GROUNDING, BONDING FOR LARGE SPACE SYSTEM TECHNOLOGY (LSST)

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Final Report

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CONTRACT NAS8-33432
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National Aeronautics
and Space Administration

George C. Marshall Space Flight Center
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NASA CR

GROUNDING/BONDING FOR LARGE SPACE SYSTEM STRUCTURES (LSST)

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by

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Prepared for
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FORWARD

This document was prepared by the Boeing Aerospace Company for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center in compliance with contract NAS8-33432, "Grounding/Bonding and Data Power Distribution connectors and Cables for Large Space System Technology (LSST).

This report is one of two volumes documenting contract results. It consists primarily of the data generated during the task on grounding and bonding for large space systems to graphite epoxy, metallic and metallic composite structural members. The studies were based on airplane and spacecraft grounding and bonding applications now in service or planned for the near future.

ABSTRACT

This conceptual design and analytical study program examined the influence of the environment and extravehicular activity/remote assembly operations on the grounding and bonding of metallic and non-metallic structures. Grounding and bonding philosophy was outlined for the electrical systems and electronic compartments which contain high-voltage, high-power electrical and electronic equipment. The influence of plasma and particulate on the system was analyzed and the effects of static buildup on the spacecraft electrical system discussed. Conceptual grounding/bonding designs were assessed for capability to withstand high current arcs to ground from a high voltage conductor and electromagnetic interference. Also shown were the extravehicular activities required of the space station and/or supply spacecraft crew members to join and inspect the ground system using manual on remote assembly construction.

KEY WORDS

Bonding
Cables
Carbon fiber/epoxy structure
Connectors
Distribution
Electrical/electronic Systems
Grounding
Particulate
Plasma
Spacecraft charging

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1.0 SUMMARY

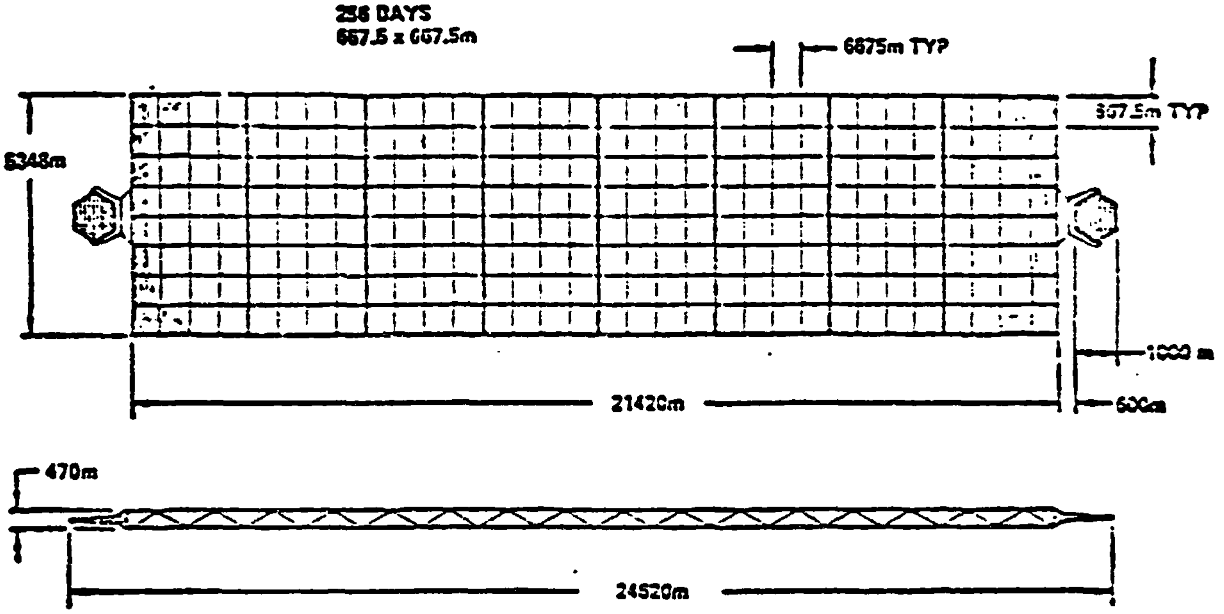
This analytic and conceptual design study program examined the spacecraft power distribution, and electrical loads and their influence on the structural grounding and bonding requirements for large space structures technology (LSST) spacecraft. Structural materials' electrical characteristics and the probable fault currents to which the structure could be subjected, were analyzed and conceptual designs for LSST grounding and bonding conceived. Available data from simulated lightning and electromagnetic pulse evaluation program for the United States Air Force were used for some of the analyses and suggested conceptual designs. New structural materials such as the metals, metallic composites and metallic-graphites materials, though in the developmental stages, hold promise of eliminating much of the bonding and grounding problem associated with graphite-epoxy to aluminum joints and structural compartments and beams.

2.0 INTRODUCTION

Studies have shown that many of the space missions proposed for the time period 1980 to 2000 will require spacecraft structures to be assembled in orbit. Large antennas and power systems up to 2.5 MW size are predicted to supply electrical/electronic subsystems, solar electric propulsion, and space processing for the near-term programs. Platforms of 100 meters length for stable foundations, utility stations, and supports for these multi-antenna and electronic powered mechanisms are also being considered.

A literature review was made of NASA, U.S. Air Force, and industry reports for large spacecraft structures. From this review it was concluded that spacecraft configurations with three power levels are planned between CY 1985 and 2005; i.e., (1) below 25kw, (2) 25kw to 2.5 megawatts, and (3) over 2.5 megawatts. Spacecraft with power levels to 25kw may use 1980 state-of-the-art materials, and bonding and grounding methodology. Spacecraft with power levels between 25kw and 2.5 MW will require higher distribution voltages and currents, depending upon the spacecraft design. Very large spacecraft and space stations, planned for the 21st century with power levels exceeding 2.5 MW will require high-voltage and high-current distribution systems.

Three structural configurations for large structure space system with power levels to 2.5 MW were selected for study of the electrical power system grounding. These configurations are shown in figures 2.0-1, 2.0-2 and 2.0-3. The configuration of figure 2.0-1 has long lines to the loads which will result in large voltage drops or very heavy conductors if low voltages are used. Thus, high voltage systems and equipment will be considered for optimal design concepts. In figure 2.0-2, a cluster type configuration is shown. Lower voltage, higher current lines can be used for this construction, provided the current can be successfully handled by the rotary joint (low losses and voltages drops). The figure 2.0-3 configuration has very long lines between



TOTAL SOLAR CELL AREA:	101.8 km^2
TOTAL ARRAY AREA:	113.2 km^2
TOTAL SATELLITE AREA:	114.5 km^2
OUTPUT:	16.93 GW MINIMUM TO SLIPRINGS

FIGURE 2.0-1 SOLAR POWER SATELLITE CONFIGURATION (CIRCA CY 2000).

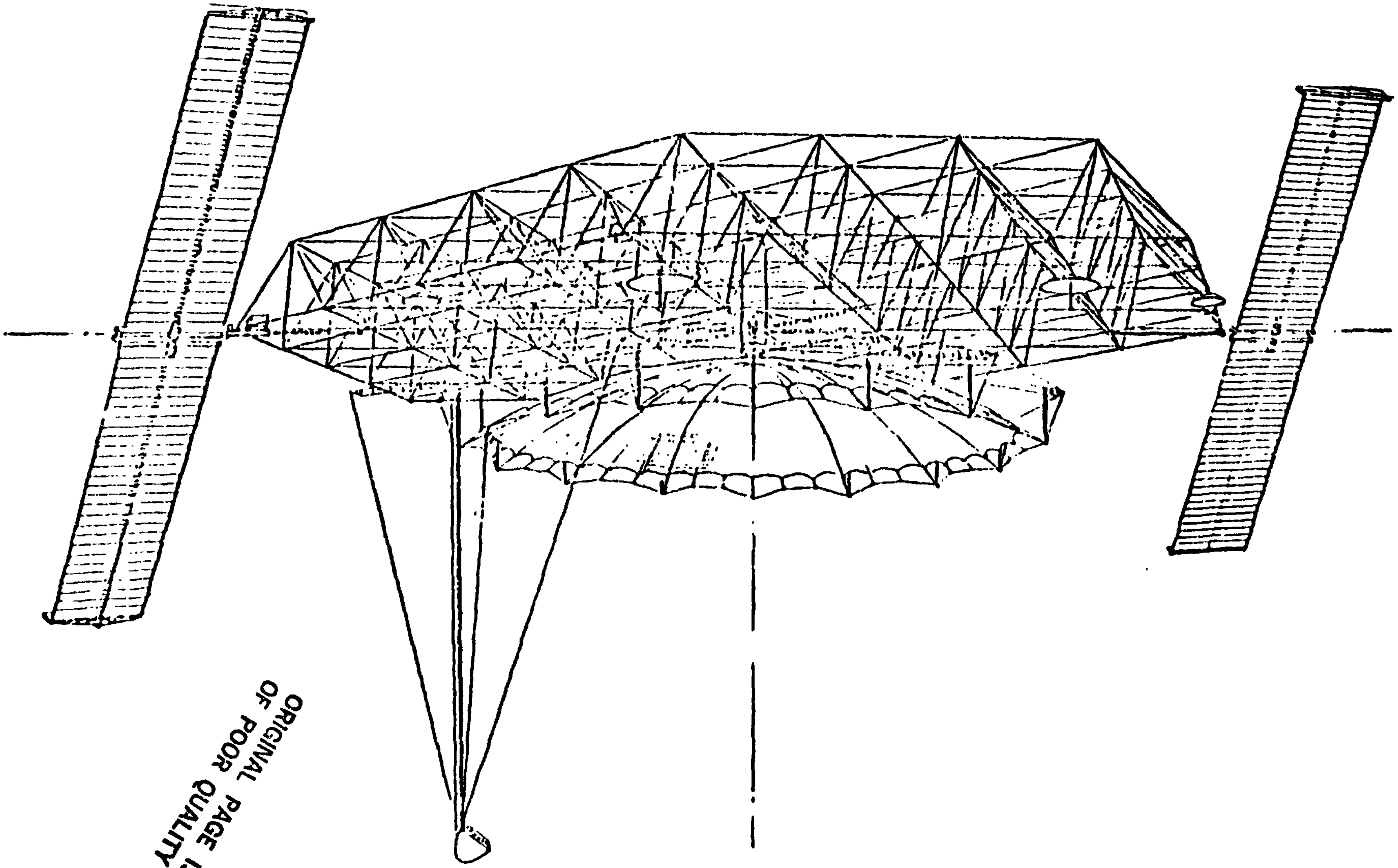
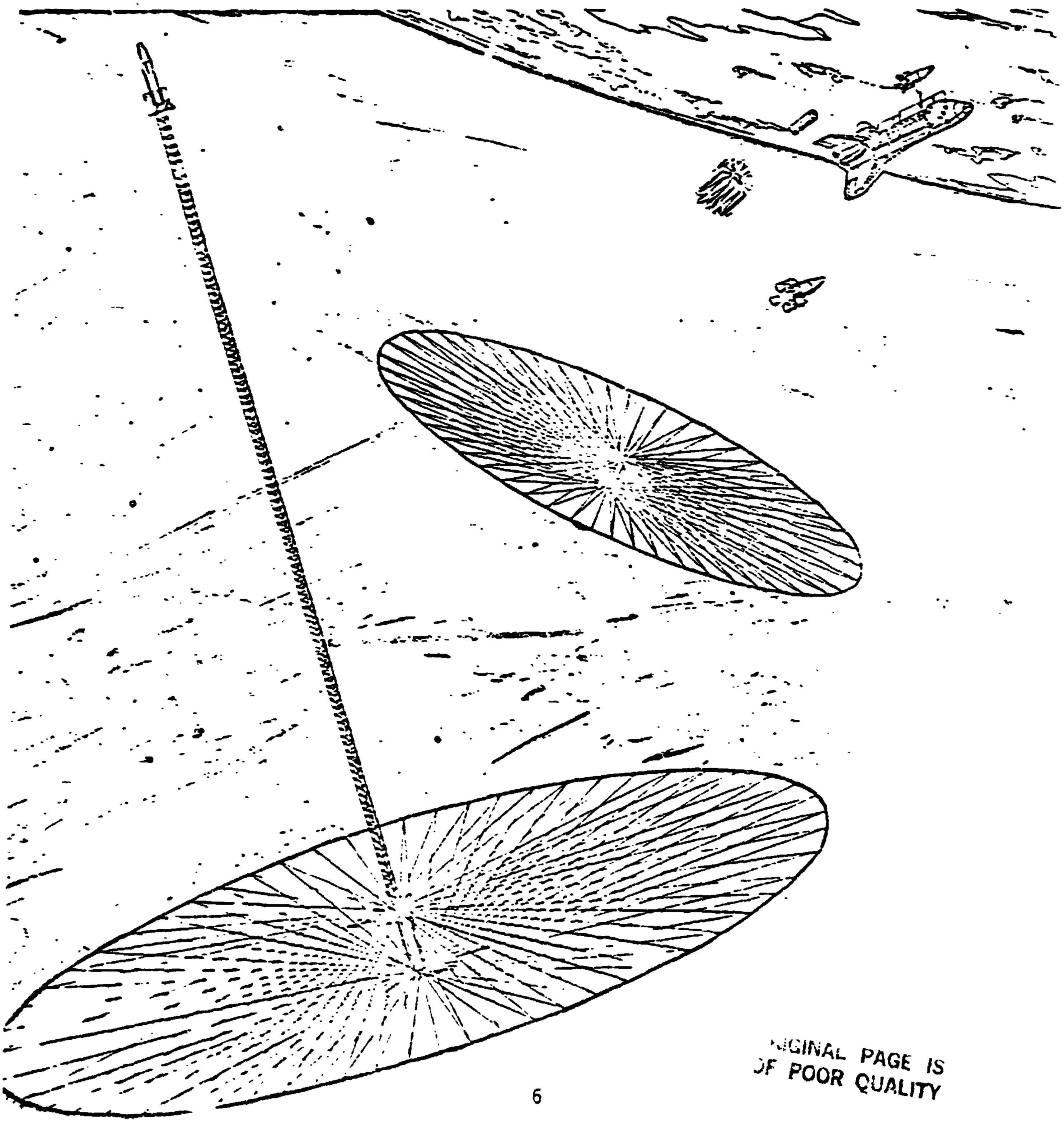


FIGURE 2.0-2 DISH ANTENNA SPACECRAFT CONFIGURATION

FIGURE 2.0-3

On-Orbit Assembly Concept Design



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the loads and the power source. This type of construction requires high-voltage transmission lines between the load and the generation center, similar to an electric utility distribution network.

This report documents the conceptual analyses and requirements plan to be used to arrive at the recommended grounding and bonding concepts. A functional flow diagram is shown in figure 2.0-4 which depicts the methodology used for the study.

