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ELECTRICAL BONDING FOR NASA LAUNCH VEHICLES, SPACECRAFT, PAYLOADS, AND FLIGHT EQUIPMENT

MEASUREMENT SYSTEM IDENTIFICATION: METRIC/SI

DOCUMENT HISTORY LOG

Status	Document Revision	Approval Date	Description
Baseline		09-08-2003	Initial Release
Revision	A	02-05-2013	Reformatted document to meet current NASA Standard Template Deleted the following document references: MIL-C-5541, MIL-STD-889, NSTS 37330, SAE-AMS-M-3171, SAE-ARP-1481 SAE-ARP-ILO1870, SSP 30245 Added the following Applicable Documents: NASA-STD-6012, NASA-STD-6016, SAE-ARP-5414 Section 3.1: Added “CFRP carbon fiber reinforced plastic” Section 3.1: Added “EMI Electromagnetic Interference” Section 3.1: Added “EUT Equipment under test” Section 3.1: Changed GFRP acronym. From: graphite filament reinforced plastic To: glass or graphite fiber reinforced plastic Section 3.2: In Electrical Bonding definition changed From: “…mechanical interfaces…” To: “…faying surface mechanical interfaces..” Section 3.2: Deleted redundant word “Provides” in third and forth bullet. Section 3.2: Added “faying surface” definition Table 1: Purpose of Class C Bond From: “Reduces power and voltage losses.” To: “Reduces power and voltage losses at the bonding interfaces.” Table 1:

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			Column: CLASS L, Row: BOND REQT. From: "Bonding components shall withstand high current." To: "Bonding components are required to withstand high current without arcing." Section 4.1.2.2 From: "…ignition point…" To: "…ignition temperature…" Added section: 4.1.2.4 Pipe, Tubing, and Hoses Section 4.1.3.d: From: "…ignition point…" To: "…ignition temperature…" Section 4.1.3.1 From: "…due to heating or arcing." To: "due to conditions including heating, sparking, or arcing." Figure 1: Changed curve title. From: "Maximum Resistance" To: "Maximum Allowable Resistance" Section 4.1.4.1: Changed paragraph title. From: "Electrical Connectors" To: "Electrical Connectors and Shield Termination" Section 4.1.5.a: Rearranged sentence to add clarity. Section 4.1.6: Converted inches to centimeters Section 4.1.6.b (1): Added requirement for conductive coatings. Section 4.1.6.b (2): Added information for surface conductivity. Section 4.1.6.2 From: "…20 decibels (dB) less than applicable minimum ignition energy (MIE) threshold

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			level…" To: "1/10 of applicable minimum ignition energy (MIE) (or 20 decibels (dB) below) threshold level…" Section 5.1.2: Moved the information from the following sections to 5.1.2 Bond Straps: 4.3.3 Bond Straps 4.4.2 Conductivity of Bond Joint 4.4.3 Bond Straps Added section "5.1.3 Fasteners" Removed detailed information on surface cleaning and finishing and pointed to NASA-STD-6012 and NASA-STD-6016 instead. Deleted the following sections: 5.2.1 Aluminum 5.2.2 Magnesium 5.2.3 Steel Deleted Table II, Galvanic Series. Deleted Section 5.4, Special Considerations, and changed to: 5.4 Graphite Filament Reinforced Plastic (GFRP). Section 5.4: Replaced "Graphite Filament Reinforced Plastic (GFRP)" with "Carbon Fiber Reinforced Plastic (CFRP)." Deleted Section 5.4.3 Multilayer Insulation Section 5.5.b: Added verbiage for end-to-end measurement option. Section 5.5.f: Added verification for conductive coatings. Section 5.5.g: Added verification for surface conductivity. Deleted Section 6.7 Surface Cleaning and Finishing

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			Moved Section 6.9 Special Considerations to the appendix and divided into the following sections: A.3.8 Pipe, Tubing and Hoses (Class S) A.3.9 Composite Materials A.3.10 Multilayer Insulation Section A.2: Added the following reference documents: NASA-HDBK-4002 NASA-HDBK-4006 NASA-STD-4005 NASA-STD-464C Section A.3.3 From: "…GFPR…" To: "…glass or graphite fiber reinforced plastic (GFRP)…" Section A.3.6: Added information on triboelectrification. Section A.3.11: Added information on verification processes. Section A.3.11: Added information on clamping pressure. Section A.3.11: Added Figure 2, Electrical Bonding Path Diagram Example

FOREWORD

This Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This Standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers.

This Standard establishes a common framework for consistent electrical bonding practices across NASA programs. The intent is to provide stand-alone requirements and to provide enough data to help modify requirements or to allow waivers if needed.

Requests for information, corrections, or additions to this Standard should be submitted via "Feedback" in the NASA Standards and Technical Assistance Resource Tool at https://standards.nasa.gov.

Original Signed By: 02-05-2013

Michael G. Ryschkewitsch
NASA Chief Engineer

Approval Date

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ELECTRICAL BONDING FOR NASA LAUNCH VEHICLES, SPACECRAFT, PAYLOADS, AND FLIGHT EQUIPMENT

1. SCOPE

1.1 Purpose

The purpose of this Standard is to define the basic electrical bonding requirements for NASA launch vehicles, spacecraft, payloads, and equipment. Its intent is to provide fundamental aerospace electrical bonding requirements, as well as to classify electrical bonds according to their purpose. This Standard also states the requirements for the various classes. The rationale for specific requirements is stated where possible. Additional data is provided to support tailoring for new applications, if necessary.

1.2 Applicability

This Standard is applicable to engineering practices for NASA programs and projects.

This Standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers, and may be cited in contract, program, and other Agency documents as a technical requirement. This Standard may also apply to the Jet Propulsion Laboratory or to other contractors, grant recipients, or parties to agreements only to the extent specified or referenced in their contracts, grants, or agreements.

Requirements are numbered and indicated by the word "shall." Explanatory or guidance text is indicated in italics beginning in section 4.

1.3 Tailoring

Tailoring of this Standard for application to a specific program or project shall be formally documented as part of program or project requirements and approved by the Technical Authority.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this Standard as cited in the text.

2.1.1 The latest issuances of cited documents shall apply unless specific versions are designated.

2.1.2 Non-use of specific versions as designated shall be approved by the responsible Technical Authority.

The applicable documents are accessible via the NASA Standards and Technical Assistance Resource Tool at https://standards.nasa.gov or may be obtained directly from the Standards Developing Organizations or other document distributors.

2.2 Government Documents

National Aeronautics and Space Administration

NASA-STD-6012	Corrosion Protection for Space Flight Hardware
NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft

2.3 Non-Government Documents

Society of Automotive Engineers (SAE) Aerospace

SAE-ARP-5412	Aircraft Lightning Environment and Related Test Waveforms
SAE-ARP-5414	Aircraft Lightning Zoning

2.4 Order of Precedence

This Standard establishes requirements for basic electrical bonding for NASA launch vehicles, spacecraft, payloads, and equipment but does not supersede nor waive established Agency requirements found in other documentation.

