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Electrical Bonding: A Survey of Requirements, Methods, and Specifications

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Preface

There are several reasons for requiring good electrical conductivity between equipment and structure and between various parts of structure. Improved electrical bonding with reduced effort can result from understanding the different types of bonding requirements and the reasons for each.

Good electrical bonding on a spacecraft is often not completely verifiable. In some cases electrical bonding specifications state requirements that are compromises so they can be verified by measurement. These compromised requirements are often met by methods that may not provide a good bond under certain circumstances.

This document attempts to explain the various types of electrical bonding requirements and to provide the basic requirement for each type where possible. In some cases the specific values of bonding resistance and impedance may vary depending upon other requirements on the program. In these cases the type of data required to determine the specific values is defined.

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ACRONYMS AND ABBREVIATIONS

A	area, square inches
"A"	class of bond relating to antennas
ac	alternating current
C	capacitance, farads
"C"	class of bond relating to current return
cm	centimeters
d	distance between box and structure, inches
d	diameter of jumper, inches
dB	decibels
dc	direct current
E ³	electromagnetic environmental effects
E _i	initial charged voltage
E _s	final "safe" voltage
EED	electro-explosive device
EMC	electromagnetic compatibility
EMI	electromagnetic interference
ESD	electrostatic discharge
f	frequency, hertz
f _{res}	resonant frequency
GFRP	graphite filament reinforced plastic
"H"	class of bond relating to fault current hazard
I _s	current through short circuit
ISS	International Space Station
k	dielectric constant
kHz	kilohertz
kV	kilovolts
L	inductance, henries or microhenries
l	length, inches
"L"	class of bond relating to lightning
ln	natural logarithm
MHz	megahertz
mA	milliamps
mJ	millijoules

NASA	National Aeronautics and Space Administration
pF	picofarads
psi	pounds per square inch
Q	ratio of reactance to resistance
R	resistance, ohms
"R"	class of bond related to radio frequencies
R_g	resistance of return path through structure
R_s	power source resistance
R_T	total resistance in shorted circuit
R_w	wire resistance from source to shorting point
RF	radio frequency
"S"	class of bond related to electrostatic charge
T	time or time constant, seconds
t	thickness of strap, inches
U	joules
V	volts
V_s	source voltage
w	width of strap, inches
X	reactance, ohms
X_c	capacitive reactance
X_L	inductive reactance
Z	impedance, ohms
λ	wavelength
μH	microhenry
π	pi = 3.1416

ELECTRICAL BONDING, A SURVEY OF REQUIREMENTS, METHODS, AND SPECIFICATIONS

1.0 INTRODUCTION

This document is the result of a review of major electrical bonding specifications and some of the processes used in the United States. Its intent is to provide information helpful to engineers imposing bonding requirements on various programs, reviewing waiver requests, or modifying specifications.

This document discusses the specifications, the types of bonds, the intent of each, and the basic requirement where possible. Additional topics discussed are resistance versus impedance, bond straps, corrosion, finishes, and special applications.

2.0 SPECIFICATIONS

MIL-B-5087B, *Military Specification, Bonding, Electrical, and Lightning Protection, for Aerospace Systems*, has been the standard for electrical bonding for space vehicles for many years. It has recently been superseded by MIL-STD-464, *Department Of Defense Interface Standard, Electromagnetic Environmental Effects, Requirements for Systems*. MIL-B-5087B classifies bonds according to the purpose of the bond and sets specific resistance or impedance requirements according to the class. MIL-STD-464 changes this policy and sets more general requirements based on the purpose of the bond to allow the equipment developer more leeway to explore new or unique methods of electrical bonding. SSP-30245, *Space Station Electrical Bonding Requirements*, is a modification of MIL-B-5087B for the International Space Station. It reduces the number of applicable bonding classes and adds a few other requirements. MIL-STD-1310G, *Department of Defense*,

Standard Practice for Shipboard Bonding, Grounding, and Other Techniques for Electromagnetic Compatibility and Safety, is applicable for shipboard bonding. It uses a classification system based on whether the bond is permanent, semipermanent, or uses a bond strap.

Table 1 presents an outline of the MIL-B-5087B bonding classes and the major electrical bonding requirements.

Table 1. - Summary of MIL-B-5087B Electrical Bonding Requirements

CLASS "S"	CLASS "H"	CLASS "C"	CLASS "A"	CLASS "R"	CLASS "L"
Electrostatic Discharge	Shock Hazard	Power Return	Antenna Ground Plane	Radio Frequency	Lightning
LOW FREQUENCY			HIGH FREQUENCY		
LOW CURRENT	HIGH CURRENT		LOW CURRENT		HIGH CURRENT
Protects against electrostatic discharge. Applies to any item subject to electrostatic charging.	Protects against shock to personnel. Applies to equipment & structure that may be required to carry fault current in case of a short to case or structure.	Reduces power and voltage losses. Applies to equipment & structure when required to carry intentional power current through structure.	Applies to structure near certain types of antennas. Limited to specific frequencies.	Applies to equipment that could generate, retransmit, or be susceptible to RF. Covers wide frequency range.	Applies to equipment or structure that would carry current resulting from a lightning strike.
Allows moderate impedance. Jumpers and straps acceptable.	Requires low impedance & low voltage across joints to prevent shock hazard due to short. Jumpers and straps acceptable.	Requires low impedance & low voltage across joints to assure adequate power to the user. Jumpers and straps acceptable.	Allows moderate impedance at high frequencies. Short, wide strap may be acceptable.	Low current allows moderate RF impedance at high frequency. Direct contact preferred. No jumpers. Short, wide strap may be used as last resort.	High current requires low impedance at moderate frequency. Straps and jumpers must withstand high magnetic forces.

3.0 REQUIREMENTS AND PURPOSE

This section discusses the various classes of bonding requirements from MIL-B-5087B and provides similar requirements from other specifications. A commentary will discuss the reasons for the requirements and possible modifications.

3.1 Power Current Return Path

MIL-B-5087B class "C" limits the total impedance of wires, cables, and ground return paths so that the voltage drop for power returned through structure is limited to 1 volt for a 28 volt system and 4 volts for a 115 volt system. It also requires special fault current bonding at joints where explosive fuel or gas may be present to prevent ignition due to heating or arcing from fault current flow. A curve limits resistance levels at each bond connection based on the maximum fault current possible. These levels are approximately 0.74 milliohms at 100 amps of fault current and 0.074 milliohms at 1000 amps

MIL-STD-464 states, "For systems using structure for power return currents, bonding provisions shall be provided for current return paths for the electrical power sources such that the total voltage drops between the point of regulation for the power system and the electrical loads are within the tolerances of the applicable power quality standard."

Commentary

Actual dc resistance values required for electrical bonds from equipment to structure and from structure to structure will depend upon the power system for the particular project and probably upon the location of the bond joint within the vehicle. Each project should require certain voltage to be delivered across the loads. The bonding requirement will then depend upon the source voltage and the maximum current draw.

Several examples of bonding methods using bonding jumpers are presented in MIL-B-5087B. Since these methods cover several

pages, they catch the attention of the first time user who immediately thinks good bonding requires a jumper. These examples are applicable only for class "C" bonds which provide current paths for power that is intentionally returned through structure. NASA space vehicles very rarely use this return-through-structure method, so class "C" is not usually applicable.

