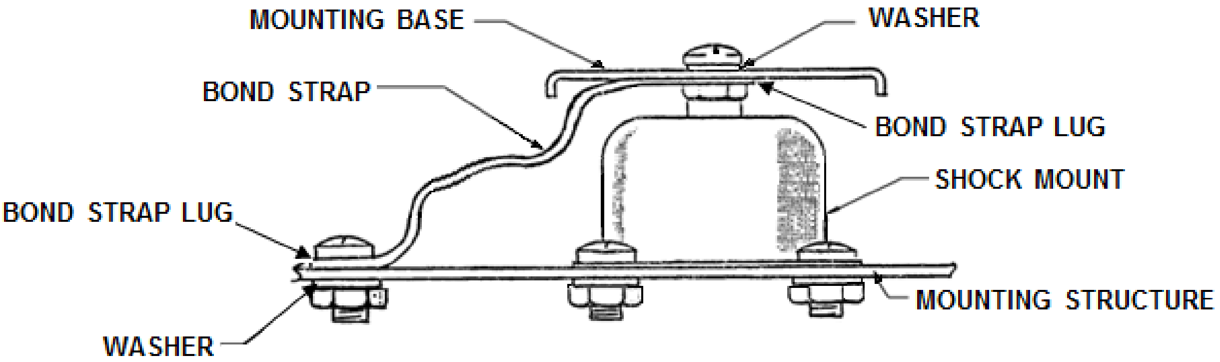
It is necessary to bond shafts of rotating machinery to prevent accumulation of static charges. Bonding is generally accomplished by use of a slip ring and brush assembly, or a phosphor-bronze finger riding directly on the shaft.

5.4.6 SHOCK MOUNTS

Bonding straps installed across shock mounts or other suspension or support devices must be capable of withstanding the anticipated motion and vibrational requirements and not impede the performance of the mounting device (See Figure 10). The designer should consider the degree of relative motion to be expected between two surfaces to be bonded, the characteristics of the materials involved, and the interference frequency range over which the bonding is required. The resiliency of the bonded mount should be determined by characteristics of the mount, not of the bond strap. In the VHF range and higher, two bond straps across each shock mount should be used.



10A. Typical Electrical Bond Strap Connection across Shock Mount Assembly



10B. Preferred Bond Strap Connection

Notes:

1. **Figure A configuration will have more impedance at higher frequencies due to loop in strap, but probably acceptable for most applications.**
2. **Install bond strap under shock mount pad so that the strap does not alter shock mount function.**

Figure 10. Electrical Bond Strap Connection across Shock Mount Assembly

5.4.7 HINGES

Anti-friction bearings, wire-mesh vibration cushion mounts, or lubricated bushings should not be used as bonding paths. Piano hinges should not be used as a bonding path if a lubricant, dry-lube, or other nonconductive element is used in conjunction with the piano hinge. Where hinges are used, establish an alternate electrical path through the use of thin, flexible straps across the hinges as shown in Figure 11.

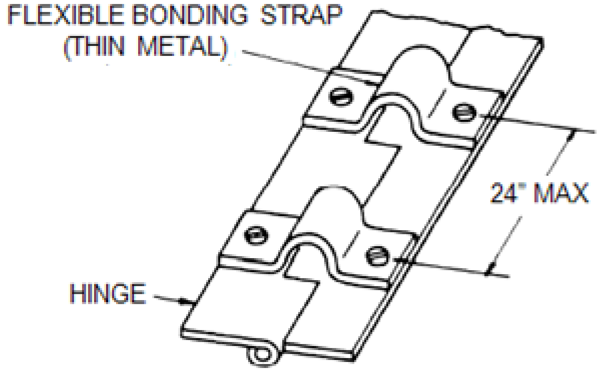


Figure 11. Method of Bonding Across Hinges

5.4.8 CABLE TRAYS

Where cable trays are used, each section of each tray should be bonded to the following section to provide a continuous path. The trays should also be connected to equipment housings either by direct mount or by wide, flexible, solid bond-straps.

5.4.9 COMPOSITE MATERIALS

Composite designs can have many advantages over conventional fabricated metallic structures, such as: design flexibility, increased strength-to-weight ratio, dimensional stability under thermal loading, light weight, ease of fabrication and installation, corrosion resistance, impact resistance, high fatigue strength, and product simplicity. The most important adverse feature of composite materials is their lower conductivity (higher resistance).

5.4.9.1 Conductivity

The conductivity factor, compared with aluminum, is 1000 times less for graphite epoxy. Some composite materials are nonconductive and should not be used where static discharge could be a problem. Graphite filament reinforced plastic (GFRP) or composite materials that contain metal particles are usually conductive enough to drain off static charges if given a conductive path from the material to metallic structure. Since these composite materials are relatively poor conductors, they should not be used to carry high current. The resistance would cause too much voltage drop for intentional power return, and short circuit current may be limited to levels too low to trigger circuit protection devices. **The short circuit current entry and exit points may cause temperatures capable of igniting graphite-epoxy material.** A fault current over 5 amps usually starts a fire at the contact point on several types of GFRP. This can also happen at a joint if the contact area is restricted to a small point. Since it is difficult to avoid this fire hazard, the design should avoid the possibility of an electrical short directly to GFRP. If fault current paths through composite material cannot be avoided, the particular material should be tested for current carrying capability. GFRP may be used as an RF ground even though its DC resistance may exceed the usual Class R limits. If the resistance through the composite structure can be kept to a few ohms, the total impedance to RF will depend upon the inductance of the configuration, just as it would with metal.

5.4.9.2 Bond Implementation

Special attention must be given to bonding of composite materials. Secondary conductive materials such as foils, wires, straps and/or coatings have typically been incorporated into the structure to improve the electrical properties. In graphite-epoxy material the graphite layers are conductive, but the outside layers of the composite may be covered by epoxy or phenolic which must be removed. All gloss must be removed from the epoxy surfaces to assure a good conductive connection. The connection should be continuous along edges that have been abraded to expose graphite. If the surface is painted, care must be exercised in selection of a paint remover chemical. Some of the more aggressive paint remover compounds will attack the epoxy. Connections may be made by overlapping panels or by adding a conductive bridge secured by metal fasteners or by conductive adhesive across the joint. Currently experiments are being performed on carbon nanotube and carbon nanofiber based composite materials. The significantly better electrical conductivity of this new material will improve electrical bonding and fulfill the requirements for lightning strike protection, electrical grounding, and EMI shielding.