2.4.1 Conflicts between this Standard and other requirements documents shall be resolved by the responsible Technical Authority.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

μH	microhenries
ac	alternating current
AWG	American Wire Gauge
CFRP	carbon fiber reinforced plastic
CLASS C	class of bond for intentional current return
CLASS H	class of bond for fault current return
CLASS L	class of bond for lightning current
CLASS R	class of bond for radio frequency current
CLASS S	class of bond for dissipation of electrostatic charge
cm	centimeter
dB	decibels
dc	direct current
EED	electro-explosive device

EMF	electromotive force
EMI	electromagnetic interference
ESD	electrostatic discharge
ETR	Eastern Test Range
EUT	equipment under test
GFRP	glass or graphite fiber reinforced plastic
MHz	megahertz
MIE	minimum ignition energy
NASA	National Aeronautics and Space Administration
RF	radio frequency
SAE	Society of Automotive Engineers
STD	standard (as in document)

3.2 Definitions

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. Good electrical bonding provides the following:

- Fault current paths for protection against fire and personnel shock.
- A low impedance bond path for antenna installations to ensure no degradation of acceptable performance and to protect the antenna element from damage caused by P-static, radio frequency (RF) currents, or lightning events.
- A current path for RFs for proper operation of filters and shields.
- Protection against the effects of lightning.
- A means to prevent or safely discharge static charges.

Electrical bonds are classified according to the purpose for the bond. Table 1, Summary of Electrical Bonding Classes, gives a summary of the classes of bonds.

Faying Surface: The surface of metal materials in contact with each other and joined together.

Flight Vehicle: The launch vehicle and spacecraft or payload (if the payload outer surfaces are exposed to the triboelectrification process), and fairings or shrouds protecting payloads.

P-static: The precipitation static due to impact of charged particles on antennas.

Q: The ratio of reactance to resistance in a tuned circuit.

Table 1—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 at the bonding interfaces. Applies to equipment and structure, which are required to return intentional current through structure.	Protects against fire or shock to personnel. Applies to equipment and structure that may be required to carry fault current in case of a short to case or structure.	Protects equipment from RF emissions. Applies to equipment that could generate, retransmit, or be susceptible to RF. Includes antenna mounts and cable shield connections. Covers wide frequency range.	Protects equipment from lightning effects. 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 REQMT.	Requires low impedance and low voltage across joints to assure adequate power to the user. Jumpers and straps acceptable.	Requires low impedance and 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 are required to withstand high current without arcing. Straps and jumpers are required to withstand high magnetic forces.	Allows moderate impedance. Jumpers and straps acceptable.
DC BOND RESISTANCE REQMT.	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. REQMT.	Low	Low	High	High	Low
CURRENT REQMT.	High	High	Low	High	Low

Low frequency bonds allow use of straps and jumpers.
High frequency bonds require low inductance paths. Short straps are sometimes acceptable.
High current bonds require large cross sectional areas.
Low current bonds allow use of small contact areas.

4. GENERAL REQUIREMENTS

This section describes the various classes of electrical bonding. Each section contains the general requirement, specific design requirements, and, in most cases, measurable resistance values for each class of bond. Guidelines in Appendix A discuss the reasons for some of the requirements and provide data for possible modifications or rationale for waivers to the requirements.

4.1 Electrical Bonding

There may be more than one purpose for bonding a specific interface, and the bond shall meet the requirements of each applicable class.

4.1.1 Assembly Drawings

Notes shall be provided on assembly drawings indicating the applicable class or classes.

4.1.2 Power Current Return Path (Class C)

All circuit and systems that use vehicle structure for a power return path shall satisfy Class C bonding requirements.

4.1.2.1 Bond Joints

a. The total voltage drop across all electrical bond joints between the power supply and the load shall be controlled in order to keep the voltage within the tolerance of the applicable power quality standard.

b. If no power quality standard is applicable, a default voltage drop value of 3.5 percent of the operating bus voltage shall be used.

Refer to Appendix A.3.2 for more information and joint resistance calculation.

4.1.2.2 Magnesium Alloy

Magnesium alloy structure shall not be used as an intentional current return path. *The temperature of a poor joint could rise to the ignition temperature of magnesium.*

4.1.2.3 Hazardous Area Bonding

a. Electrical bonding of equipment or vehicle structure in areas where flammable materials, gases, or vapors may be present shall be adequate to prevent ignition due to heating, sparking, or arcing.

b. *If at all possible, the current return path should be routed around the hazardous area.* The resistance of bond joints in hazardous areas shall not exceed the Maximum Allowable

Resistance curve shown in figure 1, Fault Current vs. Maximum Allowed Bonding Resistance in the Presence of Flammable Vapors or Liquids.

4.1.2.4 Pipe, Tubing, and Hoses

Pipes, tubing, and hoses shall not be used as an intentional return path for electrical current.

4.1.3 Shock and Fault Protection (Class H)

Fault current, due to short circuits to equipment case or structure, may cause shock or fire hazards. Refer to Appendix A.3.3 for more information.

a. Exposed cases or chassis of electrical or electronic equipment shall be bonded to structure with a resistance of 0.1 ohm or less using the methods described in section 5.1.

b. Metallic conduit, cable trays, and other conductive objects susceptible to short circuits shall have a resistance to structure of 0.1 ohm or less.

c. For personnel and fire safety, the fault current return path shall be capable of conducting a minimum of 500 percent overload current for a time period of 0.5 second.