3.2 Shock and Fault Protection

MIL-B-5087B class "H" requires less than 0.1 ohm resistance for metallic conduit at each termination and break point. It also requires resistance from exposed frames or parts of electrical or electronic equipment to structure to be less than 0.1 ohms.

MIL-STD-464 states, "Bonding of all exposed electrically conductive items subject to fault condition potentials shall be provided to control shock hazard voltages and allow proper operation of circuit protection devices."

MIL-STD-1310G requires less than 0.1 ohms dc and less than 25 ohms at 30 MHz for all electrical equipment to structure.

Commentary

Circuit protection devices limit current to levels that will not cause a significant temperature increase in the circuit wiring. The fault current resulting from a short between a power wire and a metallic equipment case or other metallic structure must be high enough to trip circuit protection devices in a timely manner.

The total resistance (R_T) in a typical shorted circuit can be found by:

$$R_T = R_s + R_w + R_g$$

Where,

R_s = power source resistance

R_w = wire resistance from source to shorting point

R_g = resistance of return path through structure

The shorted current (I_s) value is found by:

$$I_s = \frac{V_s}{R_T}$$

Where,

V_s = source voltage

Typically this 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. The fault current path usually consists of metallic structure with several joints in series. A poorly bonded joint, or a large number of joints, adds significantly to the total ground path resistance. This resistance may allow the shorting current enough time to become a fire hazard. It may even limit the current to less than the circuit breaker rating. The resulting voltage developed on the exposed chassis where the short occurs can be a shock hazard.

MIL-HDBK-274, *Military Handbook, Electrical Grounding for Aircraft Safety*, states for personnel safety the fault current return path should be able to allow up to 5 times the breaker rated current with a trip time of 0.2 seconds. Using this guideline a 120 volt, 50 amp service would require a total fault current return path resistance of 0.5 ohms or less.

MIL-HDBK-274 suggests protection from shock hazard from voltages above 30 volts, but fire hazards may occur with much lower voltages. 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 short to case.

When fault current must flow through partially conductive

structure such as graphite-epoxy, the current will be limited by the high resistance of the material as well as the joints, and the breaker may not trip. This results in a fire or shock hazard.

In an explosive atmosphere or areas where flammable vapors may occur, extra precaution must be used to ensure no arcs or hot spots can occur. A primary fault current return path should be provided around the hazardous area to limit the amount of fault current possible through joints in the hazardous area. In this case, the hazardous area fault current requirement of MIL-B-5087B class "C" may be applicable to NASA programs.

3.3 Electromagnetic Interference or Radio Frequency (RF)

MIL-B-5087B class "R" states, "All electrical and electronic units or components which produce electromagnetic energy shall be installed to provide a continuous low impedance path from the equipment enclosure to the structure. The contractor shall demonstrate by test that his proposed bonding method results in a direct current resistance of less than 2.5 milliohms from enclosure to structure. The bond from the equipment enclosure to the mounting plate furnished with the equipment shall comply also with these requirements, except that suitable jumpers may be used across any necessary vibration isolators."

It also states, "Vehicle skin shall be so designed that a uniform low-impedance skin is produced through inherent RF bonding during construction. RF bonding must be accomplished between all structural components comprising the vehicle. Hatches, access doors, etc., not in the proximity of interference sources or wiring, shall be either bonded to or permanently insulated from vehicle skin, except for the protective static bond."

MIL-STD-464 states, "The system electrical bonding shall provide electrical continuity across external mechanical interfaces on electrical and electronic equipment, both within the equipment and between the equipment and system structure, for control of E^3 such that the system operational performance requirements are met. For Navy aircraft and Army aircraft

applications, the EMI bonds shall have a dc resistance of 2.5 milliohms or less across each joint between the subsystem or equipment enclosure and the system ground reference."

MIL-STD-1310G requires less than 25 ohms at 30 MHz for all electronic equipment to structure.

SSP-30245 requires less than 100 milliohms at 1 MHz, but it does not include the impedance of straps where they are used.

Commentary

The Army and Navy retained the historical 2.5 milliohm requirement just because it was historical, and it worked. Other users settled for the general requirement for all systems to implement bonding measures adequate to ensure electromagnetic compatibility. Responsibility for specific resistance or impedance levels was left to the developing activity.

In reality there is no basis for 2.5 milliohm requirement except to ensure a good metal-to-metal contact that can be expected to be consistent. This value can be met even when mating two aluminum surfaces that have had a chemical conversion coating such as Iridite 14-2 to prevent corrosion. The basic requirement is to have a low impedance at the frequency or frequencies of interest. The value of this impedance, which is not defined, depends upon the situation. Acceptable low impedance 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 mounting feet will probably have an inductive reactance greater than 2.5 milliohms at frequencies above 10 MHz. RF bonds may be satisfactory at several ohms of impedance; but, when straps are used, even these levels will be quickly exceeded as frequency increases.

The class "R" bond is not really 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 filters and for proper operation of overall cable shields terminated to equipment

chassis. Isolated structural elements greater than $\lambda/2$ can pick up RF from high power transmitters and develop enough voltage to produce a glow discharge or arcing to other elements.

The 2.5 milliohm dc resistance requirement is probably good for a standard, but extra effort should 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.

3.4 Antenna Ground Plane

MIL-B-5087B class "A" requires radiating elements to be installed and provided with a homogeneous counterpoise or ground plane of negligible impedance within the operating frequency ranges of the equipment involved. The ground plane shall be of adequate dimensions so as not to detract from the desired antenna radiation patterns. Antennas so designed that efficient operation depends on low resistance shall have the bond installed so that RF currents flowing on the external surface of a vehicle will have a low impedance path of minimum length to the appropriate metal portion of the antenna.

MIL-STD-464 states, "Antennas shall be bonded to obtain required antenna patterns and meet the performance requirements for the antenna."

Commentary

Some types of antennas require a conductive counterpoise or ground plane for proper operation. The conductivity value and the area required should be specified by the antenna developer. This may or may not affect the bonding requirements on structure near the antenna. For proper operation of a $1/4$ wavelength rod antenna, for example, the ground plane may need to be highly conductive up to $1/2$ wavelength from the antenna. The ground plane up to several wavelengths from the antenna may affect the

antenna pattern to a lesser extent. It does not have to be a perfect conductor, but it should be stable and consistent.

3.5 Lightning Protection

MIL-B-5087B class "L" specifies that voltages developed across joints as a result of lightning shall not exceed 500 volts. It also specifies a lightning current waveform of 200 kiloamps. It is generally accepted that bonding impedance in the current path should be less than 2.5 milliohms at each joint to prevent voltages over 500 volts.

MIL-STD-464 requires the system to meet its operational performance requirements for both direct and indirect effects of lightning. It provides sample lightning current waveforms for design inputs, but it does not specify any specific electrical bonding requirements for lightning protection.

Commentary

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 the exit point. Electrical bonding helps provide the proper direction for the path. Even when a large current path is provided to carry the current, attach points across joints still may be a problem. Arcing at joints can be expected even with good 2.5 milliohm dc bonds. The arc produces an ionized path that helps carry the current. Through good electrical bonding of the vehicle skin the majority of the current can be kept on the outside of the vehicle.