The results include the following key items:

- Impact of environment on bare and insulated ground connections and bonds to the hardware.
- Compatibility of the spacecraft grounds and bonds to the power system, distribution system, and the electrical/electronic load equipment.
- Methods of bonding/grounding across flexible and insulated structural joints, compatible with the poorly conductive structural materials of a spacecraft.
- Grounding and bonding philosophy and design concepts with respect to high voltage, high current equipment, and logic and control equipment to sustain the operation of the high power equipment.
- Effects of static charge buildup on the spacecraft electrical power system and loads. Included are interactions and conceptual methods to reduce or normalize the charges.
- The effectiveness of the proposed conceptual grounds and bonds were assessed with respect to high power transients, arcs, and discharges. Methods were developed to prevent destruction of the bonded conductors or grounding system.

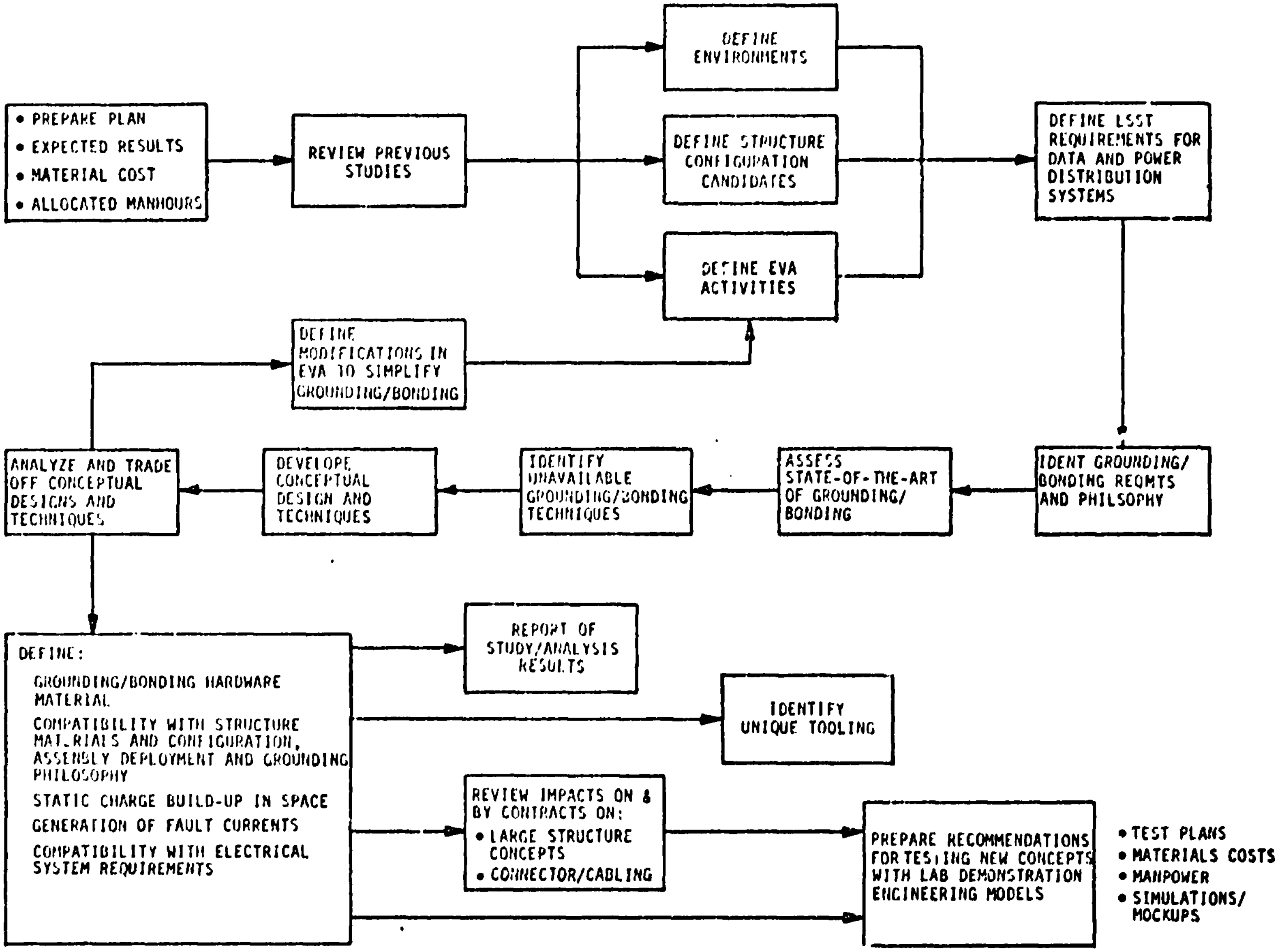

Figure 2.0-4: Functional Flow Diagram, Cable, and Conectors

- EMI radiation and conduction shielding effectiveness between the high-power system and equipment, and sensitive computer and logic control networks were evaluated on the basis of grounding/bonding effectiveness and spacecraft structures.

- EVA manipulator and teleoperator equipment concepts were defined, including unique tooling and test equipment required to inspect the grounds and bonds after assembly and/or maintenance.

3.0 BACKGROUND

The National Aeronautics and Space Administration (NASA) has future needs for the assembly of large structures in space which have large electrical power systems to supply the electrical/ electronic equipment loads. These electronic systems are used for communications, radar, and experimental equipment for aid to Earth's overcrowded communication systems, exploration of new energy resources, space exploration and eventually to supplement terrestrial electric power utilities. Some of these systems (near term, 1984-1990) have power levels to 2.5 MW. The long term programs, 1990 to post 2000, will have much higher demands - possibly into multi gigawatts.

To meet the spacecraft mission and load requirements, large spacecraft structures are required. In turn, these large spacecraft will require large power systems to operate the loads. In many cases, structural members will be manufactured on Earth, transported to a orbiting station, and the total system assembled in space. An important feature of the structures is that they be lightweight and have good structural integrity. In addition, a structure must be compatible with the power and electrical/electronics grounding and bonding system.

3.1 Survey

A survey was made to obtain data relative to problems associated with materials, grounding and bonding of structures and electrical systems in space. A list of NASA documents surveyed is given in references 1 through 12.

In addition, Boeing has published many documents for government angencies (including NASA), and has done independent research and development programs for airplanes and spacecraft. These documents also have been reviewed. One significant finding was the effects of high-current/ high-voltage arcs to various structural materials. Graphite epoxy

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materials withstand these arcs much better than many other types of epoxies, polyurethanes, and silicone-coated materials.

Many of the documents reviewed contained valuable information on the structural materials, (references 1, 2, 3, 4, and 5) and the fabrication and assembly of those structural members on Earth and in space (references 6, 7, 8, and 9). Three documents were oriented toward the electrical requirements and equipment (references 9, 10, and 11).

The data, in reference 11, is for the far-term, solar power satellite, a conceptual spacecraft system having about 10-15 gigawatts of power output. That document and many Boeing documents reviewed had much data on the power system schematic, but little data on the details involving distribution equipment or bonding and grounding. The data available were mostly oriented toward the cooling of the conductors, not the interconnects or fabrication in space by automatic or manual methods (reference 12). Information gleaned from reference 10 also involved power profile data of both large and small satellites. One document did have data on detailed concepts for cables, connectors, bonding and grounding (reference 9). This data was considered in our studies. In that study of the connector latching device it was assumed that an astronaut would be available to perform the latching. The Boeing study added concepts for connections and attachemnts by automatic methods.

3.2 System Requirements

System requirements are dictated by the spacecraft mission, design, and operational life in space. Many spacecraft are under consideration by NASA for service in the CY 1980 through 2000 time period. Some are for near-term missions through 1989, while others are in the conceptual planning stages for the CY 1990 through 2010 time period. This contract was oriented primarily toward the near-term missions, with a few applications studies for far-term missions.

S. R. Sadin (reference 13), of NASA/Hq. OAST System Planning, shows in his paper entitled "OAST System Technology Planning" a plot of space structures size and vehicle energy for the period from CY 1960 to CY 2000 (figure 3.2-1). Structural sizes are shown for 1976/1977 for Skylab, 1984 for Molecular Wake Shields, for Electronic Mail in 1990, and for SPS in 2,000. Energy levels are shown as 10^4 KWH/yr for Earth Resources in 1982; and 10^5 KWH/yr for Space Manufacturing in 1985. Also listed in the planning tables given in the paper are other high power consuming systems such as the Large Power Module in 1986 and the SPS in 2000; the power level of SPS will be 5 to 10^9 watts, which is 438 x 10^6 KWH/yr to 1,314 x 10^6 KWH/yr. Once again, the need for the LSST program is evident from the projected spacecraft requirements.

L. W. Brantley (reference 14), of NASA/MSFC in his paper "Power Modules And Projected Power Systems Evolution" shows a curve from CY 1980 through CY 2000 and power levels of 25KW Power Module in 1980 through the large power module, the SPS demonstrator, and the SPS of 5-10 GW in CY 2000. This also supports the requirement for the LSST program.

NASA near and far-term missions with respect to electrical power requirements are shown in figure 3.2-1 and in Tables 3.2-1 and 3.2-2. It is to be noted that many missions have electrical power requirements of several kilowatts to a few megawatts for the near-term missions. This implies that either very large currents at low voltage must be generated and distributed or the voltage must be increased to keep the current levels down. To meet the multimegawatt goals, both high current (over 1000 amperes) and high voltage must be considered. A plot of the current and voltage relationship to power and advanced technology distribution equipment and grounding and bonding is shown in figure 3.2-2. Three voltage regimes are shown in figure 3.2-2; voltages to 200 volts, between 200 volts and 2000 volts, and over 2000 volts. There are many specifications and standards for the lower voltages between 0 and 200 volts, few for the transition voltage (T) regime (200 to 2000 volts), and fewer for the high-voltage (HV) over 2000 volts.