5.4.9.3 Lightning and Fault Currents

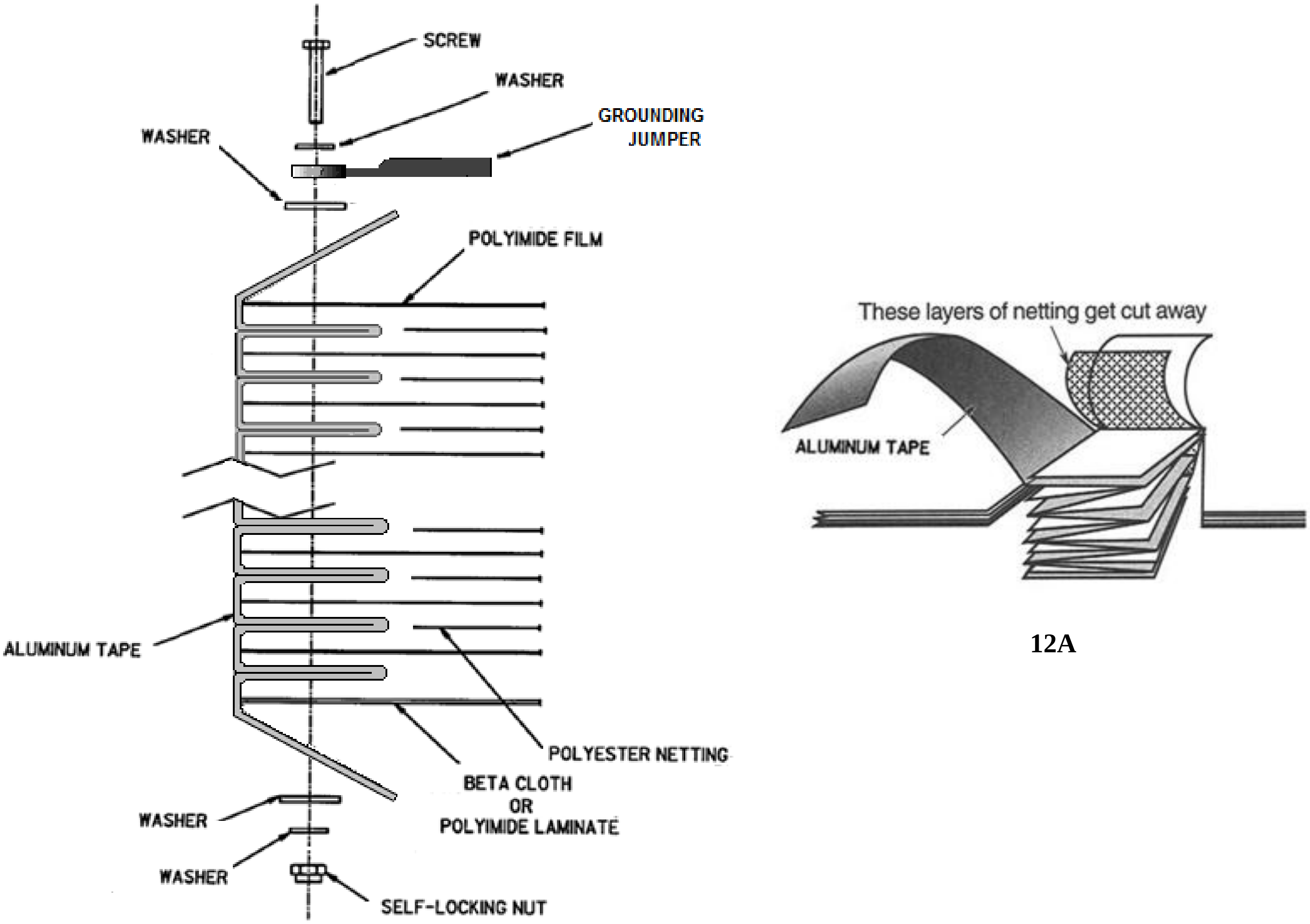
Lightning strikes can cause substantial damage to composite surface structures. There are zones on the vehicle with high probability of lightning strike occurrence. These zones are called lightning strike zones. Protection of composite structure by adding conductive materials is required on lightning strike zones and beyond them to enable conducting induced currents away from attachment zones. It is presently not possible to develop a fastener to join advanced composite materials capable of carrying the full lightning current without seriously weakening the fastener. At fasteners and connections, electrical resistance to current flow generated by lightning produces heat that causes burning and delamination. Special attention will also be required to add metallic pathways in the grounding and bonding system so that on-board systems will function properly in the presence of currents anticipated from lightning strikes. Weight savings from using composites may be negated by the added materials for lightning protection.

5.4.9.4 Non-Metallic Motor Cases

All non-metallic motor cases should have a conductive coating applied if the volume resistivity of the case is 10^8 ohm-meter or greater. All parts of the motor must be at the same voltage. After application of the conductive coating, the case must be electrically connected to structure ground.

5.4.10 MULTILAYER INSULATION (MLI)

Plasma can serve as a medium for surface charging that can result in considerable potential buildup on the external surface of the spacecraft, including the outer-cover layer of MLI blankets. This buildup can lead to static electric discharge between the MLI and the surrounding plasma or between the MLI and parts of the spacecraft that are to some degree electrically isolated. In addition to surface charging, electrons that have sufficient energy to penetrate the outer-cover layer of the blanket, but low enough energy to stop in interior layers, can charge the inner layers until a large electrostatic discharge occurs. Spacecraft, flying in orbits where charging is an issue, will typically have requirements for bonding insulation blankets. Requirements for blanket surface properties, size, and bonding locations are jointly determined by the hardware, thermal, blanket, and hopefully the EME engineers. A typical bonding assembly consists of a conductive metal strip interleaved between the blanket layers and secured by a small bolt, as shown in Figure 12. This assembly is made by cutting away a small square of the separator layers and applying a conductive tape (such as aluminum tape with conductive adhesive) accordion-style between adjacent blanket layers, as shown in Figure 12A. A hole is then punched through all layers for the bolt. The bolt passes through a flat washer, an eyelet terminal, the blanket, another flat washer, a lock washer, and a lock nut. Brass and corrosion-resistant steel (CRES) are the preferred materials for bolts, eyelets, and washers. A wire of the required length, such as 22-gauge Teflon-insulated wire, is crimped to the eyelet terminal. The electrical resistance of the assembly should be less than 1Ω. The number of bonding assemblies required depends on blanket size, the mission charging environment, and the spacecraft sensitivity to discharge. On some programs, blankets with an area less than one square meter are exempt from bonding requirements, while on others all blankets must be bonded. Blankets with areas greater than one square meter are almost always required to have at least two bond straps and often two bond straps per square meter.



12A

Figure 12: Typical MLI Bonding Assembly

5.4.11 METAL HONEYCOMB PANELS

Metal honeycomb panels are lightweight and strong, and therefore, find many uses in aerospace vehicle design. The most common metals used for the honeycomb panels are aluminum and stainless steel, with aluminum being the most frequently used of the two. Although the panels appear to be conductive, the adhesive used to attach the faceplates or skin to the honeycomb is insulative. Each side of the panels must be bonded or a path from the front to the back must be provided.

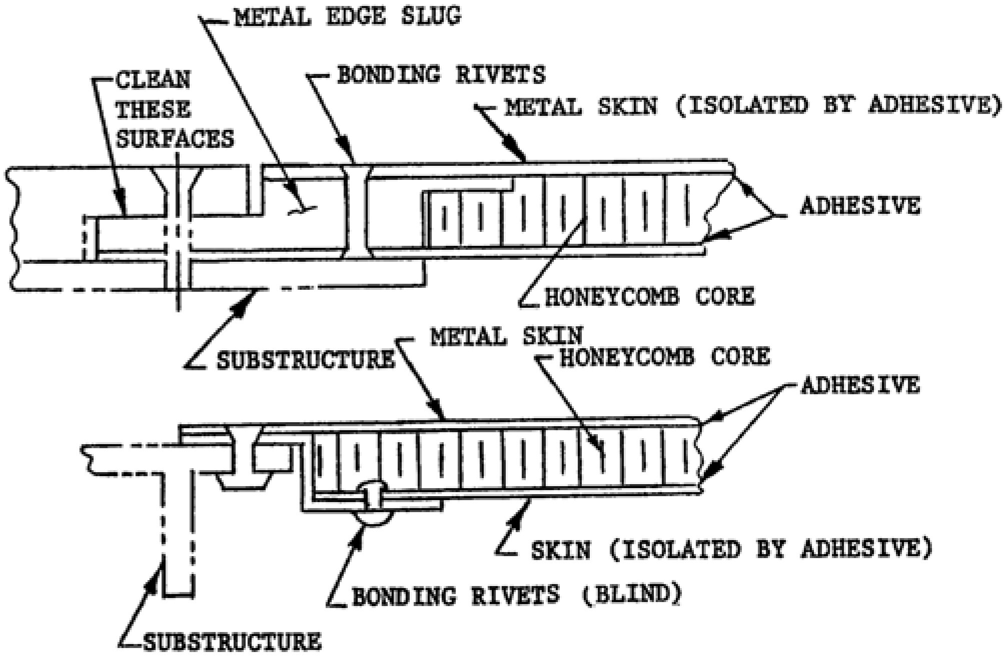


Figure 13: Typical Electrical Bond for Honeycomb Panels Insulated by Adhesives

Metal details which are completely shielded by other metal parts will not require electrical bonding. All rivet holes should be drilled and rivets installed after metal bonding adhesives are cured. Use a minimum of three rivets for any one connection.

5.4.12 EQUIPMENT RACKS

Design of racks for mounting electrical equipment is very much like designing a vehicle. The selection of material for the enclosure and design of seams will depend on mechanical requirements and the amount of shielding required. The primary structure of the rack should be metal with electrical continuity between each element provided by Class R bonding at all the joints. Ground/bonding strips should be provided at strategic locations for attaching equipment or secondary structure, i.e., brackets and panels. These bonding strips, if not galvanically compatible, must be chemically treated or plated to prevent corrosion and they must have a low impedance path to vehicle structure. For example, in the International Space Station (ISS) the structures of the racks are bonded to the connector plate at the bottom of the rack. The connector plates have provisions for attaching one or two straps to standoffs, which are in turn bonded to primary structure. The rack mechanical design must define equipment attachment points and ensure finishes are compatible with equipment to be mounted and that they will endure for the life of the mission. Equipment designs must show surface preparations required for mating with rack attach points and /or bond straps required. Figure 14 illustrates one method of attaching an electronic enclosure to a mounting bracket. Cutouts show other examples of attaching secondary brackets to vertical braces for mounting equipment. Each element must have a bond path to vehicle structure. Equipment in a facility would be bonded in the same manner, except the bond path would be to facility ground.