Joints and apertures in the skin allow some voltage to be induced into underlying cables. This voltage must be kept low enough to prevent disrupting electronic equipment. Apertures should be kept as small as possible, and joints should be bonded in several places so there will not be a long slot between bonds.

Special care must 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 conductive material grounded to structure. Wires to pyrotechnics should be shielded and the shields should have 360° terminations to the metal enclosure.

3.6 Electrostatic Discharge

MIL-B-5087B, Amendment 2, class "S" states, "All isolated conducting items (except antennas) having any linear dimension greater than 3 inches, which are external or internal to the vehicle, carry fluids in motion, or otherwise are subject to frictional charging, shall have a mechanically secure connection to the vehicle structure. The resistance of the connection shall be less than 1 ohm when dry."

"All metallic pipes, tubes, and hoses that carry petroleum products or other fluids shall have a mechanically secure connection to the structure that will measure 1 ohm or less. The pipe, tube, or hose installation shall be so designed that it will not be a path for primary electrical power under normal or fault conditions. Nonmetallic plumbing installations shall be so designed that the static voltage generated by fluid flow will not exceed 350 volts at any point outside the pipes, tubes, or hoses."

Amendment 3 deletes the two paragraphs above and sets requirements for Air Force aircraft fuel systems only. Electrically powered equipment in the fuel system is required to meet the class "C", hazardous area, requirements. Small nonelectrical components capable of delivering more than 0.25 millijoules through a static discharge must be bonded with 10 megohms or less resistance to ground, and other fuel system components shall have an electromechanically secure connection to structure that measures one ohm or less. MIL-HDBK-274 states that 0.25 millijoules is the energy level required for an arc to ignite fuel vapor.

SSP 30245 states that all parts with greater than 100 square

centimeters surface area and subject to charging shall not exceed 100 ohms to structure.

MIL-STD-464 requires the system to control and dissipate the build-up of electrostatic charges caused by precipitation static effects, fluid flow, air flow, space and launch vehicle charging, and other charge generating mechanisms to avoid fuel ignition and ordnance hazards, to protect personnel from shock hazards, and to prevent performance degradation or damage to electronics. It specifically requires external grounding provisions to prevent shock to personnel and ignition of fuel or ordnance. Grounding jacks shall be provided at fuel inlets and at convenient points for servicing and maintenance. The resistance from grounding jack to system ground shall not exceed one ohm.

Commentary

The resistance to ground 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 recommended by MIL-HDBK-274, usually function adequately. The charging current, usually in microamps, through the resistance to ground determines the voltage developed. A requirement for one ohm or less to ground is a good requirement for metal items because any good connection will measure less than one ohm. Under some circumstances, such as when semiconductive materials or complex configurations are used, this limit may be increased up to ten kilohms or even more in many cases. The contact must be secure and not intermittent. Metal straps or jumpers across joints are adequate since the current is dc.

Charging mechanisms include separation of unlike materials, charges induced from other charged items, triboelectric charging, etc. Separation of materials includes movement or removal of certain types of clothing, peeling off tape, removing dust covers, fluid flow, etc. Induction comes from an isolated item being near a second item that is being charged. If the second item is suddenly discharged the isolated item retains the charge until it drains off depending on its resistance to ground. An example is a

charged cloud causing an opposite charge to develop on a nearly isolated item on earth. If lightning discharges the cloud to ground, the earth in the area discharges quickly, but the nearly isolated item retains a charge until it can drain off through the high resistance to the earth. Triboelectric charging occurs when a vehicle hits or is hit by particles such as dust or snow. The charging current is very low, usually less than 30 microamps for wind blown dust hitting a parked airplane.

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. The likelihood of damage or upset depends upon the threshold level.

Some typical damage threshold levels are taken from MIL-HDBK-274 and presented here.

Reflex action shock	10 mJ, 50 V
Severe shock (dc)	1.35 mJ, 45 V, 3 mA
EED ignition	35 mJ
Component damage	35 mJ
Component upset	10 mJ
Fuel vapor ignition	0.25 mJ

The amount of energy stored in a charged item may be found by:

$$U = \frac{1}{2} CV^2 \quad (1)$$

Where,

U = energy stored (joules)

C = capacitance to ground (farads)

V = charge voltage

The voltage is limited to the breakdown voltage between the charged item and ground. The maximum voltage before breakdown in air is approximately 30 kV/cm or 75 kV/inch; but, typically, it is about 8 kV/cm or 20 kV/inch due to rough surfaces, corners, etc.

The capacitance between two conductive plates such as from equipment to structure is found by:¹

$$C = 0.224 \times k \left(\frac{A}{d} \right) \text{ pF} \quad (2)$$

Where,

k = dielectric constant (= 1 for air),

A = area of mating surfaces (square inches)

d = distance between the box and the structure (inches)

Capacitance values for aircraft are consistently measured at 0.002 to 0.005 microfarads with 40 megohms resistance to ground through the tires.

Conductive items capable of being charged must be electrically bonded to structure if their surface is greater than 100 square centimeters according to SSP 30245, and if their length is greater than 3 inches according to MIL-B-5087B. An example of the energy transfer possible from an item in this size range can be calculated. Assume a 10 square inch mating surface setting 0.1 inch above the ground plane.

The capacitance to ground is:

$$C = 0.224 \left(\frac{10}{0.1} \right) \text{ picofarads}$$

The maximum field strength before discharge is 75 kV/inch; and, for a separation distance of 0.1 inch, the maximum voltage that can be developed is 7.5 kV.

¹ F. E. Terman, Radio Engineers' Handbook, McGraw-Hill Co., New York, 1943.

The energy transferred is then:

$$U = \frac{1}{2} \times 22.4 \times 10^{-12} \times (7.5 \times 10^3)^2 = 0.63 \text{ millijoules}$$

Notice that if the distance from structure is reduced to 0.01 inches the capacitance is increased by a factor of 10 and the voltage is reduced by a factor of 10. Energy is reduced by a factor of 10 since the voltage is squared.

The rate of discharge after the source has been removed is defined by the time constant, and an item can be assumed fully discharged after 5 time constants.

$$T = RC \tag{3}$$

Where,

- T = time constant (seconds)
- R = resistance to ground (ohms)
- C = capacitance to ground (farads)

The time of discharge from the initial charged voltage to a final safe voltage is:

$$T = RC \ln \frac{E_i}{E_s} \tag{4}$$

Where,

- T = time (seconds)
- R = resistance to ground (ohms)
- C = capacitance to ground (farads)
- E_i = initial charge voltage
- E_s = final "safe" voltage

In summary, bonding for electrostatic charge should use the one ohm requirement for ordinary metal joints to ensure a good

connection. Good connections that measure up to 10 kilohms for unusual configurations or semiconductive materials should also be acceptable. Jumpers and straps may be used.

In borderline cases determine whether an item requires bonding for electrostatic discharge by calculating the amount of energy that can be stored on the item and compare it to damage levels for the item and for any item that may receive the discharge.

4.0 BONDING METHODS

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. Semipermanent joints are held together by screws, rivets, clamps, etc. To provide a good electrical bond the semipermanent mating surfaces should be cleaned of all insulating material before connection. A good dc connection will measure less than the 2.5 milliohm limit for class "R" bonds. Bond straps or jumpers may be adequate for some types of bonds, but it should be recognized that they will present a high impedance at high frequencies. Special requirements may be necessary for tubing, composite materials, metalized thermal blankets, etc.