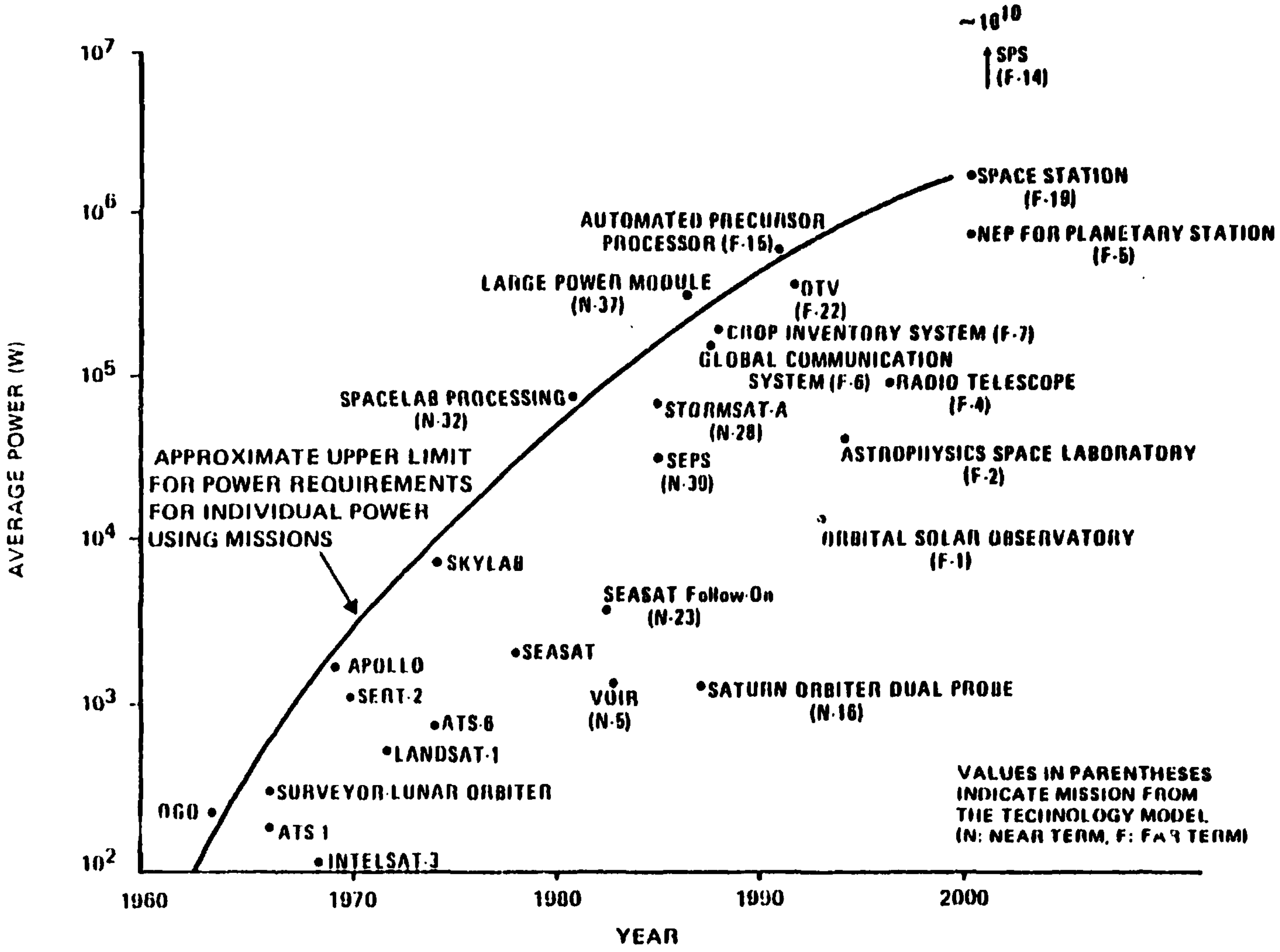


Figure 3.2-1: Mission Power Requirements

TABLE 3.2-1 INITIATIVE GROUP RANK ORDERING

INITIATIVE		IOC Date			POWER LEVEL
GROUP/ SUBGROUP	TITLE	OPTIMISTIC PROGRAM	STRETCHED PROGRAM	CONSERVATIVE PROGRAM	
2/1	PUBLIC SERVICE SYSTEMS USING LONG MICROWAVE STATIONKEPT ANTENNAS - I	1983	1983	1990	1.0 kW
3/1	POWER DISTRIBUTION SYSTEMS AND ACTIVE/PASSIVE RADAR - I	1982	1982	1989	1.0 kW
2/2	PUBLIC SERVICE SYSTEMS USING LONG MICROWAVE STATIONKEPT ANTENNAS - II	1987	1991	1994	1.3 kW
5/1	HIGH ALTITUDE NAVIGATION, LOCATION, AND RELAY SYSTEM - I	1983	1983	1990	1.7 kW
2/3	PUBLIC SERVICE SYSTEMS USING LONG MICROWAVE STATIONKEPT ANTENNAS - III	1992	1999	1999	2.0 kW
4 & 6/2	OPTICAL OBSERVATION, DESIGNATION, AND MEASUREMENT - I	1982	1982	1989	2.0 kW
9 & 11/1	SCIENTIFIC/RESEARCH EXPERIMENTS AND NATIONAL FACILITIES - I	1984	1984	1991	2.0 kW
5/2	HIGH ALTITUDE NAVIGATION, LOCATION, AND RELAY SYSTEM - II		1992	1995	2.2 kW
5/3	HIGH ALTITUDE NAVIGATION, LOCATION, AND RELAY SYSTEM - III		2001	2001	3.0 kW
1/1	SERVICE PLATFORMS USING MICROWAVE MULTIBEAM ANTENNAS - I	83	1983	1990	4.0 kW
3/2	POWER DISTRIBUTION SYSTEMS AND ACTIVE/PASSIVE RADAR - I	1986	1993	1993	5.0 kW
4 & 6/2	OPTICAL OBSERVATION, DESIGNATION, AND MEASUREMENT - II	1986	1988	1993	5.0 kW
9 & 11/2	SCIENTIFIC/RESEARCH EXPERIMENTS AND NATIONAL FACILITIES - II	1988	1991	1995	5.0 kW
4 & 6/3	OPTICAL OBSERVATION, DESIGNATION, AND MEASUREMENT - III	1990	1994	1997	10.0 kW
7/1	SPACE PROCESSING AND MANUFACTURING - I	1983	1983	1990	10.0 kW
9 & 11/3	SCIENTIFIC/RESEARCH EXPERIMENTS AND NATIONAL FACILITIES - III	1993	2000	2000	10.0 kW
4 & 6/4	OPTICAL OBSERVATION, DESIGNATION, AND MEASUREMENT - IV	1995	2002	2002	20.0 kW
1/2	SERVICE PLATFORMS USING MICROWAVE MULTIBEAM ANTENNAS - II	1987	1990	1994	25.0 kW
8/1	LARGE SCALE, HIGH ENERGY, FAR-TERM SYSTEMS - I	1982	1982	1989	25.0 kW
3/3	POWER DISTRIBUTION SYSTEMS AND ACTIVE/PASSIVE RADAR - III	1990	1997	1997	50.0 kW
7/2	SPACE PROCESSING AND MANUFACTURING - II	1988	1992	1995	50.0 kW
7/3	SPACE PROCESSING AND MANUFACTURING - III	1993	2000	2000	100.0 kW
1/3	SERVICE PLATFORMS USING MICROWAVE MULTIBEAM ANTENNAS - III	1993	2000	2000	100.0 kW
8/2	LARGE SCALE, HIGH ENERGY, FAR-TERM SYSTEMS - II	1984	1986	1990	210.0 kW
3/4	POWER DISTRIBUTION SYSTEMS AND ACTIVE/PASSIVE RADAR - IV	1994	2001	2001	300.0 kW
8/3	LARGE SCALE, HIGH ENERGY, FAR-TERM SYSTEMS - III	1987	1990	1993	2.0 MW
8/4	LARGE SCALE, HIGH ENERGY, FAR-TERM SYSTEMS - IV	1992	1996	1999	15.0 MW
8/5	LARGE SCALE, HIGH ENERGY, FAR-TERM SYSTEMS - V	1996	2000	2003	1.0 GW
8/6	LARGE SCALE, HIGH ENERGY, FAR-TERM SYSTEMS - VI	2000	2004	2007	15.0 GW

TABLE 3.2-2 INITIATIVE SUBGROUP POWER DEMAND VS IOC DATE

OPTIMISTIC PROGRAM IOC											
1982-1984		1985-1987		1988-1991		1992-1994		1995-1997		1998-2000	
CONSERVATIVE PROGRAM IOC											
1990-1992		1993-1995		1996-1998		1999-2001		2002-2004		2005 - 2007	
Subgroup	Power	Subgroup	Power	Subgroup	Power	Subgroup	Power	Subgroup	Power	Subgroup	Power
2/1	1.0 kW	2/2	1.3 kW	5/2	2.2 kW	2/3	2.0 kW	4 & 6/4	20 kW	8/6	15 GW
3/1	1.0 kW	3/2	5.0 kW	9 & 11/2	5.0 kW	5/3	3.0 kW	8/5	1 GW		
5/1	1.7 kW	4 & 6/2	5.0 kW	4 & 6/3	10.0 kW	9 & 11/3	10.0 kW				
4 & 6/1	2.0 kW	1/2	25.0 kW	3/3	50.0 kW	1/3	100.0 kW				
9 & 11/1	2.0 kW			7/2	50.0 kW	8/2	210.0 kW				
1/1	4.0 kW			8/3	2.0 kW	3/4	300.0 kW				
7/1	10.0 kW					8/4	15.0 MW				
8/1	25.0 kW										

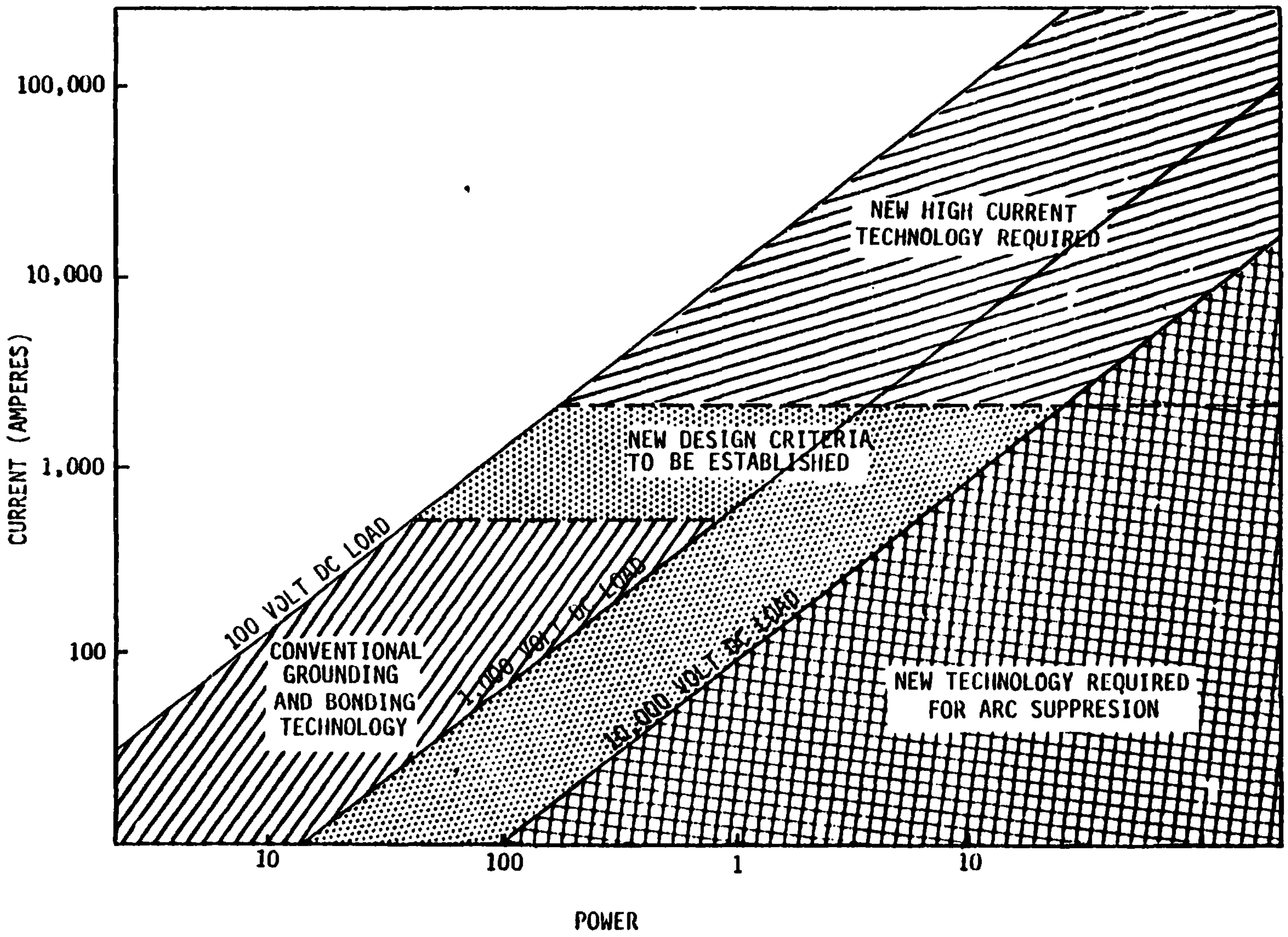


Figure 3.2-2: Bonding and Grounding Applications for Power Systems

Therefore, the space missions should identify the voltage level. This has been added to the missions shown in Table 3.2-3. Ground return via cables and connectors on composite structures will all be influenced by the voltage, current, and power level of the spacecraft. Vehicle size will affect the cable size, thus the voltage drop and voltage variance across such items as solar panels. Secondary effects will include transients, traveling waves, electrostatic charging of the plates beneath the high-voltage cables and the debris collected on the wires.

The technologies supporting the LSST program must be developed to provide those techniques and equipment compatible with the electronic data and electrical power distribution systems which will be a part of the large spacecraft. Consequently, identification of the requirements for the electronic data and power distribution systems and techniques, materials and components are important to this program.

3.3 Graphite-Epoxy Bonding Survey

Reported-experimental data for epoxy bonded graphite fibers were reviewed. Discrepancies between experimentalists data differ by as much as two orders of magnitude, conductivity, depending upon the composition of the material and fiber orientation when taking measurements.

3.3.1 Work at Notre Dame University Summary

Holzschuh (reference 15) measured free fibers and found that these fibers are ohmic at voltage gradients well above those at which graphite-epoxy composites depart from linearity. Curiously, the fibers are ohmic up to the point of thermal failure. This departure from linearity of graphite epoxy composition is not fully explained.

TABLE 3.2-3 SPACE INDUSTRY OPPORTUNITIES

SPACECRAFT		POWER KW	TIME FRAME YEAR	ORBIT	VOLTAGE LEVEL [1]
PERSONAL COMMUNICATIONS WRIST RADIO	(CC-9)	21	1990	SYNCH	S
URBAN/POLICE WRIST RADIO	(CC-2)	75	1985	SYNCH	S
3-D HOLOGRAPHIC TELECONFERENCING	(CC-11)	220	1990	GEO	T
DIPLOMATIC/U. N. HOTLINES	(CC-10)	1	1985	SYNCH	S
NATIONAL INFORMATION SERVICES	(CC-8)	15	1990	SYNCH	S
ELECTRONIC MAIL TRANSMISSION	(CC-4)	15	1990	SYNCH	S
DISASTER COMMUNICATIONS SET	(CC-3)	75	1985	SYNCH	T
ADVANCED T. V. BROADCAST	(CC-6)	150	1990	GEO	T
ENERGY MONITOR	(CS-9)	23	1985	GEO	S
GLOBAL SEARCH & RESCUE LOCATOR	(CC-1)	1	1985	MED ALT	S
NUCLEAR FUEL LOCATOR	(CO-7)	0.3	1985	SYNCH	S
VEHICULAR SPEED LIMIT CONTROL	(CS-10)	1	1990	SYNCH	S
SYNCHRONOUS METEORLOGICAL SATELLITE	(CO-12)	1	1985	SYNCH	S
ATMOSPHERIC TEMP. PROFILE SOUNDER	(CO-11)	5	1990	600 N MI	S
WATER LEVEL & FAULT MOVEMENT INDICATOR	(CO-3)	0.25	1985	GEO	S
OCEAN RESOURCES & DYNAMIC SYSTEM	(CO-4)	25	1985	300 N MI	S
FIRE DETECTION	(CO-2)	2	1985	SYNCH	S
HIGH RESOLUTION EARTH MAPPING RADAR	(CO-13)	2,500	1990	400 K M	HV
ADVANCED RESOURCES/POLLUTION OBSERVATORY	(CO-1)	12	1985	500 N MI	S
U. N. TRUCE OBSERVATION SATELLITE	(CO-6)	3	1985	225 N MI	S
BORDER SURVEILLANCE	(CO-8)	20	1990	SYNCH	S
MULTINATIONAL AIR TRAFFIC CONTROL RADAR	(CO-5)	1	1985	300 N MI	S
TRANSPORTATION SERVICES SATELLITES	(CC-5)	0.6	1985	8,000 N MI	S
COASTAL ANTI-COLLISION PASSIVE RADAR	(CO-9)	3,000	1995	SYNCH	HV

(continued)

TABLE SPACE INDUSTRY OPPORTUNITIES (CONTINUED)

SPACECRAFT		POWER KW	TIMEFRAME YEAR	ORBIT	VOLTAGE LEVEL [1]
NEAR-TERM NAVIGATION CONCEPT	(CS-16)	1	1980	SYNCH	S
PERSONAL NAVIGATION WRIST SET	(CS-7)	2	1990	SYNCH	S
VEHICLE/PACKAGE LOCATOR	(CC-12)	23	1990	GEO	S
SPACE DEBRIS SWEEPER	(CS-11)	-	1985	LEO TO GEO	S
VOLTING/POLLING WRIST SET	(CC-7)	90	1990	SYNCH	T
ENERGY GENERATION-SOLAR TO MICROWAVE	(CS-1)	107	1995	SYNCH	HV
NIGHT ILLUMINATOR	(CS-6)	1.2	1990	SYNCH	S
NUCLEAR WASTE DISPOSAL	(CS-4)	-	1995	ESCAPE	S
ENERGY GENERATION-NUCLEAR/MICROWAVE	(CS-3)	10^7	2000	SYNCH	HV
MULTINATIONAL ENERGY DISTRIBUTION	(CS-8)	20	2000	225 NMI	S
POWER RELAY SATELLITE	(CS-15)	-	1995	SYNCH	HV
AIRCRAFT LASER BEAM POWERING	(CS-5)	-	2000	300 NMI	HV
ENERGY GENERATION HIGH EFF. SOLAR CELLS CONCENTRATOR	(CS-2)	10^7	1995	SYNCH	HV
TELEPHONE LONG LINE	(X-1)	100	1995	SYNCH	T
BURGLER ALARM	(CS-14)	1	1985	SYNCH	S
MILITARY COMMUNICATIONS WRIST RADIO	(MC-10)	100	1987	SYNCH	T
COMPUTER LONG LINE	(X-2)	400	1990	SYNCH	T
MILITARY AIRCRAFT COMMUNICATIONS	(X-3)	75	1990	SYNCH	T
MOBILE COMMUNICATIONS - TRUCK	(X-4)	750	1990	SYNCH	T
GLOBAL POSITIONING SYSTEM	(MS)	1	1980		S

[1] S - 0 TO 200 VOLTS
T - 200 TO 2000 VOLTS
HV - OVER 2000 VOLTS

Scruggs (reference 16) measured slabs having no bonding features added (plain slabs). His results together with Holzschuh's are:

Composite Slab:

	Fiber	Lengthwise	Crossfiber
Max Ohmic Voltage Gradient (v/m)	4,000	250	4,000
Max Ohmic Current Density (Amps/m^2)	10^8	4×10^5	10^4
Conductivity (mhos/m)	20,600	2,000	<20
	(Holzschuh)		(Scruggs)

The team disagrees on why the fiber goes to 4,000 volts/meter while the composite becomes non-linear at 250. Scruggs claims it is due to heat, but Holzschuh disagrees. Neither article mentions the role of fiber-to-fiber junctions in lengthwise conduction; nor is there a discussion of the contradiction between crossfiber and longitudinal temperature dependance. Experimental fiber lengths varied from ¼ to full length of the slab, and the voltage gradients in the slabs were concentrated at the fiber ends.