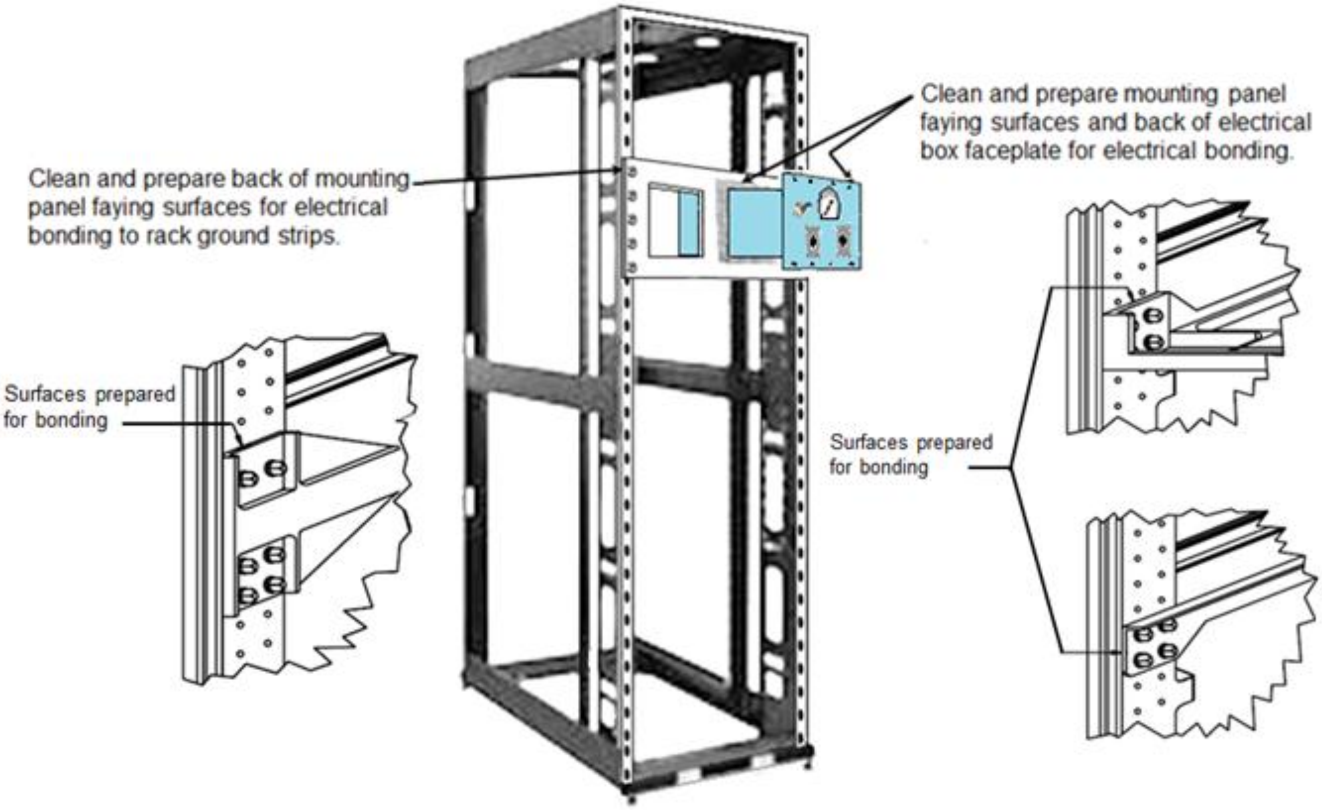


Figure 14. Generic Equipment Rack with Vertical and Horizontal Braces for Attaching Secondary Structure

5.5 VERIFICATION

Although verification is not the subject of this document, design and verification are inextricably linked. Electrical bonding should be verified by inspection of drawings and quality records. (Quality records include workmanship resistance measurements.) All bonding joints should be inspected to verify that they meet the appropriate class bond per NASA-STD-4003.

MSFC-SPEC-3659 requires resistance measurements to be made on at least two bonds of each type to verify the process and workmanship are still acceptable. This works on assemblies with multiple bonding joints. Of course if there is only one joint, then only one joint can be tested. Types of bonds are: aluminum to aluminum, aluminum to stainless steel, aluminum to titanium, electrical connectors to equipment housing, etc. Some common places for requiring resistance measurements are listed in Table VIII. The bonding resistance is measured across the bonding joint, not on the faying surface, except for MLI. Some equipment or component drawings only prepare the surface for bonding at the next assembly. These bonding surfaces must be verified by inspection.

Table VIII. Common Bonding Joints for Measuring Resistance

ITEMS BONDED	MEASUREMENT
Mounted Equipment	From chassis to mounting base
Structural Joints	From metal part to adjacent metal part
Ground Straps (Jumpers)	From strap or terminal to faying surface (Each end)
Multi-Layer Insulation (MLI)	From attach point on MLI to structure
Electrical Connector	From connector body to equipment housing
Electrical Enclosure	From side/top/base to adjacent side/top/base

6. ENGINEERING DRAWINGS

When a bonding requirement exists, the following information must be defined on the engineering drawings:

a. Areas to be bonded

b. Class of bond

c. Type of materials

d. Surface preparation

e. Type of sealant, if required, and

For indirect bonds:

a. Strap type and dimensions

b. Location of strap

Fastener type, number, and torque were omitted from the list because they would be included whether or not there was a bonding requirement. Installation/assembly drawings should call for verification of enough bonds to verify bonding process and/or critical bond paths (refer to Section 5.5). Providing adequate bonding details on the drawing ensures that Manufacturing will implement the bond correctly and aid in the verification process.

6.1 AREAS TO BE BONDED AND CLASSIFICATION

Engineering drawings should identify areas to be bonded and denote electrical bonding class per the appropriate program/project specification. Some general guidelines for determining bonding class are:

Vehicle Outer Skin

a. Metal – Outer skin must provide a continuous path to carry lightning currents and dissipate static charge buildup. (2.5 mohms, Class L)

b. Non-metal – Additions or modifications may be required to provide a path that will handle lightning currents.

Primary Structure

a. All components of primary structure must be bonded to adjacent components to provide, as close as possible, an equipotential ground reference. (2.5 mohms, Class R)

Powered Assemblies

a. If a device receives power, its enclosure must be bonded to structure with a low resistance and enough surface contact to handle fault currents until the upstream protective device opens. The rule of thumb for surface area is that it should be 4 times the cross-sectional area of a copper wire rated to carry the current. (.1 ohm, Class H)

b. If a device receives power and can generate or be susceptible to RF noise, its enclosure must be bonded to structure with a low impedance bond. (2.5 mohm, Class H and R)
(It is only necessary to denote Class R as long as the design provides for enough surface area contact to carry the fault current.)

Unpowered Assemblies

a. All conductive structural devices or passive equipment subject to charge build-up, and that are not in the bond path for active devices must have a low resistance bond to structure ($\leq 1\Omega$, Class S).

b. All conductive structural devices or passive equipment in the bond path for active devices must have a low impedance bond to structure. (Class R) Equipment racks, brackets, and secondary structure required for mounting active devices are examples of this category. Normally bonding equipment through other equipment should be avoided.

Tubes and Hoses

a. Conductive (resistivity < one Mohm/meter of length) – Only required to dissipate static charge. Round or flat jumpers are acceptable. (Class S)

b. Nonconductive – If fluid in tube is conductive (volume resistivity < 10^7 ohm-meters), no bonding is necessary. If fluid is not conductive, consider using a different tube material or provide some means of dissipating charge.

6.2 DRAWING NOTES

There are three types of notes on a drawing: general notes, local notes and flag notes. General notes are notes that apply to the entire drawing while local notes apply only to specific areas or points in the drawing. Local notes are not included in the notes section, instead they are normally attached to leaders or reside somewhere in the drawing and apply only to that area or point. Flag notes are listed with the general notes. Flag notes are similar to local notes, but apply to all locations where the flag is applied.

6.2.1 GENERAL NOTES

Since all faying surfaces must be clean prior to joining, cleaning requirements can usually be expressed in general notes such as:

MATING SURFACES SHOULD BE CLEANED OF ANODIC FILM, OXIDES, GREASES, OR OTHER HIGHLY RESISTANT FILMS.

If all faying (mating) surfaces are compatible with no nonconductive coatings, the following note could suffice; otherwise both notes may be needed.

SOLVENT CLEAN FAYING SURFACES IN ACCORDANCE WITH MIL-PRF-680 (OR APPLICABLE CLEANING SOLVENT) WITHIN 24 HOURS PRIOR TO ASSEMBLY.

Specific cleaning requirements can be placed either in a local or a flag note.
If all faying surfaces on the drawing are required to meet the same bonding class, then the following general note could apply.

THE RESISTANCE BETWEEN ALL FAYING SURFACES SHALL BE LESS THAN XX MILLIOHMS TO MEET THE BOND REQUIREMENTS OF NASA-STD-4003, CLASS X.