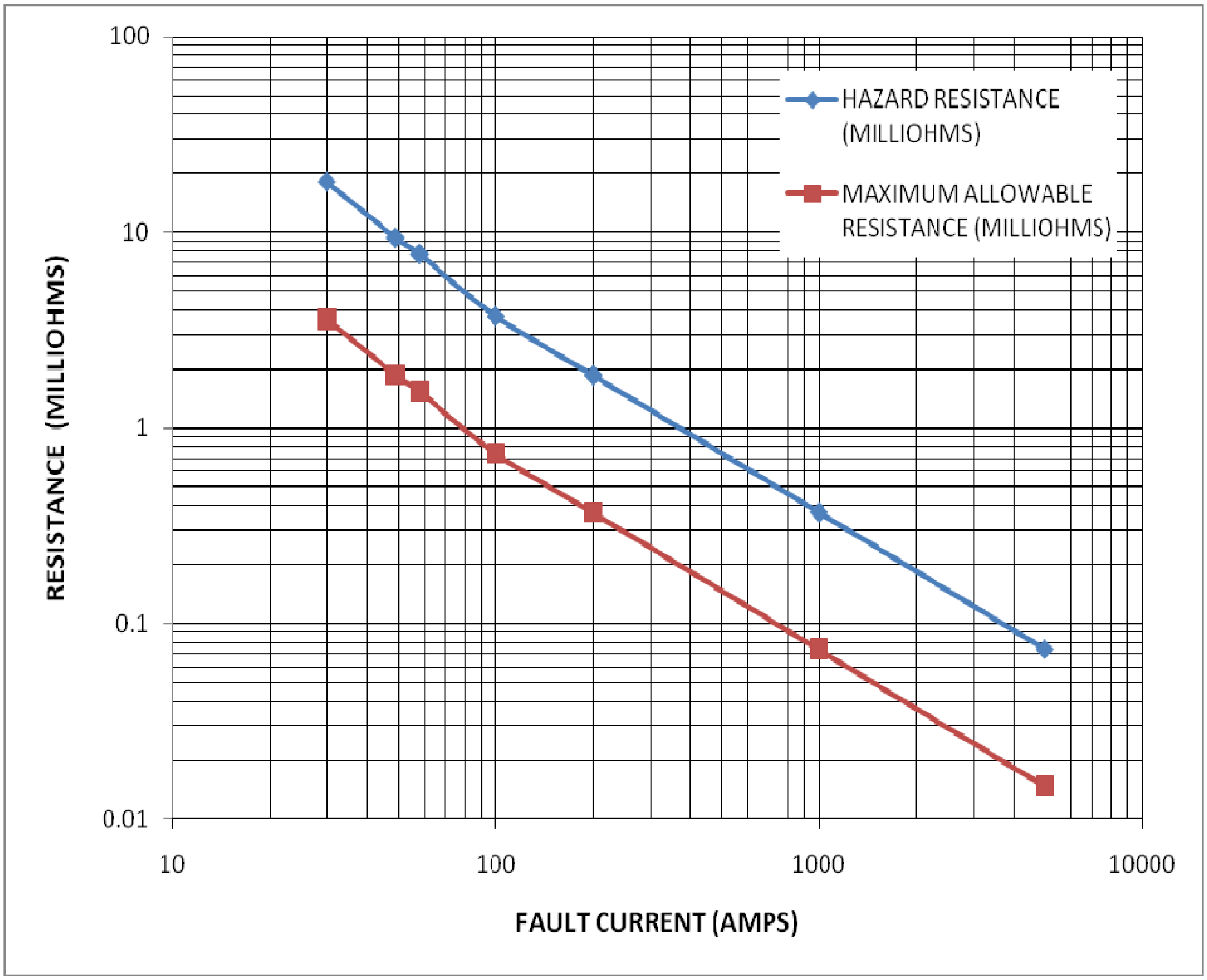
Typical personnel protection breakers will trip within 0.2 second after a hard short to case. Resultant voltage on the enclosure of the affected component should not exceed 4.5 volts, and no fire or damage to the bond is allowed.

d. Magnesium alloy structure shall not be used as a primary fault current return path. *The temperature of a poor joint could rise to the ignition temperature of magnesium.*

4.1.3.1 Hazardous Area Bonding

Electrical bonding of equipment or vehicle structure in areas where flammable materials, gases, or vapors may be present shall be adequate to prevent ignition due to conditions including heating, sparking, or arcing.

a. The resistance of bond joints in such areas shall not exceed the Maximum Allowable Resistance curve shown in figure 1.



FAULT CURRENT (AMPS)	MAXIMUM ALLOWABLE RESISTANCE (MILLIOHMS)	HAZARD RESISTANCE (MILLIOHMS)
30	3.6	18
49	1.86	9.3
58	1.54	7.7
100	0.74	3.7
200	0.37	1.85
1000	0.074	0.37
5000	0.0148	0.074

Figure 1—Fault Current vs. Maximum Allowed Bonding Resistance in the Presence of Flammable Vapors or Liquids

4.1.4 Electromagnetic Interference or Radio Frequency (Class R)

The intent of Class R bonding is to provide a uniform low impedance path for all electrical equipment at radio frequencies. Refer to Appendix A.3.4 for more information.

a. All electrical and electronic equipment shall be bonded using the methods described in section 5.1, to provide a low impedance path from the equipment enclosure to structure.

b. All Class R bond paths to structure, and the joints in that path, shall be designed such that the inductance and overall impedance, including resonances, are low enough to prevent interference at the frequencies of interest.

(1) The direct current (dc) resistance across each joint in the path shall not exceed 2.5 milliohms.

c. The design and construction of the outer mold line of the vehicle shall implement Class R electrical bonding between all outer mold line components so as to inherently provide a uniform low impedance enclosure surrounding the vehicle.

d. Hatches, access panels, doors, and other apertures in outer mold line components shall have at minimum a Class R electrical bond to the outer mold line material.

e. Vehicle structural elements shall have a Class R electrical bond between elements, as well as between structural elements and outer mold line components, so that the entire structure of the vehicle is interconnected with uniform low impedance.

4.1.4.1 Electrical Connectors and Shield Termination

a. Electrical connectors and their backshells that may be used to terminate cable shields shall be installed to provide a low impedance path from the backshell to the equipment case.

b. The dc resistance for each joint in the backshell-to-case path shall not exceed 2.5 milliohms.

Examples of such joints include between shield and backshell, backshell and connector, harness connector and enclosure connector, and enclosure connector and equipment enclosure.

4.1.4.2 Antennas

Antennas that require low impedance to the ground plane for proper operation shall meet Class R requirements.

4.1.5 Lightning Protection (Class L)

Protection against lightning strikes should be provided for launch vehicles and their payloads during transportation, storage, prelaunch, launch, and landing. Propellant, pyrotechnics, and electronic equipment are particularly susceptible to direct and indirect effects of lightning. Refer to Appendix A.3.5 for more information.

a. In order to distribute the current around the vehicle and minimize the currents near possible entry points into the vehicle and near critical areas and systems (including pyrotechnic systems, rockets motors, fuel handling and storage areas, antennas, electronic equipment, and signal and power cables), multiple low impedance paths shall be incorporated across and through vehicle outer mold line and structural components.

(1) The dc resistance of all such joints shall be no greater than 2.5 milliohms.

All joints in vehicle outer mold line components should be designed to present the minimal impedance achievable to the lightning currents that may pass across the joint.

b. Each electrical bond shall be bonded using the methods described in section 5.1, have low resistance and adequate contact area to carry its share of lightning current without sustaining a burning, melting, distorting, or other heating effect due to the long duration, high-current portion of the lightning strike.

(1) The bonds shall have low impedance to prevent arcing and coupling of voltage spikes into electronic circuits due to the fast rise time portion of the lightning strike.

c. *Hatches, access panels, doors, and other apertures in outer mold line components expected to carry high amplitude lightning currents should be bonded with multiple low impedance connections to minimize aperture size and slot length.* The dc resistance of all such joints and connections shall be no greater than 2.5 milliohms.

d. *Electrical cables that are outside the vehicle mold line or that could carry the lightning current should be completely enclosed in gross overshields with a circumferential 360 degree termination into bulkhead penetrations, connectors, or connector backshells.* All such shield terminations, and any connectors or connector backshells in the lightning current path, shall be capable of carrying expected lightning currents without damage.