The complete independence of crossfiber conduction from temperature is due to electrolytically deposited graphite (a General Electric development) conducting only in one plane. This suggests that graphite fiber conductivity and its temperature dependence may not be isotropic.

3.3.2 Work at Douglas Aircraft

Kung (reference 17) used the Thermovision camera to study fiber involvement. He noted that as the voltage across the sample rose the resistance decreased (more fibers becoming involved), but the inductance remained constant. Kung notes:

> "This non-linear resistance property has been determined by observation of the Thermovision data, to be a function of the joint design. The initial rate of rise and peak amplitude of the current waveform affects [illegible] te at which

> the number of graphite fibers become involved in the current transfer near the joint interface area, thus changing the overall test specimen resistance value. These results indicated that for a conductive joint, the design objective should be to involve as many graphite fibers as is practicable for the transfer of current in the joint interface area."

It appears that graphite joints on a space platform require treatment that is tailored to the magnitude and rate of rise of the anticipated electrical current. For example, achievement of a low resistance for low current levels will require more fiber contact than for high current levels.

4.0 GROUNDING/BONDING PHILOSOPHY

Spacecraft for the 1980's will have power requirements of a few watts to 2.5 megawatts. The bonding and grounding of these units will vary considerably. Smaller spacecraft, with powered loads to 5 KW will use standard, single-point grounding techniques with the solar arrays referenced to the central load module. Larger spacecraft using multiple solar array sections, capable of being transported to space via the shuttle and assembled in space, may have a main load center and several remote load centers. Those spacecraft will require special bonding and grounding considerations.

4.1 DECENTRALIZED LOAD CENTER

A large spacecraft may have one main load center and one or more remote load or control centers. The problem that exists for these remote centers is the voltage differential between the remote load center and the main load center due to line voltage drops. There are three methods for connecting these remote control centers to the main load center; (1) hard lines with isolating transformer, (2) fiber-optics, and (3) radio frequency link.

Hard lines require that the power, communication, and control lines all be insulated from the structure surfaces and that lines other than power be sectioned and isolated with transformers. Even so, a voltage differential would exist between the ends at the line shields and structure and/or nearby power lines. Power line transients could induce large common mode voltages into the lines creating interference to the remote sensors.

Long fiber optic lines may require repeaters. Multiple connections could be a problem. The remote centers however, would have their own grounds and be isolated from the main load center.

Radio links require added equipment as do the fiber-optics. Interference from outside sources and transceiver reliability would be a problem. The radio link is easiest to repair and maintain because each transceiver has an assigned location and controls a specific set of equipment on the spacecraft as shown in figure 4.1-1.

4.2 Ground Principles

4.2.1 Nature of Grounds

Ground is a relative concept, signifying a reference potential common to some zone of interest; it has no useful absolute meaning. For example, in the zone comprised of Earth and its atmosphere, the potential of a charged spacecraft is unambiguous. This results from the Earth being large and a conductor, thus, establishing an incontrovertible reference: a ground for its zone. But the interior of a spacecraft is a different zone with a different ground. Relative to that ground (spacecraft interior zone) the power source neutral is at zero volts, not the spacecraft charge with respect to Earth. In addition, when another spacecraft docks to the spacecraft the power source neutral is still at zero volts insofar as the interior zone observer is concerned. Likewise, the docking spacecraft will maintain its interior zone ground until the two spacecraft are connected as one unit. If the reference spacecraft is composed of a graphite composite material, the important questions are: "what is really different between the two joined spacecraft, and what is now the reference for potentials within the reference spacecraft?" The important difference is that the enveloping, dominating, metallic frame of the reference spacecraft is replaced by a structure of uncertain electrical continuity to the docked spacecraft. Earth is too far away to provide an unambiguous high frequency reference, and what nearby metal parts do exist are either too small, inaccessible, or not unipotential. Because there is nothing incontrovertible to relate to, there is no ground (except at DC). Finally, suppose that the reference

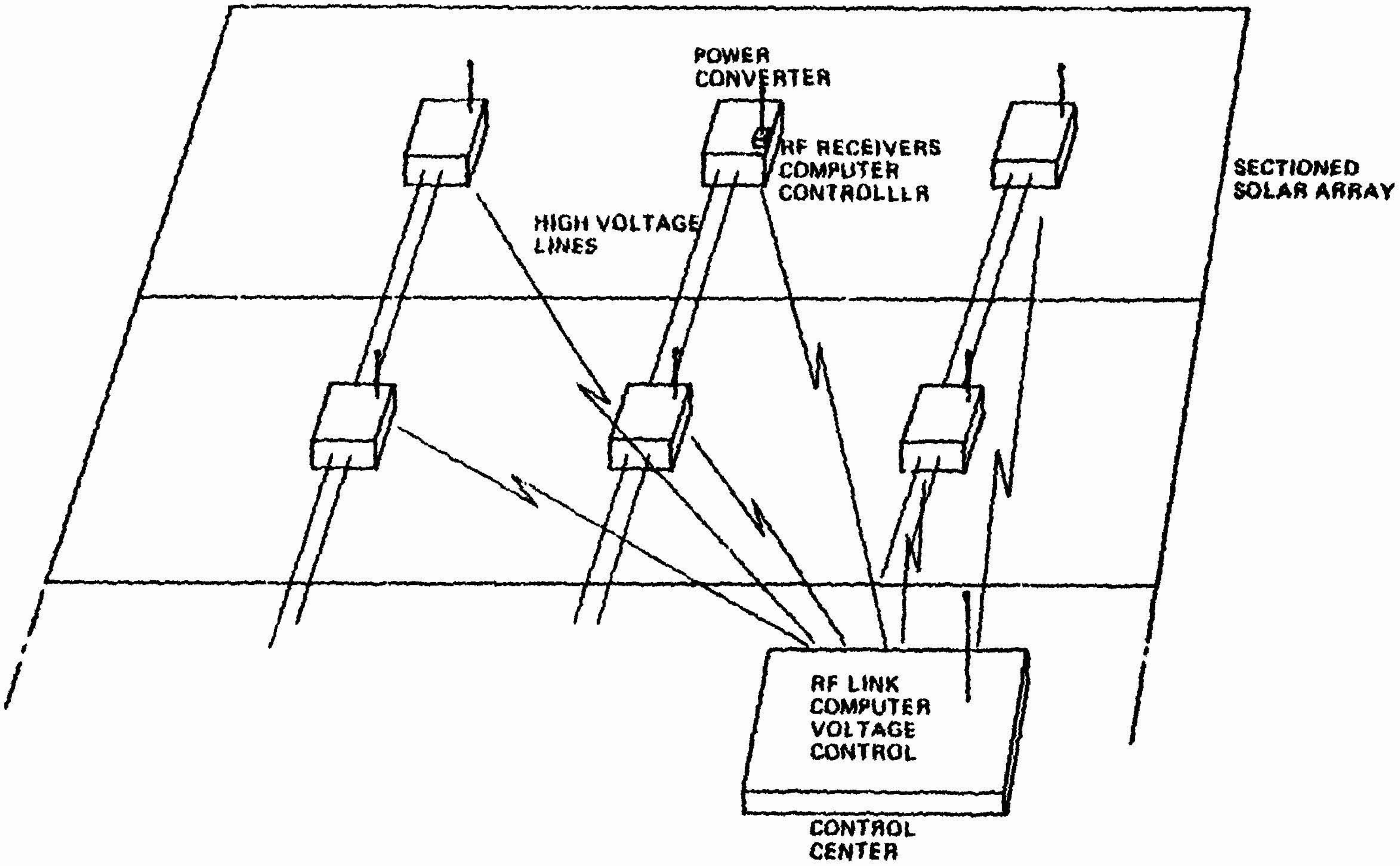


Figure 4.1-1: Spacecraft Distribution Radio Link Control System

spacecraft interior is provided with a continuous metal surface. The observers' uncertainty partially clears: object potentials near the large metal sheet can conveniently, accurately, and without controversy be measured with a voltmeter. The potentials of objects not so near the sheet remain controversial. Note that connection of the metal sheet to another vehicle or another section of the spacecraft does not affect those statements. If an interior is served throughout by a conductor wide enough to maintain a common potential even while returning large high frequency currents, then that zone has a ground. It follows that any zone within the above also has a ground (the same one, or a shielded cell), but that a larger enveloping zone may not.

4.2.2 Circuit-Ground Relationship

Interconnect circuits and ground share interdependent design requirements, a situation that must be recognized in organizing an installation into zones for grounding. In outline, cables between zones must contain only transmission lines and the zone of a ground must encompass all zone interconnects that contain circuits. A fuller statement follows.

Parameters of the interrelationship describe two sets of gross properties: first, an electrical interconnection may be characterized for grounding purposes by these common mode properties:

a) Common mode (CM) impedance: the impedance measured between the two end reference points using a perfect ground as return.

b) Common mode current: the net current found if the two end reference points are bonded to a perfect ground.

c) Common mode voltage (CMV) tolerance threshold: the permissible voltage difference between the two end reference points, applied using a perfect ground as one lead.

Some examples: An optical cable will have infinite CM impedance and CMV threshold and zero CM current. An AC power circuit will have high CM impedance and near-zero CM current (assumes no load bypass capacitors) until faulted to ground. A grounded transducer monitored by a differential amplifier via a shielded pair, shield open at the amplifier, will have high CM impedance, zero CM current and a CMV threshold of a few volts at 60 Hz, less at higher frequencies. Adding a double grounded shield to any circuit lowers the CM impedance and self-generated current but does not change the CMV threshold (except if totally shielded).

Second, a ground may be characterized for circuit protection purposes by its extent and impedance:

a) Whether or not it connects two points of interest.
b) Impedance between those two points (common path used as return).
c) Survivability, i.e., oxidation and fault current.

The interdepance can be put in the following two ways, first qualitatively: An electrical interconnection can be implemented without ground using a circuit with low CM current and high CM threshold, e.g., a reference transmission line. The transmission can also be implemented using an unbalanced, low impedance, vulnerable circuit that is protected by a good high-frequency ground. Quantitatively, a fairly general rule can be made that the impedance of the ground should be many times lower than the CM impedance of the circuit. A fixed ratio is not an appropriate guide because the environment may also drive current through the ground. In any case, the voltage drop in a ground path due to both environment and circuits should be below the CMV threshold of all circuits sharing the ground path. This interdependence is the guide for choosing the extent of a circuit zone to be provided with ground.

4.2.3 Cul-de-sac Ground Design

By putting the interior zone in a cul-de-sac, environmental currents are almost entirely excluded; whatever the quality of the zone ground, it will perform better if relieved of these external stresses. The idea is not new, being normal practice in shielded room design. In another industry which uses the cul-de-sac idea, the single area of connection is called the "grounding window". This "window" gets special attention here and will be called a "single-plate connection".

4.2.4 Single-Plate Ground Connection

Protection of a zone of electronic equipment by putting it into a cul-de-sac requires that not only the zone ground but all cables and every interconnect must run out of the mouth of the sac, the "grounding window". This can become perforce a rather large area, even an entire wall. The larger it is the greater is the likelihood of external currents coming in (figure 4.2.4-1A). The prevention is to "plug" the "window" with a sheet of metal and connect to it all entering conduit. In effect, the feed-through panel of a shielded room is installed. Considering that this metal "plug" is also the only connection between the zone and the remainder of the spacecraft, the name "single-plate" is appropriate. In summary, the single-plate does two things:

1. Shorts out external voltage differences.
2. Establishes the potential of the protected zone with respect to the zone.

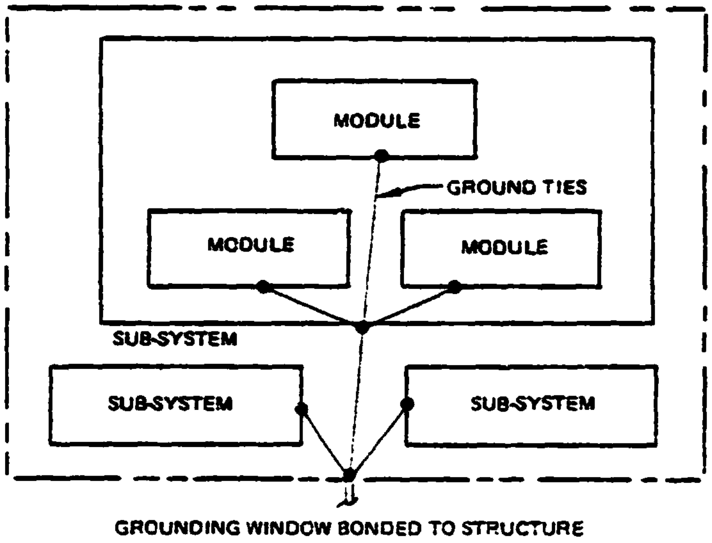
4.2.5 Electronic Areas

Electronics space can be grounded most economically if arranged in squarish "circuit zones" not too large in size. These are the cul-de-sac zones. The metal "sheet" forming zone ground is described later.

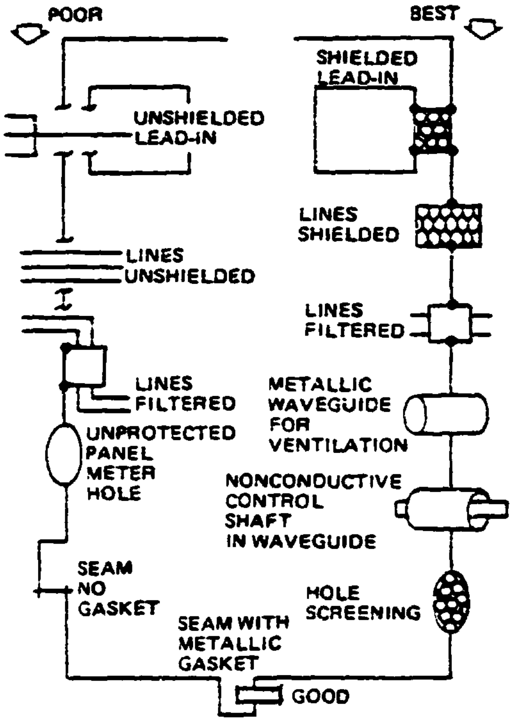
The maximum good length of an information circuit not specially designed for distance is something under 50 feet. Lacking other requirements then, the space may be subdivided into squarish zones up to 50 feet on the longest side. If a larger physical grouping is needed, then it should be subdivided electrically. The circuit zones resulting from subdivision of such a large grouping must each one be connected per the cul-de-sac idea.

4.2.5.1 Cableway Location

The cul-de-sac or, "grounding window", scheme requires that all



A. THE CONCEPT OF SEPARATE GROUND PATHS



B. APERTURE DESIGN FOR GROUNDING

Figure 4.2.4-1: Cul de Sac Ground Concept cables and conduit entering a zone do so via the single plate. This connecting plate will typically occupy much of one wall and should not extend to two walls. Cableway planning should therefore assign single-plate locations to each zone, and implement connecting routes.