4.1 Surface Cleaning and Finishing

Various bonding specifications refer to MIL-C-5541, *Military Specification, Chemical Conversion Coatings on Aluminum and Aluminum Alloys*, for protective chemical conversion coatings for aluminum and aluminum alloys. This specification provides for class 1A coatings for maximum protection and class 3 where electrical conductivity is required. Class 3 may use a different material, or it may be a thinner coating using the same material as for class 1A. The coating materials are required to meet MIL-C-81706, *Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys*, and are supposed to be preapproved and accepted for listing on the *Qualified Products List*, QPL-81706. Commonly used examples of these materials are Iridite 14-2, Alodine 600, and Alodine 1200. MIL-C-5541 describes cleaning procedures for aluminum surfaces, and it states the chemical coatings may be applied by spray, brush, or immersion after all welding and mechanical operations have been completed. The more conductive class 3 coating uses a short immersion time or is brushed on to form a thinner coating.

The hard, nonconductive aluminum oxide coating is removed during the cleaning process, and chromate coatings are applied to bare aluminum. The thickness of the coating depends upon the amount of time the metal is immersed, up to a point. After five minutes or so in the bath little thickness is added. Typical coatings may range from 10 to 1000 nanometers and may vary in color from clear to light yellow to dark brown depending upon the thickness. The thinner coatings are used as a paint base and for protection where good electrical conductivity is required. Thicker coatings may be used alone for protection. The thinner coating is most conductive, however the thicker coating is still more conductive than the aluminum oxide on the original material. To meet the usual 2.5 milliohm resistance limit a thin coating is required. However even the thicker coatings usually measure less than 10 milliohms.

As with many military specifications, this one is designed to be used for multiple units, and provisions for testing and inspection apply to each lot. Test specimens are to be coated and submitted to a 168 hour salt spray test, rinsed, and checked for compliance with spot and pit requirements. A paint adhesion test is prescribed for equipment to be painted after coating. An electrical conductivity test for class 3 coatings requires mating samples at 200 psi and measuring dc resistance across the joint. The limit is 5000 microhms per square inch immediately after joining and 10000 microhms per square inch after the 168 hour salt spray. Unless precautions are taken, chromate coatings are easily penetrated during the mechanical mating of two surfaces; and resistance measurements taken before the exposed aluminum oxidizes may be lower than later measurements.

Protective coatings for magnesium are described in MIL-M-3171C, *Magnesium Alloys, Processes for Pretreatment and Prevention of Corrosion*. Several types of coatings are described, but MIL-B-5087B recommends Type 1, chrome pickle, be used. This process uses a weak chromic acid solution to clean down to bare metal. The coating process uses sodium dichromate and nitric acid that etches some of the surface away and deposits a chromate coating.

No resistance requirements or methods of verification are given.

Resistance measurements of typical mating surfaces may be used to verify the mating process using chromate coating provides a satisfactory bond. Then all bonds using that process can be verified by similarity. When equipment is mounted in orbit, the new equipment can be protected until ready for mating, but the footprint may be exposed to the space environment for months or years in the case of the International Space Station (ISS). The ISS bonding specification recommends plating these mating surfaces with nickel. Boeing document, D683-29033-1, *Process Specification for Electrical Bonding and Grounding*, does not allow chemical conversion coatings in habitable spacecraft due to corrosion potential. However, this author has not found evidence that chromate conversion coatings on aluminum will be particularly susceptible to corrosion in the space environment. It appears that if a problem occurs, it will be from contamination settling on the footprint or from debris pitting external surfaces. These can occur whether the surfaces are nickel plated or finished with chromate coating.

4.2 Galvanic Corrosion

Where dissimilar metals are placed in contact, galvanic reaction may cause corrosion of the metal that is higher in the galvanic series. MIL-B-5087B warns that if the condition cannot be avoided the most active of the metals should be replaceable. MIL-STD-889, *Dissimilar Metals*, contains considerably more good information on the subject. The galvanic series gives a voltage level for each material while immersed in an electrolyte solution. The voltages may differ with the electrolyte and even the order of the material in the series may change. For most aerospace work the table using sea water as an electrolyte is used. Table 2 is an example. To protect against corrosion the two metals in contact should be close together in the series. The area of the most anodic metal, higher in the series, should be larger than the cathodic metal. The larger the anodic area the lower the current

density on the anode. Select small parts such as bolts and nuts of material compatible with the cathode. (This conflicts somewhat with the MIL-B-5087B warning to make the more active of the metals replaceable.) All edges should be sealed from moisture.

Table 2 - Galvanic Series²

More Active (Anodic)	
Group I	magnesium
Group II	zinc aluminum aluminum alloy 7072 aluminum alloy 7079-T6 cadmium aluminum alloy 6061-T6 aluminum alloy 2024-T4
Group III	tin stainless steel 430 (active) lead steel 1010 cast iron
Group IV	nickel chromium stainless steel 430 (passive) brass
Group V	copper Monel 400 titanium silver gold graphite
Less Active (Cathodic)	

- Metals toward the top of the series are more active and will corrode when placed in contact with a metal lower in the series in a seawater electrolyte environment.

- Generally, metals in the same group may be placed in contact with each other.

- Metals from separate groups must be protected from corrosion by coating and by sealing the edges to preclude moisture.

- Avoid leaving a small unprotected anodic area compared to the cathodic area in contact with the electrolyte. The smaller the area the greater the current density and the greater the corrosion.

- An intermediate metal should be placed between two metals that are far apart in the series to reduce the tendency to corrode. The intermediate metal can be a plating.

² Data taken from MIL-STD-8898 and AFSC DH 1-4.

4.3 Straps Where Unavoidable

MIL-B-5087B gives details of how to use bonding jumpers primarily for current return paths (class "C" bonds). It allows short jumpers across vibration mounts for class "R" and states that they should be as short as possible.

MIL-STD-1310G defines four types of bond straps -- corrosion resistant steel with lugs, corrosion resistant steel with holes, flat solid copper, and flat copper braid.

STP 6511J, *Engineering Process Specification, Electrical and Electronic Bonding Connections (Lockheed-Martin)*, describes use of jumpers and aluminum foil primarily for lightning bonds.

Some procedures limit bond strap length to width ratios to 3 to 1 or 5 to 1. The impedance of these straps exceeds 2.5 milliohms at approximately 20 kHz. It is at least 100 milliohms at 1 MHz and 1 ohm at 10 MHz. Straps may be used to meet class "C", "H", or "S" bonding requirements. They are useful in some cases for class "L", but their usefulness for class "R" bonds is very limited. They should be used only as a last resort.

4.4 Impedance and Resistance

The electrical bond path between an electronic box and 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 resistance is made up of the resistance of the material across the path. It includes any bond strap present plus the resistance of the joints in the path. This resistance is usually low and remains constant with increasing frequency except in some configurations the skin effect may cause a slight increase at higher frequencies. The inductance is directly proportional to the length of the bond path. Wider paths and multiple paths can reduce the inductance value. The inductive reactance increases 20 dB with every decade of frequency increase. The capacitance between the box and structure is proportional to the area of the interface and inversely proportional to the distance between the

box and structure. The capacitive reactance decreases 20 dB per decade of frequency increase. The circuit becomes parallel resonant at a frequency where the inductive reactance and the capacitive reactance are equal. At this point the impedance may reach thousands of ohms depending on the Q of the circuit.