(1) The dc resistance of each such shield termination shall not exceed 2.5 milliohms.

e. All paths should exhibit the minimal impedance achievable in each path. All paths shall be designed using zoning information developed in accordance with SAE-ARP-5414, Aircraft Lightning Zoning, supplemented by analysis employing lightning current waveforms defined in SAE-ARP-5412, Aircraft Lightning Environment and Related Test Waveforms.

f. The voltage developed across any joint in the lightning current path shall not exceed 500 volts.

g. Each bond in the lightning current path shall be capable of carrying expected lightning current.

4.1.5.1 Hazardous Area Bonding

a. Fuel and pyrotechnics shall be completely enclosed by a Faraday cage of conductive material bonded to structure.

b. Pyrotechnics cables and device connector shields shall have 360 degree bonded termination to the metal enclosure/backshell.

4.1.6 Electrostatic Discharge (Class S)

All conducting items, except active antenna elements, having any linear dimension greater than 7.6 centimeters (cm), which are subject to precipitation static effects, triboelectric effects, fluid flow, air flow, space and launch vehicle charging, separation of elements, and other charge generating mechanisms, shall have a mechanically secure electrical bond path to vehicle structure using the methods described in section 5.1. *See Appendix A.3.6 for more information.*

a. The resistance across the connection shall be 1.0 ohm or less.

A mechanically secure electrical bond path is a continuous bond path that maintains the default dc resistance (or lower) after exposure to shock, vibration, launch loads, and other expected mechanical movement.

A limit of 1.0 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.

b. *Higher dc resistance values acceptable for Class S electrical bonds may be determined 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.* The stored energy determined by the analysis shall be less than applicable hazard threshold levels for personnel shock, equipment upset, flammable materials, gases, or vapors, or electro-explosive device (EED) ignition for approval of the proposed electrical bond resistance.

(1) All conductive coatings, including those used to treat dielectric surfaces, shall be electrically bonded to the vehicle structure with a dc resistance of less than 10^5 ohms.

Launch services providers may levy flight vehicle surface conductivity requirements. See Appendix A.3.6 for more information.

4.1.6.1 Multilayer Insulation

a. All conductive layers of multilayer insulation with an area greater than 100 square cm shall be electrically bonded together.

(1) Provisions shall be made for attachment to the vehicle structure.

A. The conductive attach points shall be bonded directly to the structure using the methods described in section 5.1.

B. Two attach points to the structure per blanket shall be used for redundancy.

C. Resistance from attach points to the structure shall be 1.0 ohm or less.

b. Multilayer insulation with an area greater than 100 square cm shall have a minimum of one bond connection to the vehicle structure.

c. Multilayer insulation with an area greater than 1,000 square cm shall have a minimum of two bond connections to the vehicle structure.

d. A minimum of one additional bond connection to the vehicle structure shall be made for each increase of 40,000 square cm.

e. Multilayer insulation consisting of two or more sections shall have all sections electrically bonded to each other.

(1) The contiguous insulation thus formed shall be considered as one section of insulation for determination of the number of bond tabs.

4.1.6.2 Hazardous Area Bonding

a. All conductive items in areas where flammable materials, gases, or vapors may be present shall have a Class S electrical bond not to exceed 1.0 ohm.

(1) In no case shall any such electrical bond be inadequate to prevent ignition due to heating or arcing.

b. Specific Class S electrical bond values in hazardous areas shall be determined 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.

(1) The stored energy determined by the analysis shall be 1/10 of applicable minimum ignition energy (MIE) (or 20 decibels (dB) below) threshold level for the flammable materials, gases, or vapors that may be present.

4.1.6.3 Pipe, Tubing, and Hoses

a. All metallic pipes, tubes, and hoses that carry fluids shall have a mechanically secure connection to the structure that will measure 1.0 ohm or less.

b. Nonmetallic plumbing installations shall be designed so that the static voltage, generated by fluid flow, will not exceed 350 volts at any point outside the pipes, tubes, or hoses.

c. The resistance of nonmetallic hoses shall not exceed 1.0 megohm per meter of length to dissipate charges developing within the fluid or between fluid and the hose.

5. DETAILED REQUIREMENTS

5.1 Bonding Methods

The following paragraphs describe the bonding methods, with the metal-to-metal method being the preferred method. The metal-to-metal method may not be feasible, and the bonding strap or fastener method may be the best bonding alternative for the application.

5.1.1 Metal-to-Metal (faying surface to faying surface)

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 inherently bonded.

a. Semi-permanent joints held together by screws, rivets, clamps, etc., shall have their faying surfaces prepared prior to assembly in accordance with paragraph 5.2 to ensure a good electrical bond.

(1) Clamping pressure across semi-permanent joints shall be in accordance with applicable mechanical engineering assembly and installation requirements.

5.1.2 Bond Straps

Where the direct joining of structural elements, assemblies, and electrical paths is impossible or impractical, bonding straps or jumpers may be used.

Bond straps or jumpers may be used to meet Class C, H, or S bonding requirements, and are useful for some cases in Class L.

The usefulness of bond straps for Class R bonds is very limited, and should be used only as a last resort and with approval by the procuring agency.

a. Bonding straps installed across shock mounts or other suspension or support devices shall not impede the performance of the mounting device.

(1) The bond straps shall be capable of withstanding the anticipated motion and vibration requirements without suffering metal fatigue or other failure.

Extra care should be utilized in the attachment of the ends of bonding straps to prevent arcing or other means of electrical noise generation with movements of the strap.

b. For Class R bonds, the bonding straps shall be as short as possible.

(1) The bond straps shall be flat in cross-section.

(2) The bond straps shall have a length-to-width ratio of less than 5 to 1 to minimize the inductance of the strap.

c. For Class L application of bond straps, the bond straps or jumpers shall be as short as possible.

(1) The bond straps shall have adequate lug contact area and adequate wire/lug cross sectional area to carry the lightning current.

(2) The cross sectional area of any individual jumper shall not be less than number 12 American Wire Gauge (AWG) wire (6530 circular mils) for stranded copper, and not less than number 10 AWG wire (10,380 circular mils) for stranded aluminum.

These wire sizes are only valid when two or more jumpers are installed to carry lightning current and when the jumpers are not subject to a direct arc.

(3) Where the jumper is subject to arcing, a minimum of number 7 AWG (20,820 circular mils) for copper or number 5 AWG (33,100 circular mils) for aluminum for each jumper shall apply.

(4) The jumper shall be robust enough to withstand magnetic forces caused by the high current through the strap.

(5) The jumper shall not rely on soldered connections to carry lightning current.

For multistroke protection or if arcing at the jumper is expected the total cross sectional area of the straps should be 40,000 circular mils or greater.