One wall is to be designated the "interconnect window", which is to say, the site of the "single-plate" for the zone. This plate is a metal sheet with many cable and duct penetrations. The other three walls, and floor and ceiling are not to be penetrated by metallic runs of any kind.

4.2.5.2 Power Transformers

Separate power transformers are advisable for each major independently managed activity which may occupy a facility. At the least, electronics should not share a transformer with SCR-controlled motors, or solenoids.

4.2.5.3 Circuit Zone Isolation

The cul-de-sac design approach requires that the circuit zone ground and all that it connects be insulated from electrical contact with anything other than the designated single-plate.

4.2.5.4 Single-Plate Ground Connection

The single-plate shunts together all "zero" voltage conductors that connect with a circuit zone; it is also the origin of ground for that zone.

In size this plate must accomodate all penetrations of the zone as described below yet not extend beyond one wall. Material and construction should be the same as the wall of a shielded or screened room through which cabling enters. However, because the grounding function is less difficult to achieve than electromagnetic radiation shielding, it is also acceptable to use foil (0.01 inch) attached to a structural wall. The plate may be composed of smaller constituent plants, each accommodating part of the total interconnect, which are joined with wide (width a third of length) straps.

Material may be copper or aluminum. If aluminum, use extra heavy fasteners and bonding adhesive at all joints plus proper intermediate washers at dissimilar metal joints.

Incoming power conduit and safety return (green wire) must be connected to the single-plate. This should be accomplished by mounting the zone distribution panel on the single-plate, the ground bus inside connecting to the panel. Resistance from the power safety ground bus to the single-plate should not exceed 0.010 ohm.

4.2.5.5 Signal Conduit and Overall Shields

Signal conduit and overall shields should bond to the single-plate with a grounding clamp or conduit nut. Straps are less effective.

4.2.5.6 Metal Ducts and Trays

Metal ducts and trays should be bonded to the single-plate at the entry with two short straps put on at the corners.

4.2.5.7 Circuit Shields, Returns, and Coax

No fixed rule applies to circuit shields, returns, and coax incoming "zero" voltage conductors; they are explicit circuit elements. Consideration areas follow: If a zero voltage conductor connects with a nearby circuit zone, then this conductor can pass through the single-plate ungrounded by virtue of having the status of the high voltage conductor. If, however, the run connects with the exterior, then the subject conductor may be a very intense source which should be grounded to the single-plate to protect the zone from damage (figure 4.2.4-1B).

Circuit grounding to the single-plate is best accomplished by mounting to the single-plate a junction box in which the junctions have close access ($\leq$ 10 cm) to a grounding plate.

4.2.5.8 Circuit Zone Ground

Zone ground construction should utilize existing metal if such is insulated from the spacecraft structure and well bonded. The minimum design scheme is that every cable in the circuit zone requires an adjacent ground path. More width is better, but extent beyond zone boundaries is not beneficial.

If cabling is in trays, the trays can furnish a good ground. Sheet metal "floors" should be added to increase longitudinal conductance (admittance) and joints should be bonded (bolted structural connectors are adequate if the faying surfaces are bare and clean).

4.2.5.9 Power Conduit

Power conduit should be run at the same height as the zone ground and may be connected thereto.

The degree of protection afforded by zone ground increases with its size. If the ground only underlies (overlies) each cable route, then the ground is nothing more than a conduction shield. If the ground is increased to cover the floor, then it becomes an induction shield. If the ground is increased to five sides with the single-plate completing the sixth, then the ground has become a radiation shield.

Connection from the trunk ground paths to cabinets should in general be effected with two, six-inch straps per cabinet, at the extremities.

Connection from the ground to the single-plate (bonded) should be wide enough to encompass the width of cabling penetrating the single-plate. Power shall be run directly from the first panel following transformation.

If line filters are to be installed, they should be mounted on the single-plate, following shielded-room practice: install conduit from the filter to the outside of the single-plate, then penetrate.

If an isolation transformer is to be added, then the case and the second neutral are grounded to the single-plate.

4.2.6 Launch Complexes

Launch complexes are too spaced out to be made unipotential, yet they are so interconnected that a tendency exists to use ordinary interconnect circuits in spite of the large reference voltage differences. It is necessary that these differences be minimized while at the same time maintaining circuit invulnerability.

4.2.6.1 Land Lines

Each land line cable route over an earth path should be protectively run in metal trays. These must be bonded to form a lengthwise continuous path. Path width should be sufficient to permit spacing unlike cables apart by about one foot (twice the height of the highest cable pile). At building entry the tray must be well strapped to building ground.

For lightning protection an earth connection is needed just outside each building entry and at least each 1000 feet enroute. These are in addition to building earth connections.

4.2.6.2 Umbilical Towers

Electronic installations in umbilical towers are special because the cables are long and exposed to lightning induction.

The effect of distance and nearby interference currents is to create a difference of potential between different levels of the tower, a problem for any circuits running vertically.

One approach to reducing this difference is to install one or more heavy copper conductors the height of the tower, these being connected to the tower steel at only the bottom end; this approach is based on the expectation that by keeping large currents out of these conductors they will provide a quiet ground upstairs. If shielded, such busses can be of benefit, but are not an ecomonical way to achieve the unipotential goal. Further, upstairs circuits which use the singly grounded busses must themselves not connect to local structure, a handicap to shielding and filtering designs. For these reasons single point grounded vertical busses are not recommended.

Cabinet circuitry should be referenced to metal structure at its own level. Vertical reference shift is minimized by installing vertical cables in steel cableways that form an overall shield. Design of vertical circuits for this kind of ground is easier than for the single-point-grounded reference.

Primary structure of metal towers need not be specifically bonded electrically due to the good properties of large sections and high fastener pressures. Light members and hinged members require bonding. MIL-B-5087 or equivalent is a good text for treatment of all non-primary metals in the umbilical tower. Bonding is essential to the purposes of lightning protection, electrical power fault safety, electronics ground creation and radio wave heterodyne prevention. The following general rules apply to structure, and also to cabinets, ducts, brackets, stanchions and rigging.

- Bond per MIL-B-5087 all non-primary structure joints which: a) lie in or near (6 feet) the path of lightning current, b) lie in a possible electric power ground fault path, c) are traversed by electric cabling, and d) are situated in the near field of an antenna.
- Insulate or bond all non-primary structure and rigging joints which are not so directly involved as those listed above.

Incoming cable trays are to be strapped to the tower structure to provide ground path continuity for the cabling.

Tower corners are to be connected to earth.

MIL-B5087 covers bonding of rotating joints.

Due to the very large reference difference between tower (or support equipment room) and a launch vehicle, a special class of circuit design is appropriate for umbilical cables. Two of the ground ramifications are:

a) The only permissible double grounded shield is one which encloses an entire cable and terminates with a 360^0 peripheral bond to the umbilical plug shell.
b) Circuits must have high common mode impedance (at least 10,000 ohms) and high common mode voltage threshold (at least 24 volts).

4.2.6.3 Launchers

Launcher design shall incorporate a vertical conducting path from each holding support to a perimeter conductor at earth grade and past that to earth connections. The perimeter conductor is connected to the "common launch ground."

4.2.6.4 Equipment Rooms

An equipment room is a "circuit zone" that has to be protected. The "single-plate," is to be strapped to "common launch ground" and also connected to earth.

4.2.6.5 Common Launch Ground

The first priority at the earth interface for a launch complex is interconnection of the grounds of the tower, launcher, and equipment room to minimize a relative difference of potential. This should be achieved by relying on the continuous metal paths formed by interconnecting cable trays.

The second priority is making earth connections at the launcher base, tower base, and (possible, depends on arrangement) equipment room. Lightning codes provide details.

The resulting design should be reviewed to assure that every conductor entering an element of the complex has its sheath connected at the entry to the local ground. This will be, for example, the equipment room single plate, the launcher perimeter conductor, and the umbilical tower structure.

4.2.6.6 Checkout Areas

Support equipment should be organized into circuit zones. The flight hardware should be placed on a sheet of metal, a bonded frame, or other obviously dominant ground. (Connections between this support ground and the flight hardware are program peculiar). This support ground under the flight hardware is to be connected to the single-plates (or equivalent ground connection) of circuit zones with which the flight hardware has connection; these connections should be effected with a bonded cable tray. The flight hardware support ground should be insulated from other connections so that the flight hardware is in a cul-de-sac.

4.3 Bonding Principles

This paragraph defines the bonding and ground requirements for large spacecraft with singular and multiple electrical/electronic load centers powered by a single power distribution system.

4.3.1 Bonding Within Metallic Islands

The bonding design of a large platform can be resolved into bonding for long paths and bonding for short paths within discrete smaller areas. Interactions between these resolved designs are easily assessed and corrected. This approach permits each discrete smaller area, i.e. "island", to be almost completely designed without constraint from other parts of the platform design. Therefore, each island of high signal interconnectivity can be treated as a free spacecraft insofar as bonding design is concerned.

An immediate benefit of the reduction in design problem size achievable by this resolution into islands is the option to use metal structural materials. If these are chosen, then bonding design of an island reverts to present spacecraft standards. Metallic structure results in minimum electrical and electronics cost and weight because it maximizes the utility of (simple) single-ended circuit design.

If the metallic structure option is not chosen, then the island can be further resolved into smaller islands. This preliminary design process can proceed to the limiting design in which lone metal electronic cabinets are matrixed in a completely graphite-epoxy structure. Electronics cost increases as the percent of graphite-epoxy increases; this is a consequence of the increased substitution of electronic isolaters (e.g. optical links) for wiring. The optimum balance of graphite-epoxy and metal structure in designing an island will depend upon the state of electronics art at the time.

This optimum design may include the addition of non-structural metallic surfaces i.e. meshes, foils, embedded screens or colloidal sprays because these also reduce electronics cost. These processes are usually referred to as "metallization"; the result is a "metallic" structure.

Because of the inevitable existence of metallic islands or islets somewhere in a platform it is worthwhile to summarize some of the considerable body of industry experience with bonding and circuit grounding in metallic spacecraft.

4.3.2 Metallic Spacecraft Bonding

4.3.2.1 Reason for Bonding

Bonds are made to establish conducting paths in metallic structure. Path usage determines the structural conducting properties and hence the kinds of bond. There are four main usages:

i) Power return, both normal faulted
ii) Voltage reference, both intentional and spurious
iii) Antenna counterpoise
iv) Static bleed

4.3.2.2 Summary Of Present Bonding Designs

The starting design of most spacecraft utilizes structure conduction only for stray voltage reference (EMI return) and for static bleed. In a very few cases that we know of the structure does carry power intentionally. (Boosters and the shuttle orbiter structures carry power, but these are not considered spacecraft here). This avoidance of power current in structure has several origins, and one is the relatively frail nature of spacecraft structures. Magnesium is often used, and magnesium does not bond well.

In a magnetically stabilized satellite and in any spacecraft with magnetometers on board the structure carries no power because such would create an interfering magnetic field.

In large satellites and in the Apollo spacecraft one finds limited use of structure for carrying power current, and this is possible because of relatively massive sections and largely aluminum constructions.

Spacecraft with antennas receiving in the frequency range below 30 MHz must restrict the flow of power in structure for the same reason as in magnetically stabilized satellites (noted above). For antennas operating below 50 KHz the flow of power in structure is not acceptable.

Thermal isolation requirements often oppose the establishment of conducting paths in structure. A common compromise is to bond with small wire; high frequency bonding is lost, and circuit design may consequently need revision.

Bonding to achieve a voltage reference, i.e., a "ground plane" is general practice in all metallic satellites. This is done regardless of whether any current flow is predicted. The benefit is that one then has something in which to connect shields and bypass capacitors (filter cases). This benefit can cause problems if too much VLF to HF (audio to 30 MHz) current is injected into structure near antennas. In a satellite with a rigorous single-point-ground requirement plus, at the same time, a rigorous bonding requirement, one has a paradox: a ground plane is created but it must not be used. Experience shows that a good ground plane <u>can</u> be used for moderate level wideband returns near many antenna installations. In any case, a good ground plane will enable minimum electronics cost.

Antenna counterpoises and reflectors aboard spacecraft almost always are made up of dedicated structures in contrast to airplanes in which use of the primary structures for this purpose is common. Where structure does enter actively into the near field of an antenna then the necessary bonding should create a geometrically unobtrusive joint with good surface properties; a low resistance is not necessarily needed.

Multilayer thermal blankets must be provided with a static bleed for each layer to reduce spacecraft charging to an acceptable level. External non-conducting surfaces ordinarily are allowed to bleed off without special provision, however there is verying concern about this problem. Material selection is important.

4.3.3 Bond Processes

Frequency determines whether a bond need be of faying type (and, if so, fastener spacing) or jumper type. Multiple jumpers can be traded for faying bonds at medium frequency. Once the geometrical aspects have been determined, the remainder of the design concern is resistance value and reliability.

Structural fasteners are considered to provide MIL-B-5087 Class R (2.5 milliohms) bond if the joint has six or more fasteners; this assumes conducting material but no special surface preparation. If the surface is prepared (cleaning, plating etc.) then a single fastener over 0.75 cm (0.3 inch) or longer will meet Class R. Non-structural fasteners tend to produce poor bonds, and so surface preparation plus special assembly precautions are in order. Thin sections engender small fasteners, hence poor bonds. The net result of thin sections and magnesium is that spacecraft bonds tend to be aimed at 10 to 25 milliohms versus the Class R. 2.5 milliohms. This is probably one reason for the consensus on keeping power current out of structure.

4.4 Compatibility With Structure Materials And Configuration Assembly/Deployment And Ground Philosophy For LSST

The primary concern with compatibility in LSST structure materials is the use of graphite/epoxy composites in combination with various metallic structures exposed to earth storage and space operational environments. This section will discuss compatibility of structure materials in the areas of (1) differences in thermal expansion between contacting materials, (2) differences in galvanic potential between contacting materials, (3) susceptibility of epoxy matrices to moisture and space radiation, (4) vulnerability to environmental electromagnetic hazards, and (5) grounding philosophy.

Advanced composites are utilized extensively in spacecraft structures because they can significantly reduce weight, increase stiffness and dimensional stability, and reduce manufacturing costs. Composite materials are a synthetic combination of a strong, stiff, fiber (reinforcement) imbedded in an organic resin or metal (matrix).

The unique advantageous properties of advanced composites are tempered by the many compatibility problems posed by their introduction into spacecraft structures. Compatibility definition and description for this report will be limited to graphite reinforced epoxy matrix composites.

4.4.1 Thermal Expansion

Graphite/epoxy composites, when designed with correct fiber orientation, have very low or no coefficient of thermal expansion. This results in spacecraft structural members which are dimensionally stable through all temperature ranges encountered on earth and when deployed in a space environment. Figures 4.4.1-1 and 4.4.1-2 illustrate the thermal expansion characteristics of graphite/epoxy composite in the longitudinal and transverse directions, respectively (reference 18).