6.2.2 LOCAL AND FLAG NOTES

The following are examples of local bonding notes.

THE BOND RESISTANCE BETWEEN FN XX AND FN XX SHALL BE LESS THAN XX MILLIOHMS TO MEET THE REQUIREMENTS OF NASA-STD-4003, CLASS X.
THE RESISTANCE ACROSS THIS JOINT SHALL BE LESS THAN XX OHMS TO MEET THE ELECTRICAL BOND REQUIREMENTS OF NASA-STD-4003, CLASS X.

Flag notes are listed with the general notes. "Flags" referencing the notes may be in the title block or in the field of the drawing or in both places. Typically flag notes in the title block will be for materials and/or surface finish. Below is an example flag note:

4. THE RESISTANCE ACROSS THIS JOINT SHALL BE LESS THAN XX OHMS TO MEET THE ELECTRICAL BOND REQUIREMENTS OF NASA-STD-4003, CLASS X.

6.3 MATERIALS

Although type of material is a major factor in electrical bonding, identifying materials and parts is required on engineering drawings whether utilized for electrical bonding or not. Any materials and parts added for electrical bonding purposes must be capable of meeting the service conditions of the device being bonded.

6.4 SURFACE PREPARATION

6.4.1 CLEANING

All bonding surfaces should be cleaned over an area that extends beyond all sides of the bonded area on the larger member. Paint, primers, and other organic finishes must be removed from both faying surfaces. Rust, oxides, and nonconductive surface finishes such as anodize should be removed. Solvent cleaning of electrical bonding faying surfaces within 24 hours prior to assembly should be explicitly identified on the drawings. Although most of the examples provided in the document give detailed instructions for cleaning and refinishing surfaces, these details should be covered in manufacturing procedures. Mechanical drawings need only specify surfaces to be cleaned. The following example could be a flag or local note.

ELECTRICALLY CONDUCTIVE SURFACE REQUIRED FOR ELECTRICAL BONDING. PERFORM SURFACE PREPARATION AND JOINING IN ACCORDANCE WITH MSFC-SPEC-3659.

6.4.2 CORROSION CONTROL

The two primary methods of corrosion control are surface treatment and sealing to exclude moisture. (See sections 3.3.6.2 and 3.3.6.3.) Electroless nickel plated aluminum, stainless steel, inconel, and titanium may be bonded in any combination. Faying surfaces of aluminum, when mating with stainless steel, inconel, or titanium and not electroless nickel plated, should have a chemical conversion coating per MIL-DTL-5541, CLASS 3, and the bond joint should be sealed with a protective sealant. In case of conflict between corrosion control requirements and electrical bonding requirements, it is imperative that the conflict be resolved to the mutual satisfaction of all parties. This resolution should be reached as early in the design process as practical. In the event of a compromise between EMC and corrosion protection requirements, continuing maintenance instructions should be written to ensure any necessary periodic inspection and service or treatment of the affected bond(s) is performed.

An example of a note to prevent galvanic reaction between fasteners and composite materials or dissimilar metals is as follows:

SEAL AROUND PERIPHERY OF BONDING JOINT WITH SEALANT PER SAE-AMS-S-8802, TYPE I, CLASS C. FASTENERS TO BE WET INSTALLED.

A more detailed note could be:

APPLY EPOXY PRIMER PER MIL-PRF-23377 TO BOLT SHANK AND ALL FAYING SURFACES OF BOLT, WASHERS AND NUT PRIOR TO INSTALLATION. AFTER TORQUING FASTENER, REMOVE EXCESS PRIMER WITH LINT-FREE CLOTH. LEAVE SUFFICIENT PRIMER TO FORM FILLET COMPLETELY AROUND BASE OF BOLT HEAD, WASHERS AND NUT.

6.4.3 SURFACE FINISHES

Surface finishes, including platings, provided for added durability or corrosion protection, should offer high conductivity. Plating metals should be electrochemically compatible with the base metals. Unless suitably protected from the atmosphere, silver and other easily tarnished metals should not be used to plate bond surfaces. Reference Table VIII for common metal finishes.

6.4.3.1 Aluminum to Aluminum Faying Surfaces

Electrically bonded unions between chemical film treated 1100, 5000 and 6000 series aluminum generally provide low-resistance, stable bonds if they are protected from the external elements. Additional corrosion control measures should be used for 2000 and 7000 series aluminum or when the bond interfaces are to be exposed to external elements.
Detail drawings should specify the masking of any planned contact areas prior to anodizing and/or painting.

Example of note for applying chemical conversion to entire surface:

CHEMICAL CONVERSION COAT PER MIL-DTL-5541, CLASS 3.

Examples of notes for applying chemical conversion to only part of otherwise finished surfaces:

MASK INDICATED SURFACES PRIOR TO ANODIZING. CHEMICAL CONVERSION COAT PER MIL-DTL-5541, CLASS 3.

DO NOT APPLY PAINT OR ANODIZED PRIMER, ETC. (AS APPLICABLE) IN THESE AREAS.

REMOVE FINISH USING THE RECOMMENDED PRACTICE APPROVED BY THE SUPPLIER.

PREPARE AREA FOR ELECTRICAL BONDING BY REMOVING PAINT AND PRIMER. APPLY CHEMICAL CONVERSION COATING PER MIL-DTL-5541, CLASS 3.

6.4.3.2 Aluminum to Stainless Steel, Titanium, Or Inconel
Aluminum when mated to stainless steel, titanium, or inconel should be nickel-plated. Example of drawing note to nickel plate aluminum:

ELECTROLESS NICKEL PLATE PER SAE AMS 2404, CLASS X, GRADE X.

6.4.3.3 Stainless Steel Interfaces
Stainless steel surfaces should be passivated. Passivation of stainless steel removes “free iron” contamination left behind on the surface as a result of machining and fabricating processes and facilitates the formation of a very thin, transparent oxide film, which protects the stainless steel from corrosion.

Example of drawing note to passivate stainless steel:

PASSIVATE PER AMS 2700, METHOD 1, TYPE X

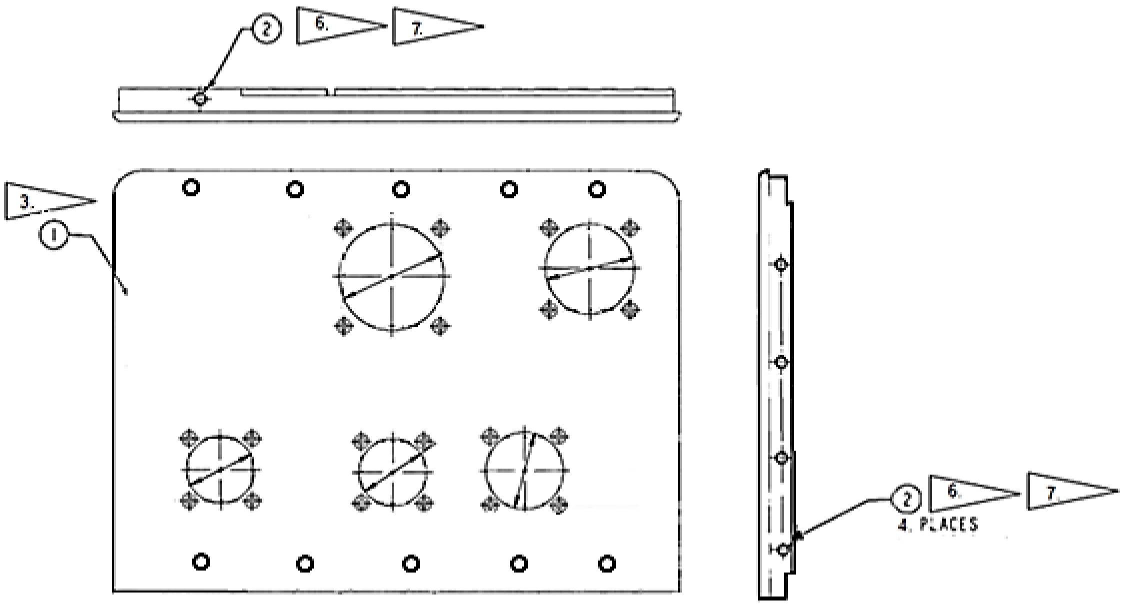
6.4.4 PROTECTION OF EXPOSED SURFACES
Prepared surfaces should be joined, sealed, and any exposed surfaces refinished within two hours to prevent oxidation. When additional time is required before joining, a corrosion inhibiting compound (CIC) or strippable plastic coating should be applied to any exposed surfaces until the bond is made.