5.1.3 Fasteners

If the bond application is approved by the procuring agency, fasteners (e.g., bolts, nuts, or studs) may be used to meet bonding requirements. Fasteners should be primarily used to maintain pressure on faying surfaces. However, in some cases 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.

a. When bolts are used as part of the bond path, an analysis shall be performed showing that the number of bolts used in the path is sufficient to provide a low impedance path.

b. Fasteners shall be sealed against moisture and air to prevent corrosion of the threads.

Rivets are acceptable if a minimum of three rivets is used per junction and they are match-drilled.

c. The following are problematic and shall not be used for electrical bonding purposes:

- Self-tapping screws.
- Zinc-plated bolts, nuts, or screws.
- Star, anodized, or zinc-plated washers.
- Cadmium-plated hardware.

d. For Class L applications, multiple rivets, bolts, or other fasteners shall be used at joints in vehicle skin and structure to ensure multiple metallic contact areas capable of sharing lightning current.

5.2 Surface Cleaning and Finishing

a. The faying surfaces of all electrically bonded metal-to-metal joints shall be cleaned of all nonconductive materials and protected against corrosion.

b. The finishes and protection methods for faying surfaces shall be per NASA-STD-6012, Corrosion Protection for Space Flight Hardware, and NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft.

(1) The protection method or finish selected shall not negate the electrical bond between the two surfaces.

c. Treated mating surfaces shall be protected by packaging materials or protective films until just prior to mating.

d. After protective material is removed, the surfaces shall be cleaned by blowing, vacuuming, or wiping with appropriate solvent as necessary to remove dust or other foreign particles before mating.

e. Non-hardening sealant or thermal grease may be applied to the faying surfaces of semi-permanent joints if tests indicate bonding requirements can be met after assembly.

If the bond is permanent, a hardening sealant, such as chromated epoxy primer, may be used if tests indicate bonding requirements can be met after assembly.

f. Surfaces that are expected to remain mated indefinitely shall be inspected periodically to ensure a good electrical bond is maintained.

5.3 Galvanic Corrosion of Dissimilar Materials

Direct contact of dissimilar materials in the presence of moisture may result in corrosion, which impairs the effectiveness of any electrical bond and weakens the structure in which it occurs. When choosing materials for a given electrical bonding application, major factors that contribute to corrosion are the degree of separation of metals in the galvanic series and the amount of moisture present.

a. Corrosion control of galvanic couples shall be in accordance with NASA-STD-6012 and NASA-STD-6016.

Refer to Appendix A.3.7 for more information.

5.4 Carbon Fiber Reinforced Plastic

Carbon fiber reinforced plastic (CFRP) provides some conductivity through the graphite filaments. However, the graphite is usually covered with nonconductive epoxy or phenolic material.

a. CFRP shall be bonded to control electrostatic discharge (ESD) and may be useful as an RF bond.

b. CFRP shall not be used in a Class C or Class H bond path.

The procedure for bonding CFRP requires removing enough nonconductive material from the mating surfaces to expose the graphite layer. Electrical bonds between CFRP sheets can be made by overlapping exposed graphite on both sheets. Conductive epoxy may also be placed on the exposed graphite, and bonding connections may be made to metallic surfaces through the conductive epoxy.

NOTE: A fire hazard exists with current flow through graphite epoxy materials.

5.5 Verification

a. Verification of electrical bonding requirements shall be accomplished by a combination of tests, similarity, analysis, and inspection.

b. The extent of verification and the methods used shall be defined for each program.

Some requirements should be verified at the equipment level, such as bonding of equipment assembly interfaces and connector backshell contacts.

The resistance of bonds may be measured on flight vehicles, but it is usually impractical to measure inductance or current carrying capability.

Verifying each joint in a bond path is not always feasible and therefore an end-to-end measurement may be an option. Controls need to be implemented in shield termination paths through connector assemblies. A realistic value would be on the order of 10 milliohms from the shield to the electronics enclosure for a cadmium-plated aluminum assembly, with 2.5 milliohms maximum for any particular joint.

c. The resistance requirement of all classes of bonds shall be verified by testing sample bonds.

Other bonds of the same type, using the same procedures, may be verified by similarity.

d. Spot checks shall be made to verify the process is still good and is being followed.

e. Class C, H, and L bonds require current carrying capability, as well as low resistance contacts. The current carrying capability shall be verified by analysis and inspection.

f. Class R and Class L bonds require low inductance paths as well as low resistance. The low inductance path shall be verified by analysis and inspection.

g. For flight vehicle surfaces that have been treated with conductive coatings (4.1.6.b.1), test or analysis shall show that the bonding requirements are met.

(1) Relaxation of this requirement shall only be granted if it has been clearly verified by test or analysis that electrostatic charges deposited on the surface of the vehicle will not be hazardous to the flight vehicle or the launch mission.

h. If flight vehicle surface conductivity requirements are imposed (4.1.6.b.2), the flight vehicle surface material resistivity requirements shall be verified through test or analysis.

(1) Relaxation of this requirement shall only be granted if it has been clearly verified by test or analysis that electrostatic charges deposited on the surface of the vehicle, caused by triboelectrification from precipitation particle impact, will not be hazardous to the flight vehicle or the launch mission.

Flight vehicle includes the launch vehicle itself, the payload (if the payload outer surfaces are exposed to the triboelectrification process), and fairings or shrouds protecting payloads.

APPENDIX A

GUIDANCE

A.1 Purpose

The purpose of this appendix is to provide information on the reasons for some of the requirements and to provide data for possible modifications or rationale for waivers to the requirements.

A.2 Reference Documents

	Fisher, Franklin A.; Plumer, Anderson J.; and Perala, Rodney A. (1990). *Lightning Protection of Aircraft*. Pittsfield, MA: Lightning Technologies, Inc. (LTI).
	Terman, F. E. (1943). *Radio Engineers' Handbook*. New York and London: McGraw Hill Book Co., Inc.
AFSPCMAN91-710V6	Range Safety User Requirements Manuel Volume 6 – Ground and Launch Personnel, Equipment, Systems, and Material Operations Safety Requirements
NASA-HDBK-4002	Mitigating In-Space Charging Effects – A Guideline
NASA-HDBK-4006	Low Earth Orbit Spacecraft Charging Design Handbook
NASA-STD-4005	Low Earth Orbit Spacecraft Charging Design Standard
MIL-HDBK-274	Military Handbook: Electrical Grounding for Aircraft Safety
MIL-STD-464C	Electromagnetic Environmental Effects, Requirements for Systems
SAE-ARP-1870	Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety

A.3 GUIDELINES

A.3.1 Design Parameters

Since a single bond may serve multiple purposes, electrical bonding is performed in accordance with the requirements of the strictest applicable class or in some cases the strictest requirements from more than one class. An example of electrical bonding for more than one purpose would be a piece of electronic equipment powered from the system power supply. It would require Class R bonding for RF and Class H bonding for fault current protection. Since both classes are applicable, the bond should be low inductance with no more than 2.5 milliohms dc resistance for Class R, and the contact area should be adequate to carry the maximum fault current that could occur for Class H.