The inductance (L) of a flat metal strap is given by:³

$$L = 5.08 \times 10^{-3} l \left[\ln \left(\frac{2l}{w + t} \right) + 0.5 + 0.2235 \left(\frac{w + t}{l} \right) \right] \mu\text{H} \quad (5)$$

Where,

l = length (inches)

w = width (inches)

t = thickness of the strap (inches)

The inductance (L) of a round jumper is given by:⁴

$$L = 0.00508 l \left[\ln \left(\frac{4l}{d} \right) - 0.75 \right] \mu\text{H} \quad (6)$$

Where,

l = length (inches)

d = diameter of the jumper (inches)

The inductive reactance (X_L) of the strap or jumper is:

$$X_L = 2\pi fL \text{ ohms} \quad (7)$$

Where,

f = frequency (hertz)

L = inductance (henries)

³ F. E. Terman, Radio Engineers' Handbook, McGraw-Hill Co., New York, 1943.

⁴ Ibid.

The capacitance between a box and structure is found by:⁵

$$C = 0.224 \times k \left(\frac{A}{d} \right) \text{ pF} \quad (8)$$

Where,

k = dielectric constant (= 1 for air)

A = area of mating surfaces (square inches)

d = distance between the box and the structure (inches)

The capacitive reactance (X_c) is:

$$X_c = \frac{1}{2\pi f C} \text{ ohms} \quad (9)$$

Where,

f = frequency (hertz)

C = capacitance (farads)

The total impedance across the joint is equal to the resistance at frequencies from dc to the point where the inductive reactance exceeds the resistance. The impedance then increases at 20 dB per decade of frequency to a frequency where the inductive reactance and the capacitive reactance are equal. At this resonant frequency the impedance may rise to thousands of ohms depending on the Q of 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.

⁵ Ibid.

The resonant frequency (f_{res}) is found by:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \text{ hertz} \quad (10)$$

Where,

L = inductance (henries)

C = capacitance (farads)

The impedance (Z) at resonance is:

$$Z = \frac{X^2}{R} \quad (11)$$

Where,

X = inductive or capacitive reactance at the resonant frequency

Q is the ratio of the reactance to the resistance:

$$Q = \frac{X}{R} \quad (12)$$

And,

$$Z = QX \quad (13)$$

It can be seen that impedance due to strap inductance quickly exceeds the standard 2.5 milliohm requirement as frequency increases. When the capacitance of the installation is considered there will be some resonant frequency where impedance is very high. Even though RF bonds may be satisfactory at several ohms of impedance the straps quickly exceed even these levels. Jumpers may be used for electrostatic discharge. Straps or jumpers are adequate for fault current returns, but low resistances are required. The inductance of the strap is not a concern since the

high current will be from a dc or low frequency ac power source.

Lightning path bonds may use straps since the frequencies involved are relatively low, but the straps should be kept short to ensure that inductance is kept as low as possible. The strap and connections should be robust enough to survive the magnetic forces resulting from high lightning currents.

4.5 Tubing

MIL-B-5087B, Amendment 2, requires tubes and hoses that carry fluids to have a connection to structure of 1 ohm or less. Nonmetallic plumbing installations shall be so designed that the static voltage generated by fluid flow will not exceed 350 volts at any point outside the pipes, tubes, or hoses. This is interpreted as a field strength of 350 volts that can be verified by use of an electric field meter. SSP 30245 also uses this requirement for the International Space Station. If nonconductive tubing has a metal sheath on the outside, it can meet the 350 volt criteria, but it may still have a problem. Charge may build within the fluid and erode the tubing with local arcs, or it can cause an arc to the metal sheath through the nonconductive tubing. This causes pin holes to develop in the tubing resulting in leaks. One solution is to use tubing that is somewhat conductive to bleed off the charge without developing enough voltage to produce an arc. A resistivity limit less than one megohm per inch of tubing has been used to satisfactorily control ESD in fluid lines.

4.6 Composite Material Enhancement

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. In either case high current entry and exit points may cause temperatures capable of igniting graphite-epoxy material.

GFRP 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 must be given to bonding across joints in composite materials. The graphite layers are conductive, but the outside layers of the composite may be covered by epoxy or phenolic. This nonconductive outer layer must 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.

SSP 30245 requires less than 1000 ohms for bonds between composite materials and structure. This resistance normally is adequate for class "S" bonds only.

4.7 Limitations on Some Materials in Space

MIL-B-5087B prohibits the use of cadmium plated steel for space applications. Cadmium sublimates and may deposit on optics, solar arrays, etc. It also prohibits the use of zinc plating. It does not allow the use of magnesium as a current return path. Magnesium is flammable if the temperature is high enough. STP 6511J does not allow tin coated hardware near gaseous oxygen. Tin oxidizes easily.

5.0 VERIFICATION

Testing of every joint in a vehicle is not required nor desirable. 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.

There are additional requirements beyond dc resistance measurements depending upon the class of bond required. For class "C", "H", and "L", the bond must have enough contact area to carry the intentional, fault, or lightning current. Class "L" bonds must also be robust enough to withstand the magnetic effects of the large current being carried if they are to be useful more than once. These requirements can only be verified by 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.

In short, bonding should be verified by some tests of actual bonds, tests of samples of a process, inspection of physical bonds and processes, and similarity to other good bonds.

APPENDIX A

LIST OF SPECIFICATIONS AND PROCESSES

The following is a list of documents related to electrical bonding. Most have been reviewed and some of the most important topics or most obvious requirements are listed as aides for further reading. These documents are the references for this report.

SPECIFICATIONS AND STANDARDS:

1. MIL-STD-464 -- Department of Defense Interface Standard, Electromagnetic Environmental Effects Requirements for Systems, 3/18/97.

- Requires bonding adequate to meet EMC requirements.
- Return path must be adequate to keep voltage within power quality standards.
- Bond to obtain required antenna pattern.
- Bond to provide continuity across electronic equipment parts and to structure for control of EMI. For Navy and Army aircraft, dc resistance across interface shall not exceed 2.5 milliohms
- Bond all exposed electrically conductive items subject to fault condition potentials to prevent shock hazard voltage and allow proper operation of circuit protection devices.
- Provide external grounding to control current flow and static charging to prevent shock, ignition of ordnance, fuel, and flammable vapors and to protect hardware from damage.
- Provide grounding jacks for aircraft.
- Requires control and dissipation of electrostatic charges to protect fuel, ordnance, electronics, and personnel.

2. MIL-STD-889 -- Dissimilar Metals, 7/7/76.

- Requires protection against galvanic corrosion of metals by insulation of joint or exclusion of electrolyte when

adjoining metals are widely separated in the galvanic series.

- Galvanic series applies to particular electrolyte solution. Table will have different values for each solution and different order of metals may occur. Galvanic series for sea water electrolyte is given.
- Avoid small anodic area relative to cathode. The larger the anode area the lower the current density on the anode. Select small parts such as bolts and nuts of material compatible with cathode.
- Seal all edges.
- Paint over welded or brazed dissimilar metals at least one third of an inch past heat affected area.
- Appendix A recommends type of protection coating for different metals. Lists specifications for coatings.
- Appendix B contains tutorial on galvanic corrosion.