Example drawing note to protect bare metal surfaces:

Apply with brush, or spray an even, thin film of strippable plastic coating in accordance with MIL-C-16173 to surface. Ensure thorough coverage of exposed surface areas.

Remove coating or CIC prior to establishing bond joint and seal around bond area as required. Refer to 4.4.2 for sealing note.

6.5 EXAMPLE DRAWINGS
Figures 15 through 20 are drawing examples. Figure 15 shows a connector panel drawing with some typical notes. Notes on figures 15 through 17 pertaining to bonding are shown in bold. A portion of the title block is shown on figure 15 to illustrate use of flag notes. Figure 16 shows a portion of an assembly drawing with the previous connector panel incorporated into an electrical equipment assembly. Figure 17 shows the equipment installed into a rack. Some details and dimensions have been omitted for clarity in all three drawings. Figures 18 through 20 show details for different applications of bond straps.



NOTES:

1. BREAK SHARP EDGES AND DEBURR

2. $\overset{63}{\surd}$ ALL MACHINED SURFACES

3. ELECTRICALLY CONDUCTIVE SURFACE REQUIRED FOR ELECTRICAL BONDING. PERFORM SURFACE PREPARATION IN ACCORDANCE WITH MSFC-SPEC-3659.

4. CHEMICAL CONVERSION COAT PER MIL-DTL-.5541, CLASS 3

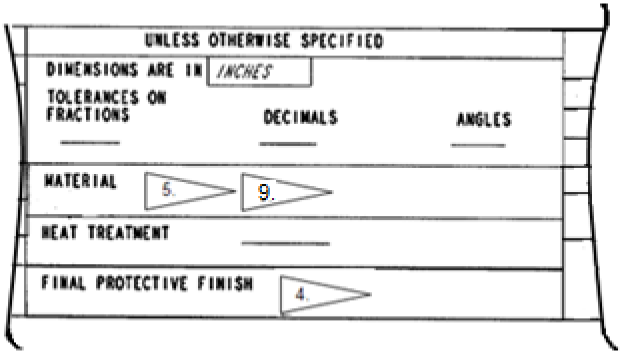
5. 7071-T651 ALUMINUM ALLOY PER: SAE-AMS-QQ-A-225/9

6. INSTALL HELICOILS WET USING PRIMER PER MIL-P-23377

7. INSTALL HELICOIL PER MS33637 CLASS 38 THREAD. REMOVE TANG AND COLOR CODE DYE. TAP DRILL MAY BREAK THRU

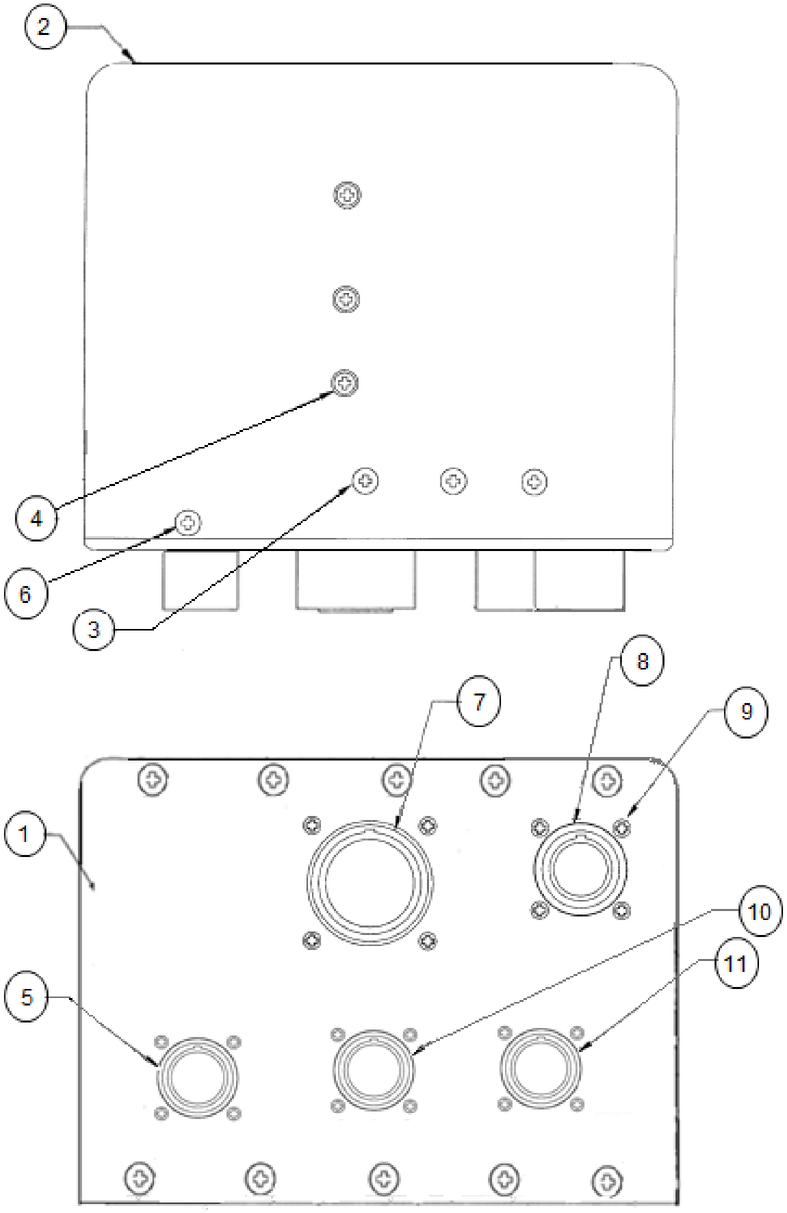
8. EXCEPT AS NOTED, ALL FILLET RADII TO BE .007 R MAX.

9. EXISTING SUPPLY OF MATERIAL PROCURED TO SUPERCEDED PROCUREMENT SPECIFICATION MAY BE USED UNTIL EXHAUSTED



UNLESS OTHERWISE SPECIFIED		
DIMENSIONS ARE IN *INCHES*		
TOLERANCES ON FRACTIONS	DECIMALS	ANGLES
MATERIAL 5. 9.		
HEAT TREATMENT		
FINAL PROTECTIVE FINISH 4.		

Figure 15. Connector Panel Drawing



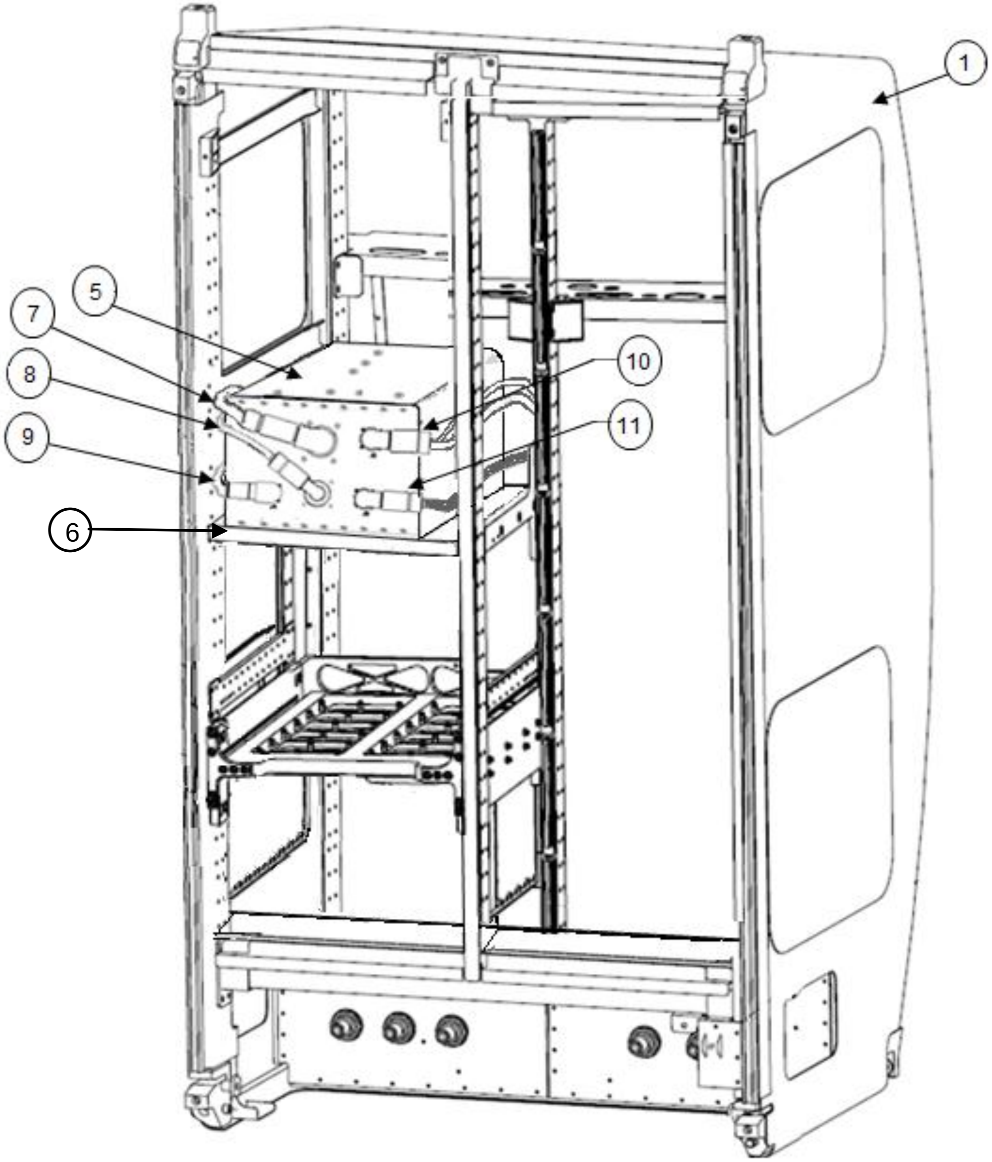
NOTES:

1. TORQUE THREADED FASTENER PER MSFC-STD-486 .

NO.4'S	4.0 TO 4. 5 IN.-LBS
NO. 6'S	9.0 TO 9.5 IN.-LBS
NO. 8 ' S	10.0 TO 11.0 IN.-LBS
NO. 1O'S	29.0 TO 30.0 IN.-LBS

2. CONNECTORS WITH REMOVEABLE CONTACTS TO BE RETENTION TESTED PER MSFC -STD-2905.
3. ASSEMBLY MUST MEET CLEANLINESS REQUIREMENTS OF JSC-SN-C-0005 VISIBLE CLEAN SENSITIVE.
4. CRIMP AND INSPECT PER MSFC-STD -2905.
5. ROUTING, LACING AND SLEEVING AS REQUIRED PER MIL-E-45782B. LACING WITH FN 36. SLEEVING WITH FN 51. COAT LACING KNOTS WITH FN 47.
6. **SOLVENT CLEAN FAYING SURFACES IN ACCORDANCE WITH MIL-PRF-680 WITHIN 24 HOURS PRIOR TO ASSEMBLY.**
7. **THE BOND RESISTANCE BETWEEN CONNECTORS AND FN 1 AND BETWEEN ALL CHASSIS JOINTS SHALL BE LESS THAN 2.5 MILLIOHMS TO MEET THE BOND REQUIREMENTS OF NASA-STD-4003, CLASS R.**

Figure 16. Equipment Assembly Drawing



NOTES:

2. TORQUE FASTENERS TO 25 to 30 IN.-LBS ABOVE RUNNING TORQUE PER MSFC-STD-486.

3. TORQUE FASTENERS TO 65 to 75 IN.-LBS ABOVE RUNNING TORQUE PER MSFC-STD-486.

4. CLEAN AND MAINTAIN TO VC-0.5-1000 LEVEL PER IEST-STD-CC1246E.

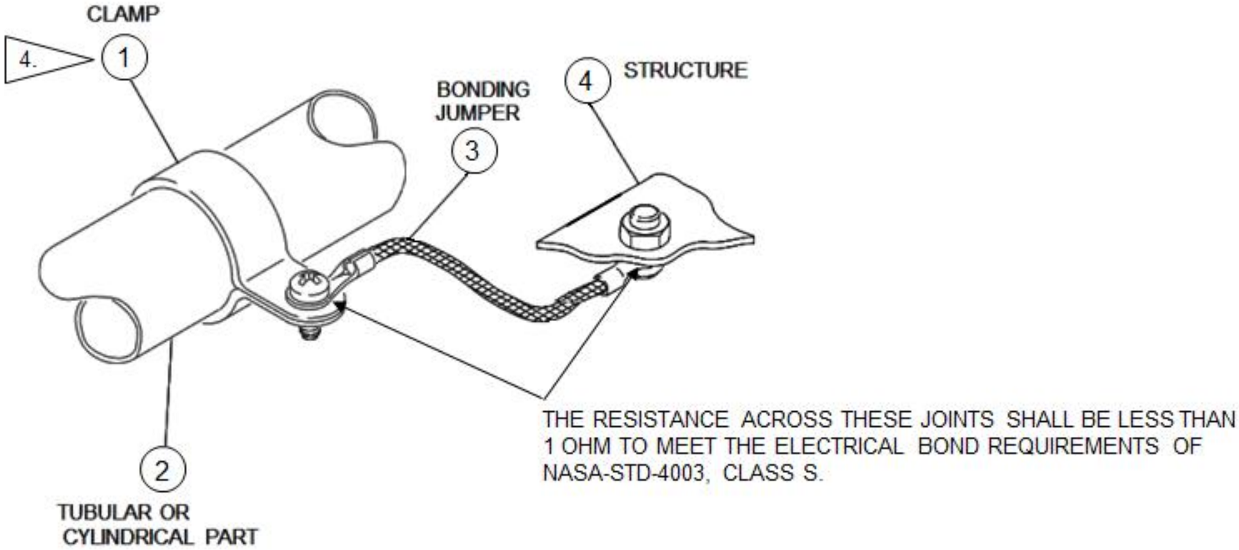
8. THE RESISTANCE BETWEEN FIND NO 5 AND FIND NO 6 SHALL BE LESS THAN 2.5 MILLIOHMS TO MEET THE BOND REQUIREMENTS OF NASA-STD-4003, CLASS R.

Figure 17. Equipment Installation Drawing

NOTES

4. ELECTRICALLY CONDUCTIVE SURFACE REQUIRED FOR ELECTRICAL BONDING. PERFORM SURFACE PREPARATION AND JOINING IN ACCORDANCE WITH MSFC-SPEC-3659.

5. THE BOND RESISTANCE BETWEEN FN 1 AND FN 2 SHALL BE LESS THAN 1 OHM TO MEET THE BOND REQUIREMENTS OF NASA-STD-4003, CLASS S.



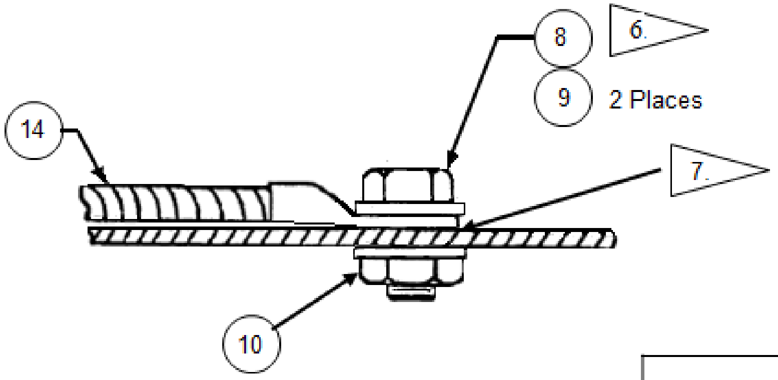
THE RESISTANCE ACROSS THESE JOINTS SHALL BE LESS THAN 1 OHM TO MEET THE ELECTRICAL BOND REQUIREMENTS OF NASA-STD-4003, CLASS S.

Figure 18. Clamps and Electrical Bonding Jumpers – Installation

4. MATING SURFACES SHALL BE CLEANED OF ANODIC FILM, OXIDES, GREASES, OR OTHER HIGHLY RESISTANT FILMS. PERFORM SURFACE PREPARATION AND JOINING IN ACCORDANCE WITH MSFC-STD-3659.

6. ELECTRICALLY BOND FAYING SURFACE PER NASA-STD-4003, CLASS S.

7. MEASURE AND RECORD RESISTANCE ACROSS THIS JOINT. RESISTANCE SHALL BE LESS THAN 1 OHM.

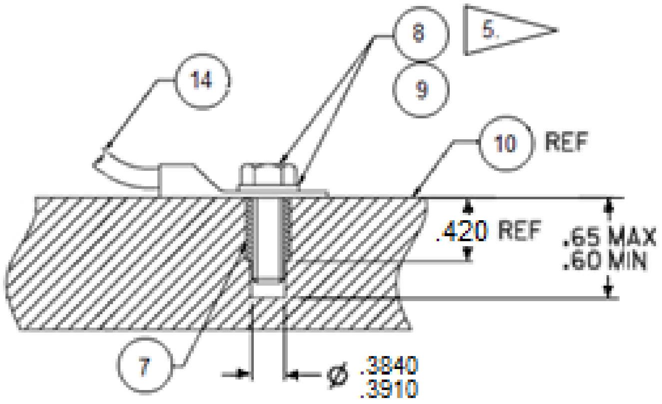


PARTS LIST			
Find No.	Part No.	Description	Qty
8	NAS1802-6-6	Screw Hex Head	10
9	NAS1149CN616R	Washer Flat	20
10	NAS1291C6M	Nut Self Locking	10
14	M83413/8-H006JJ	Bonding Jumper	1

Figure 19. Typical Bonding Jumper Termination

4. MATING SURFACES SHALL BE CLEANED OF ANODIC FILM, OXIDES, GREASES, OR OTHER HIGHLY RESISTANT FILMS. PERFORM SURFACE PREPARATION AND JOINING IN ACCORDANCE WITH MSFC-STD-3659.