A nose cone should meet the lightning and static charge requirements. The Class L requirement calls for low inductance, low resistance, and adequate area to carry lightning current. Since the bond requirement for static charge is only moderately low resistance the lightning bond will be sufficient for both.

The only requirement for conductive tubing carrying fluid will be to meet the Class S requirement. An electrical bond to basic structure of 1.0 ohm or less will be adequate.

A.3.2 Power Current Return Path (Class C)

See paragraph 4.1.2 for applicable requirements. A dedicated power return is preferred over the use of structure for power current return and will be stated as a requirement for most programs. However, structure return is occasionally used for some systems such as small satellites.

In those cases where structure current is used, the voltage drop allowed divided by the maximum current that may be delivered by the power supply will give the total resistance allowed in the circuit. This total resistance includes the wire, its connectors, and all Class C electrical bond joints in the structure return path. The resistance limit for each Class C electrical bond joint can then be determined by subtracting the resistance of the wire and interconnections from the total resistance, and dividing the remaining value by the number of Class C electrical bond joints in the path.

A.3.3 Shock and Fault Protection (Class H)

See paragraph 4.1.3 for applicable requirements. The fault current, resulting from a short between a power wire and a metallic equipment case or other conductive structure, should return through structure and the joints in the structure to its source. Circuit protection devices are intended to limit the duration of fault current events to prevent a significant temperature increase in the circuit wiring. Typically, the fault current is considerably higher than the fuse or breaker value, and it trips the device quickly. However, a circuit breaker can sometimes take several seconds to trip with a current twice its rating. Resistance across all the joints in the return path should be low enough to allow enough current to trip circuit protection devices in a timely manner.

SAE-ARP-1870, Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety, restricts voltages on electronic equipment cases to less than 4.5 volts and requires no fire or damage to the bond in the event of a short to case.

For shock protection from voltages exceeding 30 volts, MIL-HDBK-274, Military Handbook: Electrical Grounding for Aircraft Safety, recommends a circuit breaker break time of 0.2 second.

Structural material that is not highly conductive, such as glass or graphite fiber reinforced plastic (GFRP), may increase the path resistance enough to delay or prevent tripping the circuit breaker. In addition to being a shock hazard, fault current can cause ignition of graphite epoxy material.

Straps or jumpers may be adequate for fault current returns, but low resistances are required. The inductance of the strap is not a concern for fault current since the high current will be from a dc or low frequency alternating current (ac) power source. Inductance will be a concern if the strap conducts RF or lightning current.

A.3.4 Electromagnetic Interference or Radio Frequency (Class R)

See paragraph 4.1.4 for applicable requirements. The Class R bond is not required on all equipment, but it is difficult to determine in advance which equipment really needs to be well bonded. The low impedance to structure is necessary for certain power line to equipment chassis filters and for proper operation of cable shields terminated to equipment chassis. Isolated structural elements with linear dimensions approaching 1/4 wavelength, can pick up and re-radiate RF from high power transmitters or develop enough voltage to produce a glow discharge or arcing to other elements. This should be taken into account when sizing the length of straps or jumpers used for Class R bonds, as such elements themselves can become a significant source of interference under conditions described above.

There is no RF design basis for the historical 2.5-milliohm requirement except to ensure a good metal-to-metal contact that can be expected to be consistent. The basic requirement is to have low impedance at the frequency or frequencies of interest. The value of this impedance depends upon the quality of the surface preparation (e.g., the chemical formulation used for the conversion coating, and the thickness thereof), the area of the faying surfaces in contact, and the amount of pressure holding the surfaces together. The impedance of an acceptable bond may be in the ohms range for RF even though the dc resistance is less than 2.5 milliohms. The resistance is overshadowed by the inductive reactance of the configuration.

Any electronic equipment with conductive mounting feet will probably have an inductive reactance greater than 2.5 milliohms at frequencies above 10 megahertz (MHz). RF bonds may be satisfactory with several ohms of impedance; but, when straps are used, even these levels will be quickly exceeded as frequency increases. If the use of bond straps for RF bonds is unavoidable, strap length should always be limited to a length to width ratio of 5 to 1.

Monopole or half-loop antennas mounted on composite outer mold line surfaces should be provided with circular or elliptical groundplanes or counterpoises 1/4 wavelength in radii over the operating frequency range of the antenna, and should be installed with a low impedance return path to vehicle structure that exhibits a dc resistance no greater than 2.5 milliohms, so that antenna fields are not attenuated by poorly conductive composite material. Antennas mounted on composite outer mold line surfaces that do not require local groundplanes or counterpoises but that otherwise require a low impedance path to the vehicle structure for proper operation, should be installed with a low impedance return path to the vehicle structure that exhibits a dc resistance no greater than 2.5 milliohms. Antennas of all types, mounted on metallic outer mold line surfaces, that require a low impedance path to the mounting surface for proper operation, should provide a return path to vehicle structure that exhibits a dc resistance no greater than 2.5 milliohms.

The 2.5-milliohm dc resistance requirement is good for a standard, but one should not assume a good RF bond exists just because the dc resistance is less than 2.5 milliohms. Also, extra effort need not be made just to satisfy the dc requirement if the RF impedance is much higher due to the inductance of the configuration. Look at the whole configuration to get the lowest impedance possible at the frequencies of interest to produce a good RF bond.

The electrical bond path between an electronic box and the structure has a complex equivalent circuit that may be simplified to a resistance in series with an inductance all in parallel with a capacitance. The equivalent resistance includes the resistance of any bond strap present plus the resistance of the joints in the path. At higher frequencies, where the diameter or thickness of the strap significantly exceeds the skin depth, the ac resistance becomes larger than the dc resistance. The ac resistance increases with the square root of frequency.

The inductance is directly proportional to the length of the bond path, but is also a function of width and thickness. Multiple paths can reduce the inductance value by introducing additional parallel current paths. The magnitude of inductive reactance increases 20 dB with every decade of frequency increase.

The capacitance between the box and the structure is proportional to the area of the interface and inversely proportional to the distance between the box and the structure. The magnitude of capacitive reactance decreases 20 dB per decade of frequency increase.

The total impedance across the joint is equal to the resistance at frequencies from dc to the point where the inductive reactance approaches the resistance. The impedance due to inductance then increases at 20 dB per decade of frequency to a frequency where the inductive reactance and the capacitive reactance are equal. At this parallel resonant frequency, the impedance may rise to thousands of ohms depending on the ratio of reactance to resistance (Q) in the circuit. The Q is high when the resistance is low, which is usually the case for a bonding joint. At frequencies above this point, the capacitive reactance is less than the inductive reactance; and the total impedance begins to come back down. Often there are more complex series and parallel resonances; and, at the higher frequencies, the impedance may vary considerably.

Handbooks such as Terman's Radio Engineer's Handbook (1943) should be consulted for calculations of RF impedance of various bonding configurations.