Incorporation of different and necessary materials into the structure which are in direct or indirect contact with graphite composite can significantly affect attempts to maintain dimensional stability. Mechanically attached or bonded assemblies fabricated under or exposed to temperature changes in space are most difficult to control. Aluminum and magnesium components with relatively large coefficients of thermal expansion present the greatest problem of residual stress and structural distortion. Steel and titanium are more compatible but must be carefully disigned into the structure.

Development in alternate materials or more compatible materials is required to minimize mismatch in thermal coefficient of expansion with composite structures.

4.4.2 Electromotive Potential

Electrical conductivity of graphite/epoxy composite occurs through the graphite fibers. Therefore, electrical contact between the composite and surrounding structure involves graphite and another (metallic) material. The electromotive potential between graphite and metal/metal alloys is sufficient to be of major concern from a corrosion standpoint. The

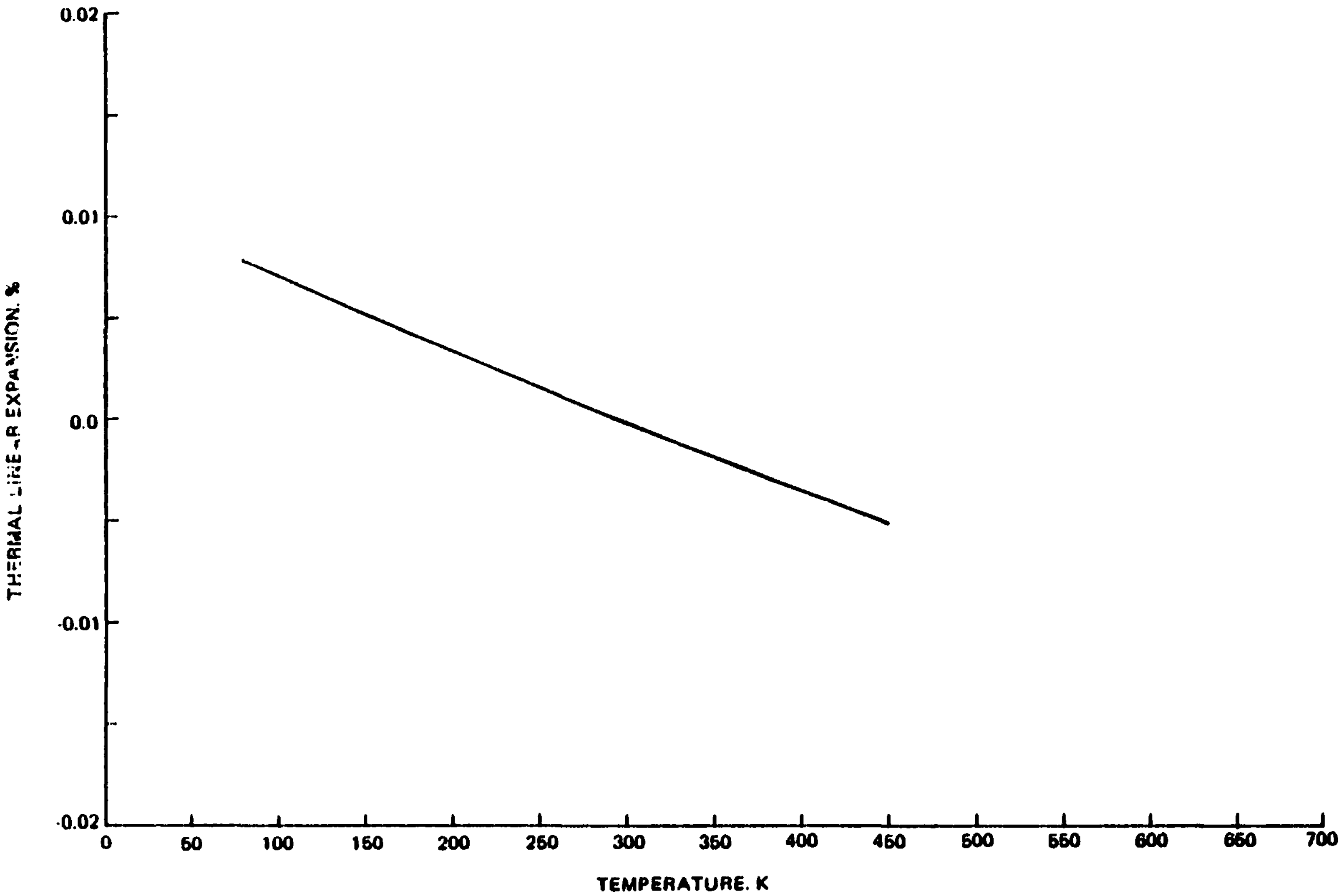


Figure 4.4.1-1: Longitudinal Thermal Linear Expansion of High Strength Graphite Fiber Epoxy Composites

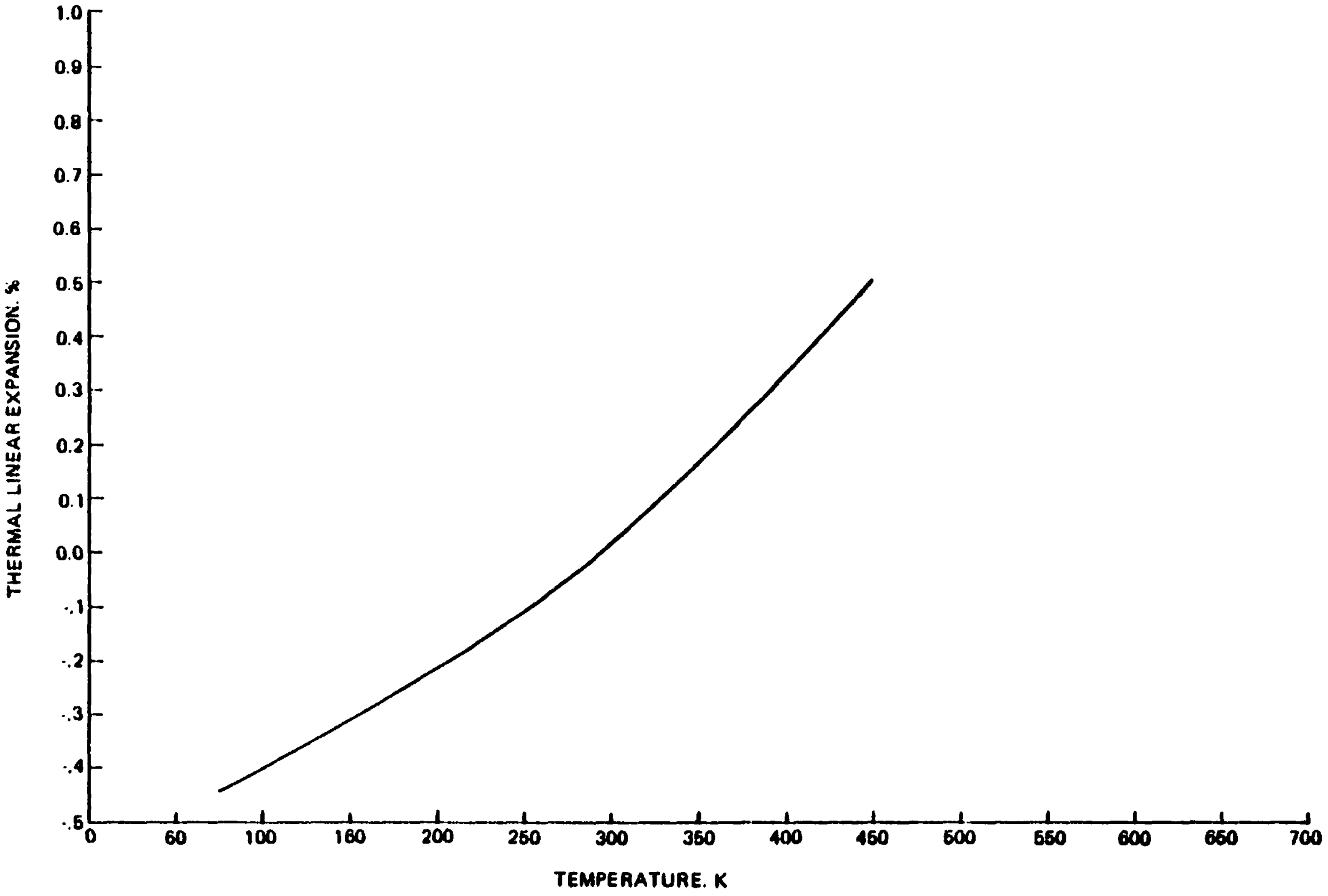


Figure 4.4.1-2: Transverse Thermal Linear Expansion of High Strength Graphite Fiber Epoxy Composites

potential difference between graphite and aluminum can theoretically reach approximately 2 volts in the presence of contaminating moisture. Structural components of dissimilar materials (prior to assembly and launch) must be maintained in a clean, sealed, moisture-free environment. Alternate protective measures involve electrical isolation of the different materials through priming and painting with non-conductive paints and finishes. This latter method, however, does not allow for electrical continuity.

Spacecraft respond to the natural space environment by assuming a range of potentials relative to the plasma potential depending on the plasma density, charged particle flux, and solar illumination. Thus, it is necessary to maintain continuous electrical paths throughout the structure. Current spacecraft already use insulators, such as Kapton, and have met the spacecraft charging problem with reasonable success. The use of a composite structure will change the nature of the spacecraft ground and complicate grounding procedures. Concerns such as electrical continuity through the structure will become more important through the composite joint problem. However, initial results with composite spacecraft have indicated that composite joint designs are workable. As a result of this potential corrosion problem, Boeing has established the design criteria shown in Table 4.4.2-1 for composite/metallic joints in spacecraft (reference 19).

TABLE 4.4.2-1

RECOMMENDATIONS IN DESIGNS WHERE GRAPHITE/EPOXY IS COUPLED WITH OTHER MATERIALS, FOLLOW THE RULES BELOW:

METAL GROUPING

I	II	III	IV
MAGNESIUM AND MAGNESIUM ALLOYS	ALUMINUM ALLOYS, CADMIUM AND ZINC PLATE	LEAD, TIN, BARE IRON AND CARBON OR LOW ALLOY STEELS	CRES, NICKEL, AND COBALT BASED ALLOYS, TITANIUM, COPPER, BRASS, CHROME PLATE

- DO NOT COUPLE GROUP I, II, OR III METALS DIRECTLY TO GRAPHITE/EPOXY.

- WHEN GROUP I, II, OR III METALS ARE WITHIN 3 INCHES OF GRAPHITE/EPOXY AND CONNECTED BY AN ELECTRICALLY CONDUCTIVE PATH THROUGH OTHER STRUCTURES, ISOLATE* THE GRAPHITE/EPOXY SURFACES AND EDGES.

- TITANIUM, CRES (A286 OR 300 SERIES STAINLESS STEEL), NICKEL, AND COBALT-BASED ALLOYS MAY BE COUPLED TO GRAPHITE/EPOXY STRUCTURES. WHEN OTHER GROUP IV METALS ARE COUPLED, ISOLATE* THE GRAPHITE/EPOXY SURFACES AND EDGES.

* ISOLATION SYSTEM:

- ONE LAYER OF TEDLAR; OR TYPE 120
  GLASS FABRIC WITH A COMPATIBLE RESIN;
  OR FINISH

4.4.3 Susceptibility Of Epoxy Matrices To Moisture and Space Radiation

Cured epoxy resins contain highly polar molecular groups which have a strong affinity for water. Environmental moisture is absorbed into the epoxy matrix of graphite composites. The absorbed water acts as a plasticizer significantly reducing the mechanical and thermal properties of the epoxy, and in turn, the composite matrix dominates loaded structure.

Protective coatings applied to the composite surface to prevent water absorbtion are ineffective since most of the coatings also absorb water. Many spacecraft structures are being designed with composites that are stiffness critical. Absorbed moisture decreases composite stiffness and contributes to dimensional instability. The actual rate of deterioration in properties is dependent upon the specific resin matrix, orientation of the graphite fiber, exposure temperature, relative humidity, and ratio of structural surface area to volume.

Controlled temperature and humidity for spacecraft during storage is vital to assure maximum performance when placed in space.

Non-permeable metallic coatings significantly affect structural weight, as well as contribute to distortion which makes them a poor solution to this compatibility problem.

The effect of humidity upon epoxy resins has been studied extensively the last few years. Results of these investigations indicate significant water weight gain and a corresponding drop in glass transition temperature (Tg). Figures 4.4.3-1 and 4.4.3-2 illustrate a typical response of epoxy composites to moisture environment (reference 20).

Moisture is obviously not a concern for the space environment, however, during fabrication and storage of space vehicles there could be intolerable moisture accumulation within the composite structures. Minimum safeguards should be imposed with respect to permissible humidity

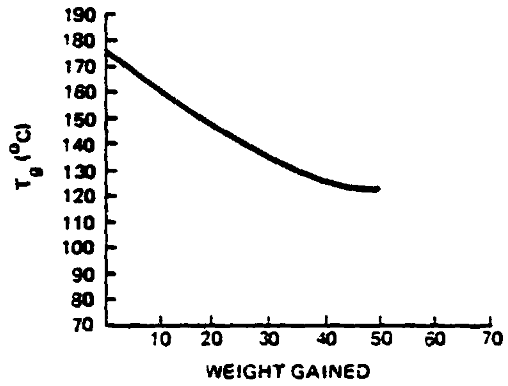


Figure 4.4.3-1: Glass Transition as a Function of Absorbed Moisture for 75% RH Exposure

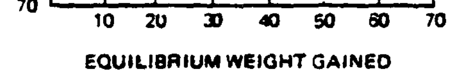


Figure 4.4.3-2: Glass Transition Versus Equilibrium Weight Gain

levels to which composite structure is exposed during manufacture and storage to reduce potential problems discussed previously.

Space radiation is probably the most damaging environment to which space vehicles composite structures are exposed. Unprotected composite is affected by both ultraviolet (UV) and high energy radiation. Although information on the direct effect of space radiation on these materials is available, limited work in space simulated environments has been conducted.

Epoxy resin or any other organic matrix is severely degraded by space radiation (electrons and protons) which can cause surface and bulk damage. The rate of damage is dependent upon the radiation intensity and the matrix molecular structure. Graphite fiber affects the photochemical behavior of the resin because it (graphite) is a strong absorber of ultraviolet radiation. This absorbed energy is transferred to the polymer matrix promoting degradation at the composite surface. At layers below the composite surface, graphite acts as a UV screen protecting the composite interior. However, the impinging radiation can be converted by graphite fiber to longer wave length thermal energy which causes degradation through the composite. Typical damage which occurs in the organic matrix as a result of radiation energy includes outgassing (and contaminations of surrounding surfaces), shrinkage, cracking, crazing, pitting, embrittlement, and discoloration. In addition to degradation in mechanical or thermophysical properties, dimensional changes can occur which affect critical structural alignments (references 21 and 22).

Protection of composite structures may be possible through use of thermal control coatings. However, undesired weight increase and inability to protect against high energy electrons are major disadvantages for this protection method.