3. MIL-STD-1310G -- Standard Practice for Shipboard Bonding, Grounding, and Other Techniques for EMC and Safety, 6/28/96.

- Sets requirements for bonding per class 'A', welded; class 'B', bolted; and class 'C', straps.
- Electronic equipment, class 'B' or 'C', mating surfaces must not exceed 0.1 ohms for safety and 25 ohms at 30 MHz for RF.
- Seal all bonding surfaces.
- Defines four types of bond straps -- corrosion resistant steel (CRES) with lugs, CRES with holes, flat solid copper, and flat copper braid.
- Don't use chains above deck except for anchors.
- Equipment operated by external power source of 30 volts or more shall be grounded for shock hazard.
- Ship's metallic hull and all class 'A' bonded equipment is considered the ship's ground plane.
- Electronic equipment, class 'B' or 'C' bonded to ground plane, is considered grounded but not part of ground plane.
- Computer equipment has separate ground system.
- Non-metallic ships require ground plate in contact with sea

water for ground plane.

- Large hardware items on deck to be class 'B' or 'C' bonded if greater than 10 feet in length.
- Equipment with metal case must have three prong plug with resistance > 1 megohm from two hot wires to case and < 0.1 ohm from ground prong to case.
- Non-conductive case does not require third prong.
- To bond equipment, clean surfaces, use MIL-T-22361 antiseize compound, wipe off, lay bead of MIL-S-45180 sealant to edges, paint area.
- Calls out requirements for commercial-off-the-shelf (COTS) equipment.
- Cable ground system for non-metallic hulls is described.

4. MIL-B-5087B -- Bonding, Electrical and Lightning Protection, 7/30/54, Including Amendment 3, 12/24/84.

- Cadmium plated hardware prohibited for space vehicles.
- Zinc plating prohibited.
- Prepare surfaces by removing all anodic film, grease, paint, lacquer, or other high resistance finishes from immediate area to ensure negligible RF impedance.
- Class "A" -- Antennas, except those where ground plane is part of the equipment, shall be installed to provide a homogeneous counterpoise, or ground plane, of negligible impedance within the operating frequency range.
- Class "C" -- Bond between equipment and vehicle structure adequate to carry power return current. Table allows 1 volt drop for 28 volt system, 4 volts for 115 volt system.
- Do not use magnesium as current return path.
- To prevent ignition in hazardous fuel or vapor areas, resistance values shall not exceed curve -- ($R < 0.74$ milliohms at 100 amps fault current and $R < 0.074$ milliohms at 1000 amps.)
- Class "H" -- Bond conduit less than 0.1 ohms to structure.
- Electrical and electronic equipment with exposed metal parts shall be bonded to structure by less than 0.1 ohms.

- Class "L" -- Provide lightning protection at all points of entry. Several pages of suggestions designed to prevent damage to equipment and prevent sparking or voltages in excess of 500 volts.
- Class "R" -- All electrical electronic units that produce electromagnetic energy shall provide a continuous low-impedance path to structure. DC resistance shall not exceed 2.5 milliohms from enclosure to structure.
- Vehicle skin shall be designed so that a uniform low-impedance skin is produced through inherent RF bonding. RF bond between all structural components.
- Class "S" -- Air force requires bonding of all metallic components in the aircraft fuel system. Other services require bonds for items that are longer than 3 inches, that carry fluids, or are otherwise subject to frictional charging. Bond less than 1 ohm.
- Specification requires dissimilar metal corrosion protection.
- Gives details of how to bond using jumpers, primarily for class "C" bond.
- Gives cleaning and finishing instructions.
- Uses Iridite 14-2. Other finishes for aluminum not mentioned.

5. MIL-C-5541 -- Chemical Conversion Coatings on Aluminum and Aluminum Alloys, 1/9/50; Rev E, 11/30/90.

- Two classes of chemical conversion coatings are defined, class 1A for maximum protection against corrosion and class 3 for protection where lower electrical resistance is required.
- Material used must meet MIL-C-81706 and be accepted for listing on the Qualified Products List, QPL-81706.
- Do not use steel wool or steel wire to clean parts since particles may become embedded in aluminum.
- Chemicals may be applied by spray, brush, or immersion after all welding and mechanical operations have been completed.
- Specimen samples will be coated and submitted to 168 hour salt spray test, rinsed, and checked for compliance with spot

and pit requirements.

- Requires paint adhesion test.
- For class 3, electrical contact resistance test will be performed on samples. Requirements to be specified by procurer.
- Class 3 conversions may be thinner versions of class 1A using the same materials. Difference is in immersion time. Same material may be on QPL list for both classes.
- Electrical contact test uses 200 psi and requires no greater than 5000 microhm per square inch as supplied and no more than 10000 microohms per square inch after 168 hour salt spray. Consider flatness and roughness of sample.

6. MIL-M-3171C -- Magnesium Alloys, Processes for Pretreatment and Prevention of Corrosion, 7/11/66; Amendment 1, 3/14/74.

- Use solvent cleaning, mechanical cleaning, alkaline cleaning, or acid pickling before surface treatment. All cleaning methods are described.
- Cleaning operation shall be free of metallic impurities such as salts of heavy metals.
- Methyl alcohol is specifically prohibited for cleaning.
- Each surface treatment process is described:

Type I	Chrome Pickle
Type III	Dichromate
Type IV	Galvanic anodizing
Type VI	Chromic acid brush-on
Type VII	Fluoride anodizing process plus corrosion prevention
Type VIII	Chromate
- All processes are for surface protection and paint retention. Does not contain much information on conductivity.
- Use Type I, chrome pickle treatment, where electrical bonding is a concern.
- Magnesium parts should be anodized by fluoride treatment prior to attaching to dissimilar metals.

7. MIL-S-5002D -- Surface Treatments and Inorganic Coatings for Metal Surfaces of Weapon Systems, 11/30/89; Amendment 1, 3/24/94.

- Requirements for cleaning, surface treatments, and inorganic coatings for metallic surfaces of weapons systems parts.
- Cleaning of metal parts explained and exceptions noted for titanium, aluminum, steel, and magnesium.
- Metallic coatings applied by listed methods. Special specs and some restrictions listed for coatings of cadmium, tin, aluminum, zinc, chromium, nickel, silver, gold, palladium, rhodium copper, and zirconium oxide.
- Surface treatment and oxide coatings listed for aluminum, magnesium, and steel.
- Temperature limits for various coatings are listed.

8. MIL-C-81706 -- Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys.

9. ASTM-B539-96 -- Standard Test Methods for Measuring Contact Resistance of Electrical Connections.

- Methods of resistance measurement for contacts through wire terminations, connectors, soldered joints, wire-wrapped connections, etc.
- Four-terminal measurements made at three current levels.
 - Test Method A -- Standard Test Current -- Unless otherwise specified use 1 amp.
 - Test Method B -- Rated Current Testing -- Rated currents specified by manufacturer. Usually large enough to cause heating.
 - Test Method C -- Dry Circuit Testing -- Use voltage less than 20 millivolts and current less than 100 milliamps. Intent is to use levels that are too low to break down oxide films or contaminants on contacts.