5. ELECTRICALLY BOND FAYING SURFACE PER NASA-STD-4003, CLASS S.



.375-24 UNF-3B X 1 HELICAL COIL INSERT THREAD PER NASM33537. INSTALL INSERT AFTER APPLICATION OF PROTECTIVE FINISH TO INSIDE OF HOLE AND REMOVE TANG.

PARTS LIST

Find No.	Part No.	Description	Qty
8	NAS1802-6-6	Screw Hex Head	1
9	NAS1149CN616R	Washer Flat	1
7	MS21209F6-10L	THREADED INSERT	1
14	M83413/8-H006JJ	Bonding Jumper	1

Figure 20. Bonding Jumper Termination Using Threaded Insert

7. ELECTRICAL BONDING CHECKLIST

a. Areas to be electrically bonded are designated on the mechanical drawing and notes provide enough detail to ensure bonds meet requirements for their designated Class.

b. Design specifies mating surfaces are clean and free from oil, dirt, oxides, or other contaminants before bonding or before applying bonding materials to surfaces.

1. All nonconductive material must be removed. Such materials include paints and other organic finishes; anodize films; oxide and sulfide films; and oil, grease and other petroleum products.

2. All corrosive agents must be removed. Such agents include water, acids, strong alkalis, and any other materials which provide conductive electrolytic paths.

3. All solid matter which would interfere with the establishment of a low resistance path across the bond interface or which forms a wedge or barrier to keep the bond area open to the entrance of corrosive materials or agents must be removed. Such solid materials include dust, dirt, sand, metal filings, and corrosion by-products.

4. Only remove protective finishes from mating surface areas.

5. Any damaged or removed areas of finish, adjacent to the bond, shall be re-applied.

c. Bond joints are composed of compatible materials or steps have been taken to control corrosion.

d. Contact surfaces of mating metals are of adequate cross-sectional area to carry fault current.

e. Any structure or equipment exposed to the lightning environment is bonded to structure with a low impedance and high current carrying capability to handle the high current and magnetic forces associated with lightning.

f. Electrical components are bonded directly to structure (primary or secondary), not through other bonded components. (Bonding in series is permitted for plumbing lines.)

g. Bonding locations, where possible/practical:

1. In areas protected from hostile environments,

2. In accessible areas to permit ease of inspection and, if necessary, replacement.

h. Bonding straps or jumpers are only used where the direct joining of structural elements, assemblies, and electrical paths are impossible or impractical.

1. Bonding straps should not impede the performance of the mounting device.

2. They should be kept as short as possible (length to width ratio < 5:1).

3. Faying surfaces of bond straps are treated the same as other faying surfaces.

4. Bond straps or wires must be sized to carry fault current.

i. Any coating used to preserve a clean surface for later bonding is compatible with the surface being protected.

j. Tubes and hoses that carry fluids have a connection to structure of 1 ohm or less (Class S). Nonmetallic tubing material should have a resistivity of less than 1 megohm per inch.

k. Installed clamps:

1. Clamps for bonding are of electrically conductive. (Do not use cushion clamps.)

2. Clamps are installed tightly around tubular or cylindrical parts without crimping or damaging.

3. The area under clamps should be cleaned of paint and other foreign material.

4. Install washers as necessary between the clamp tangs to prevent damage to the part. Use washers that are made of material compatible with the clamp.

5. Clamps and connections to straps or structure will not break or loosen due to vibration, expansion, or contraction (movement that occurs during usual service).

Appendix A

Glossary of Terms

Impedance – A generic term applied to any electrical device that impedes the flow of current. In a dc circuit impedance is the same as resistance. In an ac circuit the impedance includes the resistance in the circuit plus the reactance of the capacitance and inductance in the circuit. Impedance is a complex quantity which varies with frequency and is determined by:

$$Z = \frac{V}{I} \cos \theta$$

Where Z = impedance,

V= voltage,

I = current, and

θ = the phase angle between the voltage and current

Z can also be expressed as: $z = R + j(X_L - X_C)$

Where $|Z| = \sqrt{R^2 + (X)^2}$

$\theta = \tan^{-1} \frac{X}{R}$

$x = (X_L - X_C)$

R = resistance

X = reactance

X_L = inductive reactance

X_C = capacitive reactance

$j = \sqrt{-1}$, or indicates the imaginary part of a complex number

Resistance – The total impedance to the flow of current in a dc circuit. Since the reactive components do not come into play in a dc circuit, the phase angle is zero, making Z = R.

Faraday cage – A solid shield that completely surrounds a product. It is not necessary to tie the Faraday cage to ground for it to be an effective shield for electromagnetic radiation, but safety requirements usually require the Faraday cage to be grounded to prevent an electrical shock hazard.

To fay - A shipbuilding term meaning to fit closely, to join.

Faying surface - Either of a pair of metal surfaces that are in contact in a joint, also, the contact surface between two adjoining parts.

FOD – Foreign object/debris.

Electrical bonding – The process of providing good electrical connection across faying surface mechanical interfaces to minimize electrical potential differences between equipment and individual parts of structure.

Ground plane – A surface, all points of which are assumed to be at the same potential, usually the zero reference potential for the system. (Note: A true, equipotential ground plane does not exist in practice. The deviations from the ideal increase with the frequency of the signals appearing on the ground plane conductor and can become a very important consideration in system design.) In most cases, the ground plane is the vehicle or payload carrier structure.

Grounding vs. Bonding – Because the terms “grounding” and “bonding” are often used interchangeably, it leads to confusion. Electrical circuits are grounded to Earth or a common reference plane for preventing shock hazards and/or for enhancing operability of the circuit and EMI control. This handbook only addresses the grounding of metallic components such as electrical equipment cases, cabling conduit, pipes, and hoses (bonding), not the grounding of electrical circuits.

Aperture – An opening in an enclosure. Apertures are usually a shielding concern, but since the maximum dimension of an aperture determines the amount of radiation that can enter or exit an enclosure, electrical bonding comes into play. The spacing of fasteners in an enclosure lid or seam, as well as the conductivity of the mating surfaces, affects the shielding effectiveness of the enclosure.

Primary, Secondary, & Tertiary Structure

a. Primary structure is the major framework that carries all of the major loads imposed on the vehicle.

b. Secondary structure includes all essential appendages and support structures (such as solar arrays, antennas, fuel tanks, plumbing, mounting brackets, etc.)

c. Tertiary structures are less-essential mounting hardware (brackets, component housings, connector panels)

Appendix B
CLEANING METHODS

Alkaline cleaning

Alkaline cleaning is the mainstay of industrial cleaning and may employ both physical and chemical actions. These cleaners contain combinations of ingredients such as surfactants, sequestering agents, saponifiers, emulsifiers, and chelators, as well as various forms of stabilizers and extenders. Except for saponifiers, these ingredients are physically active and operate by reducing surface or interfacial tension, by formation of emulsions, and suspension or flotation of insoluble particles. Solid particles on the surface are generally assumed to be electrically attracted to the surface. During the cleaning process, these particles are surrounded by wetting agents to neutralize the electrical charge and are floated away, held in solution suspension indefinitely, or eventually are settled out as sludge in the cleaning tank.

Electrolytic cleaning

Electrolytic cleaning is a modification of alkaline cleaning in which an electrical current is imposed on the part to produce vigorous gassing on the surface to promote the release of soils. Electrolytic cleaning can be either anodic or cathodic cleaning. Anodic cleaning is also called "reverse cleaning," and cathodic cleaning is called "direct cleaning." The release of oxygen gas under anodic cleaning or hydrogen gas under cathodic cleaning in the form of tiny bubbles from the work surface greatly facilitates lifting and removing surface soils.

Emulsion cleaning

Emulsion cleaning depends on the physical action of emulsification, in which discrete particles of contaminant are suspended in the cleaning medium and then separated from the surface to be cleaned. Emulsion cleaners can be water or water solvent-based solutions; for example, emulsions of hydrocarbon solvents such as kerosene and water containing emulsifiable surfactant. To maintain stable emulsions, coupling agents such as oleic acid are added.