The complex nature of reactions between organic matrices and environment which contain moisture or high energy radiation requires systematic analysis to understand basic degradation mechanisms. Increased knowledge can be applied to formulation of environmentally stable materials or practical protection procedures.

4.4.4 Cold Welding or Adhesion of Metals in Hard Vacuum

It is possible for metals to weld at low temperatures if intimate contact is made between the metal surfaces through the thin film of oxide, nitride, or carbide normally present on these surfaces. Intimate contact between surfaces is defined, in this case, by the overlap of electronic charge distributions due to load pressure. This charge distribution overlap results in covalent bonding. Depending on the temperature of the interacting materials, there may also be some diffusion of atoms across the interface which tends to enhance the weld strength.

In order for adhesion of metals to occur, it is necessary that the metal surfaces be free of oxide. This may occur in a space environment several possible ways: outgasing of chemisorbed molecules from the metal surface may occur at low temperatures because the Van Der Waals binding forces are very weak; the oxide thin film may be scraped away by a mechanical abrasive action; or the brittle oxide may be broken through by a plastic deformation of the underlying metal from load pressure. Adhesion may also occur without significant loading pressure when sliding surfaces generate local temperatures that approach the melting point of the metal or when material temperatures are sufficiently high to allow diffusion of the contaminants away from the interface.

Empirically it has been found that adhesion is proportional to the load primarily because the metal contact area is proportional to the load. From this empirical data an adhesion coefficient equal to the ratio of weld strength to contacting load has been calculated for various homo and hetero-junctions. These are listed in Tables 4.4.4-1 and 4.4.4-2 and, in conjunction with adhesion time dependence shown in Table 4.4.4-3, may be used to develop design criteria for spacecraft.

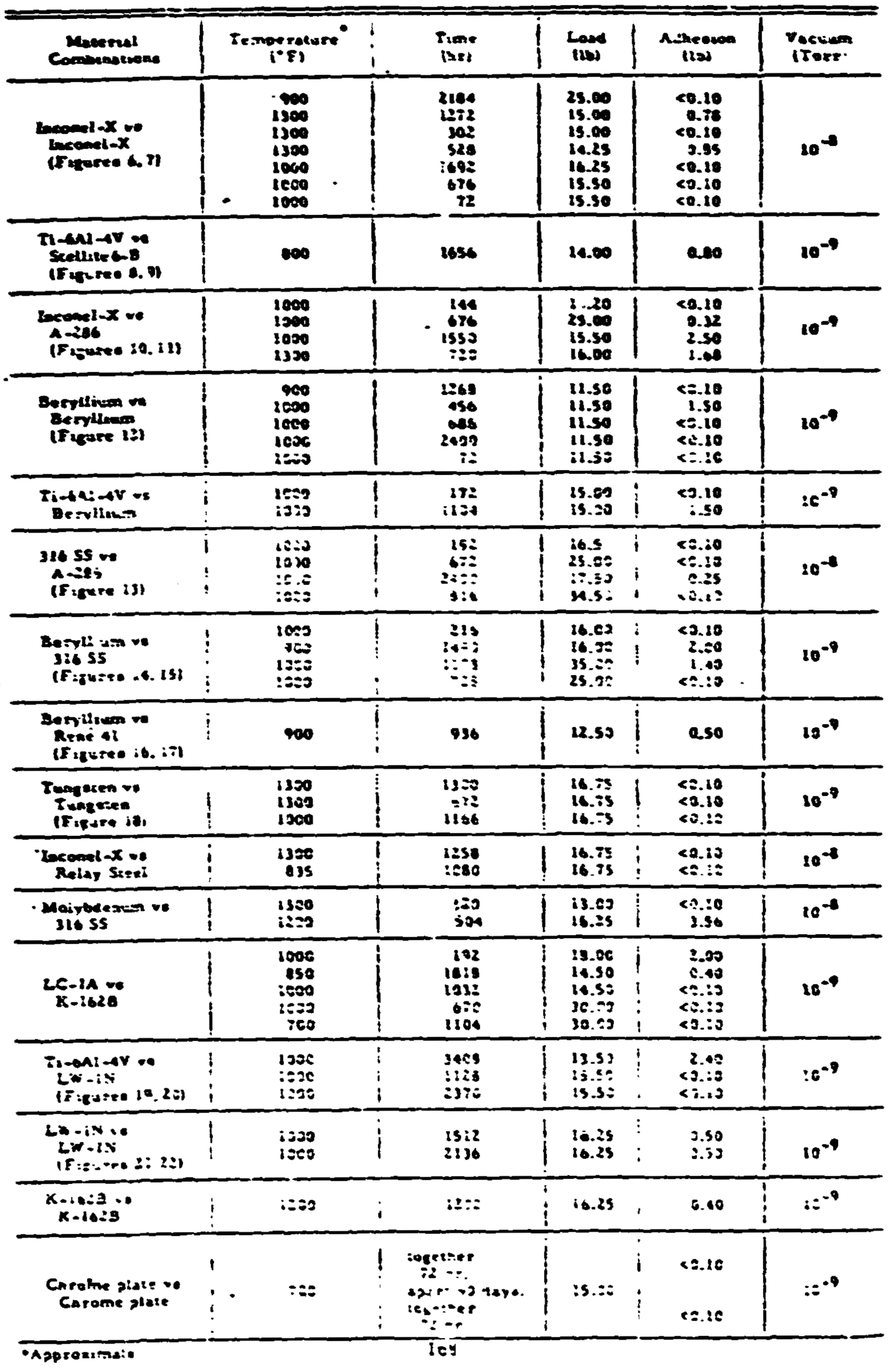
Table 4.4.4-1 THE ADHESION AND FRICTION COEFFICIENTS OF METALS AS DETERMINED BY VARIOUS METHODS

Metal	Crystal habit	Adhesion or friction coefficient		
		Present study a_1	Sikorski [23] a	Rabinowicz [24] f
		$\frac{\text{Adhesion}}{\text{Load}}$	$\frac{\text{Adhesion}}{\text{Load}}$	$\frac{\text{Friction}}{\text{Load}}$
Pb	fcc	0.95	3.5	1.14
Pb + 5% Sb . . .	fcc	0.95	...	...
Al	fcc	0.84	1.8	1.28
Cu	fcc	0.78	0.7	1.18
Ag	fcc	0.78	0.8	1.15
Ti	hcp	0.52	0.2	0.58
Zr	hcp	0.42	0.1	...
Mg	hcp	0.37	0.05	0.6
2024-T4 Al	...	0.31	...	...
17-4PH	...	0.3	...	0.68
α-brass	...	0.1	...	...
Bi	rhom	0.10	...	...

Table 4.4.4-3 THE DEPENDENCE OF ADHESION UPON CONTACT DURATION FOR METALS OBEYING $a=ct^n$.

Material	c (a at t = 1 sec)	n
Pb	0.38	0.14
Pb + 5% Sb	0.75	0.14
Al	0.60	0.06
Cu	0.60	0.03
Zr	0.17	0.01
Mg	0.13	0.21
Bi	0.05	0.16

Table 4.4.4-2 . SELF-WELD DATA SUMMARY GROUP METALS VS METAL



Material Combinations	Temperature* (°F)	Time (hr)	Load (lb)	Adhesion (lb)	Vacuum (Torr)
Inconel-X vs Inconel-X (Figures 6, 7)	900	2184	25.00	<0.10	10^{-8}
	1300	1272	15.00	0.78	
	1300	302	15.00	<0.10	
	1300	528	14.25	3.95	
	1000	1692	16.25	<0.10	
	1000	676	15.50	<0.10	
	1000	72	15.50	<0.10	
Ti-6Al-4V vs Stellite 6-B (Figures 8, 9)	800	1656	14.00	0.80	10^{-9}
Inconel-X vs A-286 (Figures 10, 11)	1000	144	[illegible]	<0.10	10^{-9}
	1300	676	25.00	0.32	
	1000	1553	15.50	2.50	
	1300	720	16.00	1.68	
Beryllium vs Beryllium (Figure 12)	900	1268	11.50	<0.10	10^{-9}
	1000	456	11.50	1.50	
	1000	686	11.50	<0.10	
	1000	2499	11.50	<0.10	
	1000	72	11.50	<0.10	
Ti-6Al-4V vs Beryllium	1000	172	15.00	<0.10	10^{-9}
	1300	1134	15.20	1.50	
316 SS vs A-286 (Figure 13)	1000	152	16.5	<0.10	10^{-8}
	1000	672	25.00	<0.10	
	1000	2400	17.50	0.25	
	1000	[illegible]	34.50	<0.10	
Beryllium vs 316 SS (Figures 14, 15)	1000	216	16.00	<0.10	10^{-9}
	900	[illegible]	16.00	2.00	
	1300	[illegible]	35.00	1.40	
	1000	[illegible]	25.00	<0.10	
Beryllium vs René 41 (Figures 16, 17)	900	936	12.50	0.50	10^{-9}
Tungsten vs Tungsten (Figure 18)	1300	1320	16.75	<0.10	10^{-9}
	1300	672	16.75	<0.10	
	1300	1166	16.75	<0.10	
Inconel-X vs Relay Steel	1300	1258	16.75	<0.10	10^{-8}
	835	1080	16.75	<0.10	
Molybdenum vs 316 SS	1300	120	13.00	<0.10	10^{-8}
	1200	504	16.25	3.56	
LC-1A vs K-162B	1000	192	18.00	2.00	10^{-9}
	850	1818	14.50	0.40	
	1000	1032	14.50	<0.10	
	1000	670	30.00	<0.10	
	700	1104	30.00	<0.10	
Ti-6Al-4V vs LW-1N (Figures 19, 20)	1300	3409	13.50	2.40	10^{-9}
	1000	1128	15.50	<0.10	
	1200	2376	15.50	<0.10	
LW-1N vs LW-1N (Figures 21, 22)	1300	1512	16.25	3.50	10^{-9}
	1000	2136	16.25	3.53	
K-162B vs K-162B	1200	1272	16.25	6.40	10^{-9}
Chrome plate vs Chrome plate	700	together 72 hr.	15.00	<0.10	10^{-9}
		apart 48 days.			
		together 72 hr		<0.10	

*Approximate

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4.5 Grounding and Bonding for Metal Structures

A procedure for the grounding and bonding of metallic structures follows.

4.5.1 Cleaning of Metal Surfaces for Bonding or Grounding

a. General Requirements
  1) The areas to be cleaned are as defined on the Engineering drawing.
  2) Do not allow particles from abrasives used in preparing bonding surfaces to contaminate operating parts of delicate mechanisms or electrical equipment.
  3) Do not use caustic solutions such as lye, alkaline paint remover, or hydroxides, for cleaning of bonding surfaces.
  4) Do not apply abrasive cleaning materials or wire brushes to plated or clad surfaces, nor to metals normally left unpainted, such as corrosion resistant steel or 6061 aluminum (use Type V solvent cleaning).
  5) After completing the bond, inspect surface to determine if resurfacing is required.

4.5.2 Specific Cleaning Practices

To permit Engineering drawing callout of a specific cleaning practice, type numbers have been assigned to each method detailed in the following items. Where the drawing does not specify a particular cleaning technique, the methods listed below are optional, except as restricted under general requirements.

4.5.2.1 Type I: Hand Application of Abrasives

Clean the specified faying surfaces or spot areas by hand application of abrasive material. If practical, use a circular or elliptical motion of the abrasive to provide a uniformly smooth finish. If abrasive sheet is to be reused, reuse only on the same type of metal on which originally used.

4.5.2.2 Type II: Spot Cleaning by Bonding Brush, Stainless Steel (Rotary)

This method is effective in removing paint from any metal, or for removal of Alodine, Iridite, or light anodize from aluminum. Using a drill motor or other suitable drive, apply a stainless steel bonding brush of the proper size to clean the specified spot diameter. Apply the brush intermittently, keeping the cutting face parallel with the surface. Inspect the result after each application. Continue the operation until the required area is completely cleaned, but hold surface damage and loss of metal to an absolute minimum.

Anodic films vary greatly in thickness, and difficulty may occasionally be experienced in removal of these coatings by means of a wire brush. In such instances, the abrasive disc method will prove more effective in completing the operation with a minimum of damage to the underlying metal.

Quality Control shall be on the alert against possible use of carbon steel bonding brushes rather than stainless steel. Because of the probability of serious corrosion resulting from embedment of steel particles into the metal surfaces, parts which have been prepared by means of carbon steel brushes shall be rejected.

4.5.2.3 Type III: Spot Cleaning by Rotary Abrasive Disc

This method is effective for removal of unpainted Anodize, Iridite, Alodine, or similar hard finishes. Paint may also be removed by this method, but rapid plugging will require frequent replacement of the abrasive disc. Select the proper size disc and matching mandrel to provide the required spot diameter. Using a drill motor or other suitable drive, apply the abrasive disc to the bond-spot intermittently, and with a light pressure. Keep the face of the disc parallel to the metal surface, and inspect the area after each application. Also, examine the condition of the disc frequently, and replace for more effective action, if plugged. Continue the operation until a bright surface is visible throughout the required area. Avoid unnecessary removal of metal.

If an abrasive disc is reused, reuse only on the same type of metal on which originally used.

4.5.2.4 Type IV: Removal of Paint with Lacquer Thinner

For removal of primer (MIL-P-6889) or lacquer-based paint or enamel from clad aluminum or other metal surfaces, apply lacquer thinner or methyl ethyl ketone to the specified area, using a clean cotton or linen cloth or gauze applicator. Use an uncontaminated portion of the cloth for each application, taking care to avoid overrun or spillage beyond the desired limits of the bond. When the designated area is completely clean, immediately wipe dry with a clean cloth or gauze.

4.5.2.5 Type V: Solvent Cleaning of Bare, Clad, or Plated Metal

Apply cleaning solvent such as n-Heptane to the bonding surface, using a non-metallic brush or cloth applicator. Scrub as necessary to remove visible contamination. Immediately dry the surfaces by wiping with a suitable lint-free guaze or cloth.

n-Heptane vapors are flammable. Keep away from heat, sparks and open flame. Avoid breathing vapors. Avoid prolonged or repeated skin contact.

Optional: Nonflammable Solvent

A nonflammable solvent or solvent mixture such as Freon BF, Freon TF, Genensolv B or Genesolv D for a specific cleaning application will be determined by the operator based on the solvent evaporation rate, size of area to be cleaned, and ambient conditions.

4.5.2.6 Type VI: Solvent Cleaning of Bare Titanium

Apply cleaning solvent to the bonding surfaces, using a non-metallic brush or cloth applicator. Scrub as necessary to remove visible contamination. Immediately dry the surfaces by wiping with a suitable lint free gauze or cloth.