10. SAE-ARP-1870 -- Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety, 1/12/87.

- Requirements for electrical bonding of electrical, avionic, armament, communications, and electronic equipment.
- Similar to MIL-B-5087B but contains more guidelines or helpful information than requirements.
- Covers types of bonds, straps, jumpers, finishes, metal surface preparation, bonding methods, and dissimilar metals.
- Recommends 2.5 milliohms for most bonds, but table gives other requirements for different parts of aircraft.

11. SSP 30245 -- Space Station Electrical Bonding Requirements, Rev. B. 6/3/94.

- Requirements for Space Station similar to MIL-B-5087B.
- Covers class "H" (shock hazard), class "R" (RF), and class "S" (static charge).
- Special requirements for composite materials (1000 ohms), mechanical subassemblies (1000 ohms), pipes and hoses (1 ohm, <350 volts), homogeneous structural materials (1 ohm), and multilayer insulation (1 ohm, 2 places).
- Surface treatment described for magnesium (MIL-M-3171) and aluminum (MIL-C-5541).
- For removable bonding surfaces, plated metallic finishes are required. Nickel is preferred.

COMPANY SPECS AND PROCEDURES:

12. D683-29033-1 -- Process Specification for Electrical Bonding and Grounding, (Boeing).

- Lists cleaning methods to use before bonding several materials.
- Describes fabrication and installation of 5:1 bond straps.
- Describes surface preparation methods for nickel plating bonding areas on anodized, painted, or conversion coated equipment.
- Does not allow chemical conversion coated material in habitable spacecraft modules.
- Aluminum with nickel plate, CRES, or titanium may be bonded in any combination inside or outside habitable modules.
- Sets specific bonding resistance values for classes "S", "R", and "H".

13. MP-200 -- Cleaning Procedure for Low Strength Steel and Steel Alloy, High Strength Steel and Steel alloy, and Aluminum and Aluminum Alloy, (NAS, Inc.).

- Provides instruction and checklist for cleaning steel and aluminum prior to coating application.

14. MP-204 -- Procedure for Chemical Conversion Coating for Aluminum and Aluminum Alloys, (NAS, Inc.).

- Provides instruction and checklist for applying conversion coating to aluminum.
- This procedure applies specifically to Iridite 14-2 coating.

15. Technical Data Sheet -- Iridite 14-2 AL-COAT for Aluminum and Aluminum Alloys, (Allied-Kelite).

- Manufacturer's instruction sheet for cleaning aluminum and coating with Iridite 14-2 by spray, dip, or brush.

16. STP 3001J -- Chemical Films for Aluminum and Aluminum Alloys, (Lockheed Martin).

16. STP 3001J -- Chemical Films for Aluminum and Aluminum Alloys, (Lockheed Martin).

- Requirements for Lockheed Martin and subcontractors for application of chemical conversion coatings to aluminum.
- Engineering drawings shall specify class 1A (maximum protection) or class 3 (electrical conductivity) and the areas that do not need masking.
- Table 1 lists Iridite 14-2 as the coating, class 1A (Immersion 1-6 minutes) and class 3 (Immersion 30-60 seconds).
- Cleaning requirements and solutions are listed.
- Details for stripping, cleaning, and applying coatings are listed.

17. STP 3003 -- Epoxy Coating, Corrosion Inhibiting, Application of, (Lockheed Martin).

18. STP 6511J -- Engineering Process Specification, Electrical and Electronic Bonding Connections, Rev. 12/18/96 (Lockheed Martin).

- Requirements for fabrication of electronic bonding connections in airborne hardware.
- Engineering drawings will show list of items including class of bond, finishes to remove, torque on bolts, sealant, etc.
- Requires three classes of bonds ("L", "R", and "S").
- Resistance shall be greater than zero and less than 2.5 milliohms for classes "L" and "R" and one ohm for class "S".
- No tin coated hardware near gaseous oxygen.
- Describes different types of bonding methods --
 - Type I, jumpers
 - Type II, inherent
 - Type III, semi-permanent
 - Type IV, aluminum foil.
- Individual shields to be carried through connector pins. Overall shields have 360° connections to backshell measuring less than 2.5 milliohms.

- Surface preparation per STP 3001, class 3, etc.
- Figures for installing straps, etc., similar to MIL-B-5087B with more detail.
- Discussion of use of aluminum tape for bonding connection.
- Sealing discussion uses epoxy primer per STP 7001 and/or zinc chromate.

HANDBOOKS AND GUIDELINES:

19. MIL-HDBK-132 -- Base Metal Protective Finishes.

20. MIL-HDBK-274(AS) -- Electrical Grounding for Aircraft Safety, 11/1/83.

- Provides guidelines for electrical safety grounding of U.S. Navy aircraft primarily while on ground or carrier.
- Section 2 provides illustrations and procedures for grounding each type of operational Navy aircraft.
- Section 3 provides information to understand the need for grounding and bonding aircraft for protection against static charge and fault current.
- Section 4 provides theoretical basis for aircraft grounding.
- Section 5 describes methods of making earth ground resistance measurements.
- Static grounds are less than 10,000 ohms referenced to earth. Power grounds are less than 10 ohms referenced to power system neutral.
- Power systems used are 28 volts dc and 3 phase, 115 volts, 400 Hz, ac.
- Ten ohms to ground is not low enough to blow a 50 amp breaker. Hot ground wires may be the only indication of fault.
- Examples of problems resulting from poor grounds are given.
- Useful formulas and calculation examples for charge and fault current are found in sections 4 and 5, including airplane and human capacitance and damage threshold levels.

21. MIL-HDBK-419A, -- Vol. 1, Basic Theory, Grounding, Bonding, and Shielding for Electronic Equipments and Facilities, 12/29/87.

- Addresses earth electrodes, lightning, fault current protection, and signal references for facilities with associated bonding, wiring, shielding, etc. Contains good explanations applicable to flight equipment as well as

facilities.

- Earth electrode resistance-to-earth limits are usually 25 ohms for houses and 10 ohms for communications/electronics facilities. Typical soil resistivity and measurement methods are given along with earth electrode construction methods in chapter 2.
- Lightning protection theory including lightning rods, down conductors, earth grounds, and separation distances is presented in chapter 3.
- Chapter 4 describes fault protection schemes for single phase 115 volts ac and 3 phase 230 volts ac.
- Chapter 5 discussed single point grounds, floating grounds, and multipoint grounds for signal reference.
- Chapter 6 includes methods of noise coupling into signal circuits.
- Chapter 7 states bonding resistance of 50 kilohms or higher is adequate for ESD control and 50 milliohms for noise immunity (class "R"), but fault current and lightning may require much lower resistance. One milliohm indicates a very good bond.
- Discussions of bonding resistance variations due to contact pressure, surface hardness, surface roughness, and surface area are also in chapter 7 along with capacitance to ground, inductance of straps, coatings, and galvanic reaction.
- Shielding effectiveness formulas for materials and apertures and results from several samples are given in chapter 8.
- Protection of personnel from shock, static discharge, RF and Laser hazards, and X-rays is discussed in chapter 9.

22. MIL-HDBK-419A, -- Vol. 2, Applications, Grounding, Bonding, and Shielding for Electronic Equipments and Facilities, 12/29/87.

- Includes practical procedures and details of facility development to ensure lightning protection, fault protection, and provide signal reference. Bonding and shielding practices and earth grounding are described.