For electromagnetic interference (EMI) testing, the equipment under test (EUT) bonding method to the copper-top test table will be as close as practicable to the flight configuration (i.e., bond strap, surface mating, etc.). Only the provisions included in the design of the equipment and specified in the installation instructions will be used to bond units, such as equipment case and mount, together or to the ground plane. If the EUT is secured to mounting bases, incorporating shock or vibration isolators, such mounting bases will be used in the test configuration. Bonding straps furnished with the mounting base will be connected to the ground plane. Where mounting bases do not incorporate bonding straps, bonding straps will not be used in the test setup. If installation conditions for the EUT are unknown, the EUT will not be grounded. Portable equipment should be tested while bonded to the ground plane and also while not bonded to the ground plane.

A.3.5 Lightning Protection (Class L)

See paragraph 4.1.5 for applicable requirements. Electrical bonding in itself does not ensure lightning protection, but it is a major part of the overall plan. 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 provide a path to some exit point. A good current path should be provided around the outside of the vehicle to help protect internal equipment. Electrical bonding helps provide the proper continuity for the path.

Even when a large current path is provided to carry the current, attach points across joints still may present a problem. Arcing at joints can be expected even with good electrical bonds. Lightning current waveforms, as defined in SAE-ARP-5412, have rates of rise of 1×10^{11} amps/second. Considering a bond connection with inductance of 0.1 μH would result in a voltage spike across the joint of 10,000 volts. The arc produces an ionized path that helps carry the current. The majority of the current can be kept external to the vehicle through good electrical bonding of the vehicle skin.

When bonding straps are used, they should be kept short to ensure that inductance and resistance are kept as low as possible. The strap and connections should be robust enough to survive the high lightning current and the magnetic forces resulting from high lightning current. Straps should not have loops or bends greater than 45 degrees to avoid damage from magnetic forces. Information concerning lightning bonds may be found in "Lightning Protection of Aircraft" by Lightning Technologies, Inc.

Apertures should be kept as small as possible. Joints should be bonded in many places to prevent long slots between bonds. Joints and apertures in the skin allow some voltage to be induced into underlying cables. This voltage should be kept low enough to prevent disrupting electronic equipment.

Special care should be taken to route current around fuel or pyrotechnics to prevent arcs that can ignite fuel or current that can fire 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 degrees terminations to the metal enclosure.

A.3.6 Electrostatic Discharge (Class S)

See paragraph 4.1.6 for applicable requirements. The resistance to ground, structure, or another lower charged object affects the rate of discharge for an item being charged. A low resistance reduces the charge faster, but bonds with resistances that would be considered high, such as 10 kilohms to 100 kilohms, usually function adequately. The charging current, usually in microamps, returning through the resistance to ground determines the voltage developed.

Electrostatic charges should be controlled and dissipated to avoid fuel ignition and ordnance hazards, to protect personnel from shock hazards, and to prevent performance degradation or damage to electronics. A requirement for 1.0 ohm or less to ground is a good requirement for metal items because any good metal-to-metal connection will measure less than 1.0 ohm. Under some circumstances, such as when semiconductive materials or complex configurations are used, this limit may be increased. Metal straps or jumpers across joints are adequate since the current is dc.

An arc discharge can cause direct effects to the item being discharged and to the item receiving the discharge. Indirect effects may be caused by voltages induced into neighboring items. Direct or indirect effects include physical damage to an item, upset of operation, ignition, or shock to personnel.

Engineering guidelines and design practices to minimize the effects of spacecraft surface and internal charging in space environments is given in NASA-HDBK-4002A, Mitigating In-Space Charging Effects – A Guideline. It serves as a reference source that contains suggested detailed spacecraft design requirements and procedures to minimize the effects of spacecraft charging and to limit the effects of the resulting ESD. This Handbook is complementary to NASA-STD-4005, Low Earth Orbit Spacecraft Charging Design Standard, and NASA-HDBK-4006, Low Earth Orbit Spacecraft Charging Design Handbook. NASA-STD-4005 and NASA-HDBK-4006 addresses Low Earth Orbit spacecraft charging at the auroral zones (attitude from 200 and 1000 km and latitude between -50 and +50 degrees).

Launch service providers, such as the Eastern Test Range (ETR), may impose additional requirements on the flight vehicles that launch from their range. The ETR levies a surface conductivity requirement on flight vehicles to protect from triboelectrification effects. Air Force specification, AFSPCMAN91-710V6, Range Safety User Requirements Manual Volume 6 – Ground and Launch Personnel, Equipment, Systems, and Material Operations Safety Requirements, contains the following triboelectrification requirements:

> "Section A.7.2.5.4 Natural and Triggered Lightning Launch Commit Criteria
>
> "A7.2.5.4.10. Triboelectrification. Do not launch if a vehicle has not been treated for surface electrification and the flight path will go through any clouds above the –10 °C level up to the altitude at which the vehicle's velocity exceeds 3,000 ft/sec. A vehicle is considered "treated" for surface electrification if:

"A7.2.5.4.10.1. All surfaces of the vehicle susceptible to precipitation particle impact have been treated to assure

"A7.2.5.4.10.1.1. *That the surface resistivity is less than* 10^9 *ohms/square;*

and

"A7.2.5.4.10.1.2. *That all conductors on surface (including dielectric surfaces that have been treated with conductive coatings) are bonded to the vehicle by a resistance that is less than* 10^5 *ohms;*

or

"A7.2.5.4.10.2. It has been shown by test or analysis that electrostatic discharges (ESDs) on the surface of the vehicle caused by triboelectrification by ice particle impact will not be hazardous to the launch vehicle or the mission. In A7.2.5.4.10.1.1 above, the correct unit for surface resistivity is ohms/square. This means that any square area of any size measured in any units has the same resistance in ohms when the measurement is made from an electrode extending the length of one side of the square to an electrode extending the length of the opposite side of the square. The area-independence is literally valid only for squares; it is not true for other shapes such as rectangles and circles."

In summary, bonding for electrostatic charge should use the 1.0-ohm requirement for ordinary metal joints to ensure a good connection. The 1.0-ohm requirement simply ensures the metal-to-metal bond is a clean, quality bond that will retain its conductivity. Good connections that measure up to 100 kilohms from equipment to ground for unusual configurations or semiconductive materials may be acceptable. Jumpers and straps may be used.

A.3.7 Galvanic Corrosion of Dissimilar Materials

See paragraph 5.3 for applicable requirements. NASA-STD-6012 and NASA-STD-6016 contain considerably more information on this subject.

Two materials may be placed in direct contact if the electromotive force (EMF) difference between their groups is not more than 0.25 volts. Where other dissimilar materials are placed in contact, galvanic reaction may cause corrosion of the material that is higher (more anodic) in the galvanic series. Corrosion impedes current flow and damages materials. When two materials form a couple that is incompatible, the materials should be plated, coated, or otherwise protected with a conductive finish compatible with each; or a material compatible with each should be inserted between the two materials.