Solvent cleaning

Solvent cleaning, as the name implies, is the dissolution or separation of contaminants by an approved solvent. The solvent can be applied by swabbing, tank immersion, spray or solid stream flushing, or vapor condensation. Vapor degreasing is accomplished by immersing the work into a cloud of solvent vapor; the vapor condenses on the cooler work surface and dissolves the contaminants. Subsequent flushing with liquid solvent completes the cleaning process. Temperature elevation accelerates the activity. One major drawback of solvent cleaning is the possibility of leaving some residues on the surface, often necessitating additional cleaning steps. Another more significant disadvantage is the environmental impact of solvent cleaning processes. In fact, much effort is being expended on replacing solvent-based processes with more environmentally acceptable aqueous-based processes.

Acid cleaning

Acid cleaning is used more often in conjunction with other steps than by itself. Acids have the ability to dissolve oxides, which are usually insoluble in other solutions. Straight mineral acids, such as hydrochloric, sulfuric, and nitric acids, are used for most acid cleaning, but organic acids, such as citric, oxalic, acetic, tartaric, and gluconic acids, occupy an important place in acid cleaning because of their chelating capability.

Pickling

Pickling is the chemical treatment of metallic materials with an aqueous acid solution that results in the removal of surface oxides or scale formed during heating. This method also removes other foreign metals and other substances.

Abrasive cleaning

Abrasive cleaning uses small sharp particles propelled by an air stream or water jet to impinge on the surface, removing contaminants by the resulting impact force. A wide variety of abrasive media in many sizes is available to meet specific needs. Abrasive cleaning is often preferred for removing heavy scale and paint, especially on large, otherwise inaccessible areas. Abrasive cleaning is also frequently the only allowable cleaning method for steels sensitive to hydrogen embrittlement. This method of cleaning is also used to prepare metals, such as stainless steel and titanium, for painting to produce a mechanical lock for adhesion because conversion coatings cannot be applied easily to these metals.

Wire brushes

Either manual or power brushes may be used for removal of weld, scale, and light oxides. Compatibility between the brush material and the material being treated must be carefully considered. Wire brushing should be avoided on finished machined articles as it can damage sealing surfaces, remove protective coatings, and work-harden metals.

Molten salt bath cleaning

Molten salt bath cleaning is very effective for removing many soils, especially paints and heavy scale. However, the very high operating temperatures and high facility costs discourage widespread use of this process.

Saponification

Saponification is a chemical reaction that splits an ester into its acid and alcohol moieties (parts) through an irreversible base-induced hydrolysis. The reaction products are more easily cleaned from the surface by the surface-active agents in the alkaline cleaner. Excessive foaming can result if the alkalinity in the cleaner drops to the point where base-induced hydrolysis cannot occur; the reaction of the detergents in the cleaner with oil on the work surface can make soaps, which causes the characteristic foaming often seen in a spent cleaner.

Ultrasonic cleaning

Ultrasonic cleaning uses sound waves passed at a very high frequency through liquid cleaners, which can be alkaline, acid, or even organic solvents. The passage of ultrasonic waves through the liquid medium creates tiny gas bubbles, which provide a vigorous scrubbing action on the parts being cleaned. Although the mechanism of this action is not completely understood, it yields very efficient cleaning. It is ideal for lightly soiled work with intricate shapes, surfaces, and cavities that may not be easily cleaned by spray or immersion techniques. A disadvantage of ultrasonic cleaning processes is the high capital cost of the power supplies and transducers that comprise the system. Therefore, only applications with the most rigorous cleaning requirements are suitable for this technique.

Hand Cleaning

The nature of some surfaces restricts the use of highly abrasive methods. Hand methods should be used for cleaning small, delicate, confined surfaces where parts cannot tolerate other cleaning methods or when accessories/facilities for other methods are not available. Tarnish and light corrosion can be removed from such surfaces by hand rubbing with a pencil eraser, brushes, and nonabrasive pads. Surfaces such as covers, connectors, receptacles, antenna mounts, equipment racks, chassis, etc., may have light to moderate corrosion removed by an abrasive mat or cloth. The following list contains some of the equipment that may be utilized for hand cleaning:

a. Lint free cloth, per MIL-C-85043;

b. Cheesecloth;

c. Cotton tip applicator;

d. Acid brush;

e. Toothbrush;

f. Other soft bristle brushes; and

g. Plastic manual spray bottle.

APPENDIX C
REFERENCE DOCUMENTS

DOCUMENT NO.	TITLE
A-A-3165	Commercial Item Description Lacquer, Gloss, for Aircraft Use
A-A-59569	Commercial Item Description Braid, Wire (Copper, Tin-Coated, Silver-Coated, or Nickel Coated, Tubular or Flat), Rev C, January 2009
ASTM A380	Cleaning, Descaling and Passivation of Stainless Steel Parts, Equipment and Systems
ASTM B700	Standard Specification for Electrodeposited Coatings of Silver for Engineering Use
ASTM B488	Standard Specification for Electrodeposited Coatings of Gold for Engineering Uses
ASTM B545	Standard Specification for Electrodeposited Coatings of Tin
ASTM B733	Standard Specification for Autocatalytic (Electroless) Nickel-Phosphorus Coatings on Metal
MIL-A-46146	Adhesives-Sealants, Silicone, RTV, Noncorrosive (for use with Sensitive Metals and Equipment)
MIL-C-16173	Corrosion Preventive Compound, Solvent Cut Back, Cold Applications
MIL-C-81302	Cleaning Compound, Solvent, Trichlorotrifluoroethane
MIL-DTL-24749	Detail Specification, Grounding Straps and Bosses, Electromagnetic General Specification for, Rev A, August 1997
MIL-DTL-45204	Gold Plating, Electrodeposited
MIL-DTL-5541	Detail Specification, Chemical Conversion Coatings on Aluminum and Aluminum Alloys, Rev F, July 2006
MIL-DTL-81706	Detail Specification, Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys

MIL-DTL-83413/8C	Detail Specification Sheet, Connectors and Assemblies, Electrical, Aircraft Grounding: Type IV Jumper Cable Assembly, Lead, Electrical, w/Amendment 2, October 2012
MIL-DTL-83488	Coating, Aluminum, High Purity
MIL-HDBK-1250	Department of Defense, Handbook for Corrosion Prevention and Deterioration Control in Electronic Components and Assemblies
MIL-M-3171	Magnesium Alloy, Processes for Pretreatment and Prevention of Corrosion
MIL-PRF-23377	Primer Coatings: Epoxy High-Solids
MIL-PRF-680	Degreasing Solvent
MIL-PRF-81733	Sealing and Coating Compound, Corrosion Inhibitive
MIL-STD-171	Department of Defense Manufacturing Process Standard: Finishing of Metal and Wood Surfaces, Rev F, MAY 2011
MIL-STD-403C	Military Standard Preparation for and Installation of Rivets and Screws, Rocket, Missile, and Airframe Structures, October 2001 (Not for new design)
MIL-STD-464C	Electromagnetic Environmental Effects Requirements for Systems, December 2010
MIL-STD-889	Dissimilar Metals
MMPDS – 08	Metallic Materials Properties Development and Standardization (MMPDS)-08, Structural Joints
MSFC-SPEC-3659	MSFC Process Specification for Electrical Bonding, February 2012
NASA-STD-4003	Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment, Rev A, February 2013
NASA-STD-5020	Requirements for Threaded Fastening Systems in Spaceflight Hardware.
NASA-STD-6012	Corrosion Protection for Space Flight Hardware
NASM33522	Rivets, Blind, Structural, Mechanically Locked and Friction Retainer Spindle, (Reliability and Maintainability) Design and

	Construction Requirement for, National Aerospace Standard, March 2011
NASM33557	Nonstructural Rivets for Blind Attachment, Limitations for Design and Usage
SAE AMS 2403	Plating, Nickel General Purpose
SAE AMS 2404	Plating, Electroless Nickel, Rev E, 2003
SAE AMS 2408	Plating, Tin
SAE AMS 2418	Plating, Copper
SAE AMS 2451/12	Plating, Brush, Tin
SAE AMS 2460	Plating, Chromium
SAE AMS 2477	Conversion Coating for Aluminum Alloys Low Electrical Resistance Coating
SAE AMS 2700	Passivation of Corrosion Resistant Steels
SAE AMS 3266	Sealing Compound, Polythioether Elastomeric Two- Part Electrically Conductive
SAE AS14244	Clamp, Loop Type, Bonding, Metric
SAE AS7351	Clamp, Loop Type Bonding
SAE-AMS-S-8802	Sealing Compound, Temperature Resistant, Integral Fuel Tanks and Fuel Cell Cavities, High Adhesion