- Modifications for existing facilities and a checklist for inspection are included.
- Some equipment design criteria and a typical inspection checklist is included to assure whole system operates compatibly.

23. MIL-HDBK-454 -- General Guidelines for Electronic Equipment, Notice 1, 5/28/97.

- Lists individual guidelines for equipment by number. The number 1 item is Safety Design Criteria - Personnel Hazards. No details came with document; assume this individual guideline should contain shock hazard information.

24. AFSC DH 1-4 -- Air Force Design Handbook, Series 1.0, Electromagnetic Compatibility, Fourth Edition, Rev. 1, 1/31/91.

- Contains sections on bonding and grounding. Generally follows MIL-B-5087 requirements for bonding.
- Sections are as follows:
 - DN 5D2 -- Electrical Bonding Considerations
 - DN 5D3 -- Corrosion and Dissimilar Metals
 - DN 5D4 -- Methods of Electrical Bonding
 - DN 5D5 -- Grounding Considerations
 - DN 5D6 -- Bonding and Grounding to Prevent Fault Currents
 - DN 5E1 -- Constructing an Earthing System
 - DN 5E2 -- External Aircraft Grounding

25. EEB 3-2020-BKT -- EMC Design Guide, 9/66, Chapter 6, Bonding, (Boeing).

- Gives reasons for bonding and lists types of bonds -- permanent, direct, indirect, etc.
- Stresses calculations for inductance of straps and capacitance from box to structure. Determines impedance of the combination.

26. Metals Handbook, Ninth Edition, Vol. 13, Corrosion, Chromate Conversion Coatings, Karl Korineck.

- Explains chromate conversion coating preparation and application process.
- Describes properties of chromate coatings.
- Many commercial coatings available with a variety of chemical solutions applied by several methods.

27. Interference Reduction Guide, Vol. I, U.S. Army Electronics Laboratories, Fort Monmouth, N. J., 8/1/64, (Filtron Co., Inc.).

- Bonding effectiveness at radio frequencies depends upon the inductance of the bond path and the capacitance between the two items being bonded.
- The dc resistance can be used to determine whether a bond is grossly defective. The dc resistance of a good bond should be between 0.25 and 2.5 milliohms.
- When bond straps must be used for RF, they should be flat and solid. Even then their impedance will increase with frequency due to the inductance. The inductance of the strap and the capacitance across the joint may provide a parallel resonant circuit that produces even higher impedance at some frequencies.
- Dissimilar metals may cause galvanic corrosion. Use platings where necessary to prevent corrosion.

28. TIS 65SD230 -- Handbook of Electromagnetic Interference, 10/65, (G.E.).

- Lists reasons for electrical bonding.
- Stresses ground strap impedance, and gives impedance values of samples.
- Discusses corrosion and gasketing.

STUDIES AND MISCELLANEOUS:

29. IN-R-ASTR-64-15 -- Internal Note, Metal-to-Metal Bonding for Transfer of Radio Frequency Energy, R. Evans, 6/25/64.

- Uses aluminum samples to demonstrate resistance and impedance across bonded joint using various coatings and platings.
- Results indicate resistance varies with coating but impedance increases with frequency.
- Impedance quickly becomes higher than the resistance with increased frequency, and it is the same as other identical samples at higher frequencies regardless of the coatings.
- A round foot of one square inch area and one eighth inch height exceeds 2.5 milliohms at 7 MHz.

30. MDC-95-H-0004 -- Electrical Impedance of Space Exposed Alodine Used on ISSA, McDonnell Douglas Aerospace, 1/95.

- Study concentrates on effects of vacuum on Alodine surfaces.
- DC resistance and RF impedance measurements were made on Alodine 600, 1200, and 1500.
- Alodine 1200 as used at MDC resulted in high resistance across joints (2.5 to 100 milliohms).
- Four terminal measuring instrument appears to have leads connected to each other before connection to sample. This would cause resistance measurement to be through 3 joints instead of 1 joint.

31. MDC 95H0260 -- Electrical Bonding Surfaces for Space Station Replacement Hardware, McDonnell Douglas Aerospace, for Boeing Defense and Space Group, 4/95.

- Advocates use of Alodine 600 rather than Alodine 1200.
- Electroless and electrolytic nickel meets class "R" requirement.
- Electrolytic tin plating provides lowest resistance.
- Alodine 600 resistance not dependent upon roughness of

surfaces from 60 to 500 rms., immersion time from 1 to 7 minutes, or aging from 1 to 24 hours.

- Mate Alodine 600 within 24 hours or protect with tape up to one month.
- Nickel oxidizes to some extent but can be protected by a thin layer of gold plating.
- Some problem with nickel to aluminum adhesion for flat patches. Does better when nickel encapsulates aluminum part or otherwise is locked down.
- Some corrosion between nickel and aluminum. Edges should be protected.
- Tin oxidizes but soft oxide is easily penetrated with low load to give class "R" bond.
- Needs Nickel over aluminum for good adhesion, plate tin over nickel.
- Tin to aluminum has less corrosion problem than nickel to aluminum.
- Tin should be alloyed with 2% lead and 0.2% antimony or bismuth to prevent whisker growth.

32. N68-88150 -- Development of a Space Vehicle EMI/EMC Specification, MSC, Contract Number 9-7305, 6/28/68, (TRW).

- Reasons for bonding include intentional paths for circuit return, unintentional paths through capacitance, and magnetic field induction.
- Discusses grounding, wiring, and shielding.

33. TO-00-25-172 -- Air Force Aircraft Grounding.

34. MMS K406 -- Zinc Chromate Paste.

BOOKS:

35. Handbook Series on Electromagnetic Interference and Compatibility, Vol. 2, Grounding and Bonding, Michel Mardiguian, 1988.

- Purposes of bonding include proper performance of cable shields, shielded housings, and filters.
- One milliohm is considered a good dc bond, but ac impedance depends on the configuration.
- Parallel resonance of bond straps and capacitance between bonded parts is stressed.
- Equivalent contact area and impedance of bond with varying roughness is calculated.
- Bonds with various rivet and fastener configurations are presented.
- Finishes and oxide resistance are covered.
- corrosion and dissimilar metals are covered.

36. Introduction to the Control of EMI, Chapter 11, K. Javor, 1993.

- MIL-B-5087B classes "C", "H", and "R" bonding are discussed since they are the areas most likely to present problems.
- Class "C" sets resistance limits for bonds but actual resistance required is determined by the amount of current required and the voltage drop allowable.
- Class "R" impacts EMI performance.
- For containing conducted RF in filtered equipment, bond within equipment is important, but bond to ground plane is not important.
- For protection against conducted external noise the bond to structure is important.
- Bonding to contain radiated RF is important within the equipment and shielded cables between equipment. Bond of equipment case to structure not important except to protect against RF. Line to ground filters and case shields are affected.

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13. ABSTRACT (Maximum 200 words) This document provides information helpful to engineers imposing electrical bonding requirements, reviewing waiver requests, or modifying specifications on various space programs. Electrical bonding specifications and some of the processes used in the United States have been reviewed. This document discusses the specifications, the types of bonds, the intent of each, and the basic requirements where possible. Additional topics discussed are resistance versus impedance, bond straps, corrosion, finishes, and special applications.				
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