If the mating of dissimilar materials cannot be avoided, the most active of the materials should be replaceable in reusable vehicles. In all applications the electrolyte contact area of the most anodic materials, higher in series, should be larger than that of the cathodic materials. The larger the anodic area the lower the current density will be on more cathodic-materials. An approved sealant should be used to seal all edges from moisture.

A.3.8 Pipe, Tubing and Hoses (Class S)

See paragraph 4.1.6.3 for applicable requirements. The movement of fluid through a hose or tubing provides a charging source. If the fluid is not conductive, it can carry charges to conductive items in the fluid path. Conductive items in the fluid flow path should be bonded to structure to prevent a static charge buildup.

Conductive hose or tubing grounded to structure will help prevent charging. Conductive fluids can also prevent the charge separation. With a nonconductive fluid in nonconductive tubing, the charge may transfer to conductive items in the line or, if enough potential develops, a discharge may occur through an arc from the fluid through the tubing to a metal sheath or other conductive items outside the tubing. This arc may produce small holes in the tubing.

Tubing is available that is somewhat conductive and prevents the separation and movement of the charge if its resistivity is less than 1 megohm per meter of length. Fluids with volume resistivity less than 10^7 ohm-meters are conductive enough to prevent the separation of charge, but there is seldom a choice of fluids.

A.3.9 Composite Materials

Some composite materials are nonconductive and should not be used where static discharge could be a problem. CFRP, or composite materials that contain metal particles, could be conductive enough to drain off static charges if given a conductive path from the material to metallic structure. See paragraph 5.4 for applicable CFRP requirements when using materials, such as honeycomb graphite panels.

Since these composite materials are relatively poor conductors, they should not be used to carry high current. The resistance would cause excessive voltage drop for intentional power return, and short circuit current may be limited to levels too low to trigger circuit protection devices.

CFRP may be used as 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.

Special attention should be given to bonding across joints in composite materials. The graphite layers are conductive, but epoxy, phenolic, isocyanate, polyimide, or other polymeric resin may cover the surface of the composite. This nonconductive outer layer should be removed to expose the graphite so conductive connections may be made at joints. If the bond is for RF purposes, do not depend on narrow straps. The connection should be continuous along edges that have been abraded to expose graphite. Connection may be made by overlapping panels or by adding a conductive bridge secured by metal fasteners or by conductive adhesive across the joint.

A.3.10 Multilayer Insulation

The conductive layers of multilayer insulation may be bonded together at several points using accordion-shaped metal foil fitted into the edges of the conductive layers so that each conductive layer contacts the foil. A rivet or bolt through the layers and the foil will assure contact and will provide a point for attachment to structure. Good conductivity should be verified by test.

A.3.11 Verification

See paragraph 5.5 for applicable requirements. Testing of every joint in a vehicle is neither required nor desirable unless specifically noted by the procuring agency. Usually tests of certain processes can verify that the process will result in a satisfactory bond. Other bonds using the same process can be verified by similarity. Verification that the same process was used on each bond should be adequate. Testing to verify resistance limits may be required depending upon the criticality of the equipment and the purpose of the bond as determined by the specific project. For example, all antenna installations and all electronic equipment may be required to be tested for resistance to structure, but the low impedance and current carrying requirements will still be verified by inspection and analysis.

The processes chosen to implement each bond should be tested to ensure they will meet the bond resistance requirements. These processes should also be called out on fabrication drawings and verified by quality.

There are requirements in addition to dc resistance measurements that depend upon the class of bond required. For Class C, H, and L, the bond should have enough contact area to carry the intentional, fault, or lightning current. Class L bonds should also be robust enough to withstand the magnetic effects of the large current being carried, if they are to be useful for more than one strike. These requirements are typically verified by analysis and inspection of the drawings and the installation.

Class R bonds should be low impedance at the frequency of interest. Calculations should be made to determine the impedance of any RF bond other than direct metal-to-metal contact over a large surface area.

The effectiveness of a direct bond is dependent upon the clamping pressure. A maintenance program should be put in place to verify these bonds still meet the requirements throughout the life cycle of the system.

In short, bonding should be verified by analysis, some tests of actual bonds, and tests of samples of a process, inspection of physical bonds and processes, and similarity to other good bonds. An electrical bonding path diagram may aid in verification of the complete bonding path. An example of a bonding path diagram is shown in figure 2, Electrical Bonding Path Diagram Example. It is not required to use the same symbols or even the same structure.

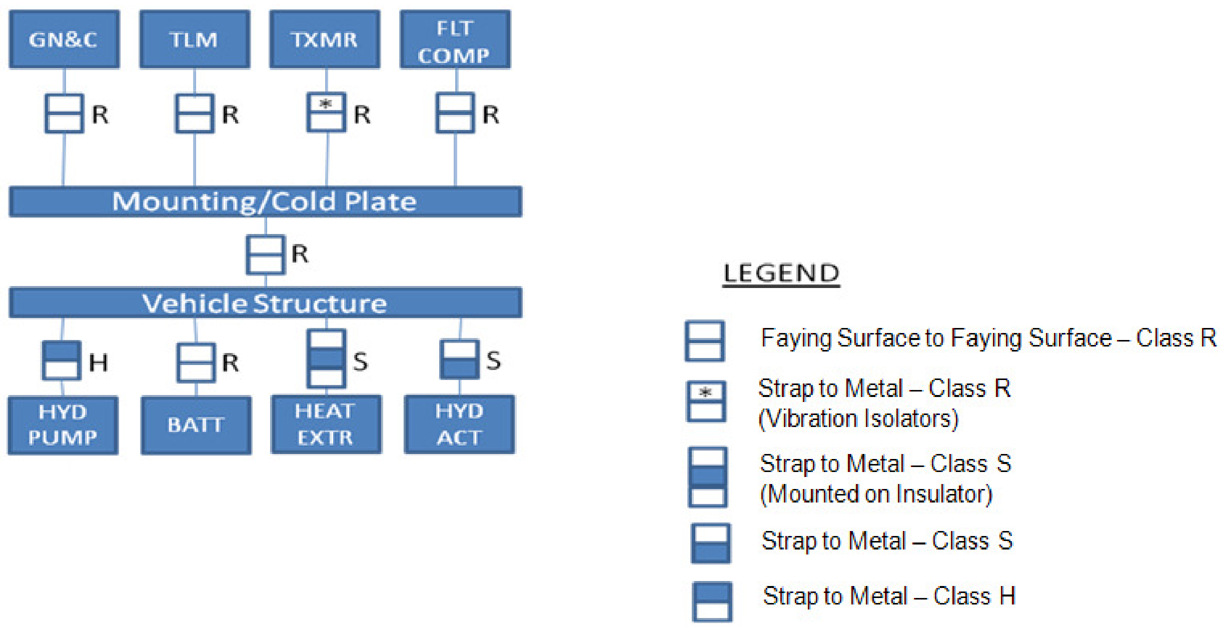


Figure 2 – Electrical Bonding Path Diagram Example