4.5.3 Bonding Jumper and Ground Lead Installation

a. When installing jumpers, position them to avoid interference with movement of parts. Particular care must be exercised in installing jumpers on moving shock-mounts, and similar items involving motion between attaching points.

b. Exercise caution to avoid crushing or damaging tubing when tightening clamps used for attachment of bonding jumpers.

c. When the Engineering drawing specifies attaching a number of jumpers or ground lead terminals to structure by means of a single fastener, place the largest terminal nearest structure; with the others stacked in order of decreasing size. Where space permits, fan the terminals.

d. Do not use face dyed, or other type non-conductive coated washers in the conducting path of a bond.

e. Attach jumpers or designated ground leads from equipment to metallic structure (including the frames of electronic racks or consoles) as shown in figures 4.5.3.-1 and 4.5.3-2.

f. All terminals for attachment to current return ground studs shall be cleaned with a clean cloth, soaked in solvent and

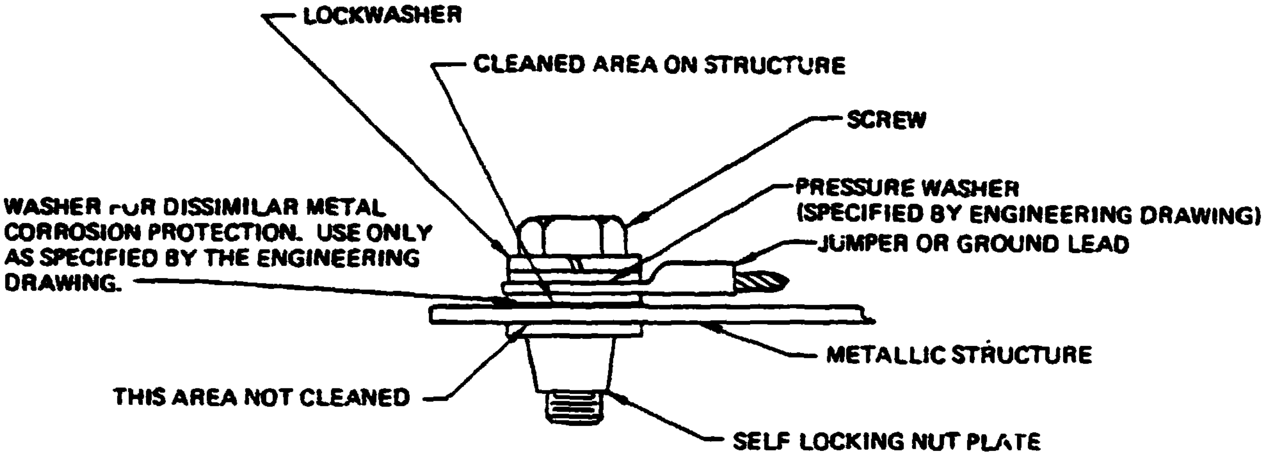

Figure 4.5.3-1: Single Lead to Ground

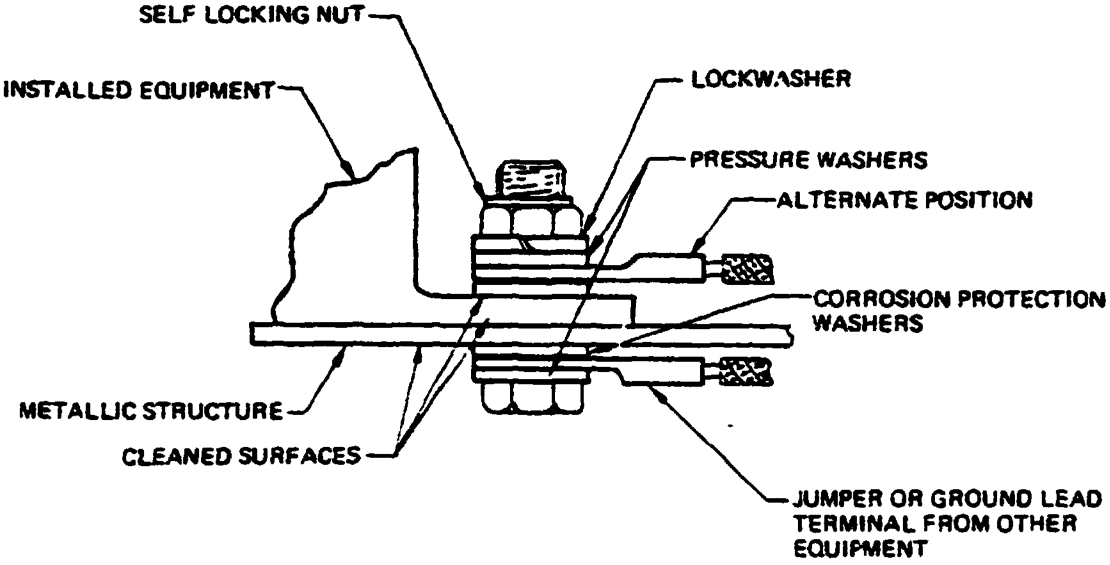

Figure 4.5.3-2: Double Lead to Ground - Two Sides

thoroughly dried with a clean cloth before assembly and before each reassembly before launch.

g. Where practical, electric bonding measurements shall be made only with the original leads and probes furnished with the instrument. Where for any reason, special probes or leads are required, they shall be tested with the intended instrument, and be certified for acceptable accuracy (also restricted in range where necessary).

h. Tightening shall be as required by Engineering drawing to maintain required bonding resistance. Use self-locking steel nuts (NAS 679) for fastening aluminum and copper terminals to steel studs and screws. Where necessary to obtain the required bonding resistance specified on the Engineering drawing, nuts can be torqued to the values in Tables 4.5.3-1, 4.5.3-2 and 4.5.3-3. For stud and screw sizes that have no torque value given in the tables, make sure that the nuts and screws are tight by noting that the lock washers (if used) are fully compressed. Make sure that there is no movement between terminal hardware in assemblies using self-locking nuts. Check for tightness only in the direction of tightening.

   Avoid galling terminals with wrenches. Galled terminals are cause for rejection. Avoid excessive torque and use care to prevent damage to hermetic seals.

Installation of Faying Surface Bonds

a. Where the parts to be bonded are to be installed immediately after completion of the cleaning operations, give the mating surfaces a final precautionary wipe-off with a clean, lint-free cloth to insure the removal of any remaining traces of abrasive or other foreign materials.

TABLE Table 4.5.3-1 INSTALLATION TORQUE FOR COPPER TERMINALS

Stud Size	Self-Locking Nuts (In-Lbs.)
10-32	30^{+5}_{-2}
1/4 - 28	70 ±5
5/16 - 24	140 ±5
3/8 - 24	190 ±5
1/2 - 20	500 ±5

Table 4.5.3-2 INSTALLATION TORQUE FOR ALUMINUM TERMINALS

Stud Size	Self-Locking Nuts (In-Lbs)
10 - 32	35^{+5}_{-2}
14 - 28	80^{+10}_{-5}
5/16 - 24	145^{+20}_{-10}
3/8 - 24	230^{+20}_{-10}
1/2 - 20	450^{+40}_{-20}

Table 4.5.3-3 INSTALLATION TORQUE FOR NICKEL-PLATED COPPER TERMINALS TO TITANIUM

Bolt and Nut Material	Ti 6Al-4V, A286 and PH 13 - 8 Mo.
Stud Size	Self-Locking Nuts (In-Lbs.)
10 - 32	35^{+5}_{-2}
1/4 - 28	95^{+10}_{-5}
5/16 - 24	182^{+20}_{-10}
3/8 - 24	320^{+30}_{-20}
1/4 - 20	770^{+70}_{-40}

b. Where previously cleaned bonding surfaces show signs of contamination reclean in accordance with Type V.

c. Bonding resistance shall be as required on the Engineering drawing.

4.5.4 Resurfacing Cleaned Areas

a. After joining, where the original paint finish has been removed, apply a minimum of one coat of the primer and matching finish specified by the drawing to all exposed bare metal not covered by faying surfaces. Do not attempt to duplicate the original chemical treatments such as Alodine, Iridite, or Anodize except as specifically directed by the drawing.

b Reprime magnesium parts within 24 hours after removal of the original finish. Where the specified finish consisted of a conversion coating only, such as Dow 17 anodize, apply a minimum of one coat of primer to all bare metal surfaces exposed after installation of the part.

c. Refinish metals other than magnesium within one week after cleaning of the bonding areas.

d. Do not paint machine-finished flanges of such articles as pumps, valves, and similar equipment which must maintain a liquid-tight seal at the mounting surface.

e. There are no refinishing requirements where the applicable Engineering drawing for tne part specifies use of bare or plated metal devoid of any surface treatment or protective coating.

f. After bonding, the cleaned areas of anodized or alodized aluminum fluid lines shall be protected by a coating.

g. After joining, apply protective coating to exposed bare aluminum parts from which finish has been removed. This requirement applies to parts not otherwise covered by specification or Engineering drawings.

4.5.5 Drawing Call Out of Bonding and Grounding Requirements

All bonds and grounds are classified as either "designated" or non-designated.

4.5.5.1 Designated Bonds or Grounds

Refer to the applicable Engineering drawing for maximum resistance, hardware and all other specific requirements for designated bonds and grounds.

Drawings, where callouts for electrical bonding is required, but detailed information is not given, shall be referred to Engineering Liaison.

4.5.5.2 Standard Requirements For Nondesignated Bonds and Grounds

Where the Engineering drawing does not specify the bond requirements, all conductive objects having any linear dimension of three inches or larger shall meet one of the following requirements:

a. Where the conductive object being considered mounts directly upon basic structure, and accordingly, only a single junction between surfaces is involved, the maximum resistance between the object and such structure shall not exceed 0.1 ohm.

b. Where one or more intervening metallic substructural members are stacked in series between the object to be bonded and the basic structure, the maximum over all resistance from the object to basic structure shall not exceed one ohm.

4.5.6 Testing of Bonds and Grounds

4.5.6.1 General Requirements

a. Measure the resistance of all designated bonds on a 100 percent basis, for compliance with the requirements specified by the Engineering drawing.

b. Nondesignated bonds need be measured for conformance with standard requirements only on the first production unit, or major model change which, occurs on each type of spacecraft, missile, ground operations equipment, or other manufactured product.

c. For bonds employing a jumper or designated ground lead, the control points for measuring the resistance shall be within the limits of the cleaned areas contacted by each terminal, and preferably within 0.25 inch of the extremities of the terminals.

5.0 BONDING AND GROUNDING CONCEPTS

A fault current return path is necessary in the event of a ground fault to prevent:

- Shock to persons working on the spacecraft
- Direct damage to the electrical system
- Detonation of electro-explosive devices.

The joint concepts described below are designed to provide good electrical conduction across joints in composite structures. They must be mechanically and electrically analyzed for applicability on a spacecraft.

5.1 Composite To Composite Joints

Conduction between two composite members may be provided by a screen joint, an adhesive bond using a conductive metal-filled epoxy, or by metal fasteners such as rivets or bolts. The screen joint, shown in figure 5.1-1, provides good conduction due to a large screen-to-graphite fiber contact area. It lacks mechanical strength, but may be supplemented by mechanically or adhesively fastened doubler plates. A screen joint which does not require doublers is shown in figure 5.1-2. Screen joints are difficult to fabricate and require that structural members be laid up individually rather than in a continuous process to provide conduction across a butt, scarf, or stepped lap joint (figure 5.1-3), due to good contact with the fiber ends. Like the screen joint, these joints must be reinforced with doubler plates due to the lack of strength of metal-filled epoxy.

Mechanically fastened joints as in Figure 5.1.-4 would have good structural strength, but would have electrical resistivity of about 2 orders of magnitude higher than that of the screen joint.

5.2 Composite-To-Metal Joints

In many cases it will be necessary to bond graphite-epoxy

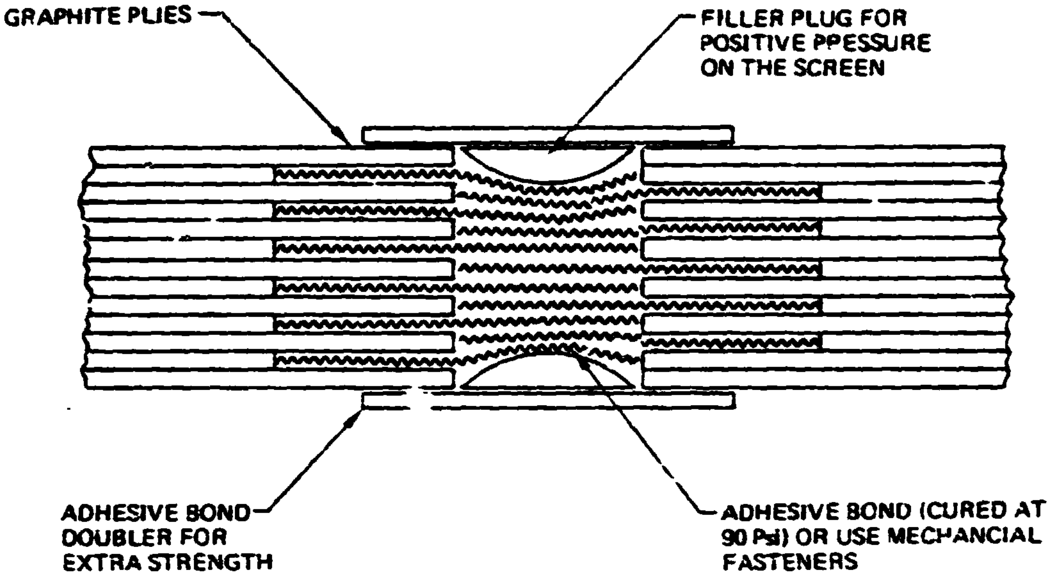

Figure 5.1-1: Multiple Screen Interleaved Lap Joint

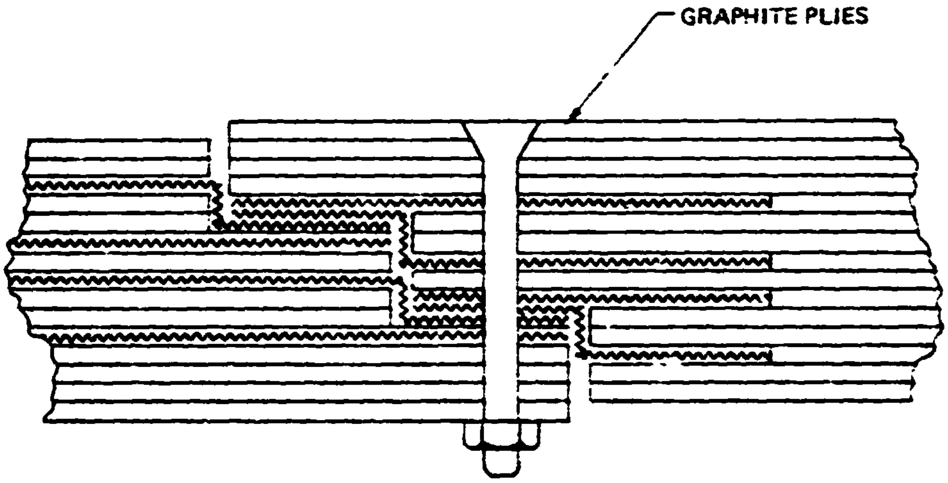

Figure 5.1-2: Multiple Exposed Screen, Mechanically Fastened Stepped Lap Joint

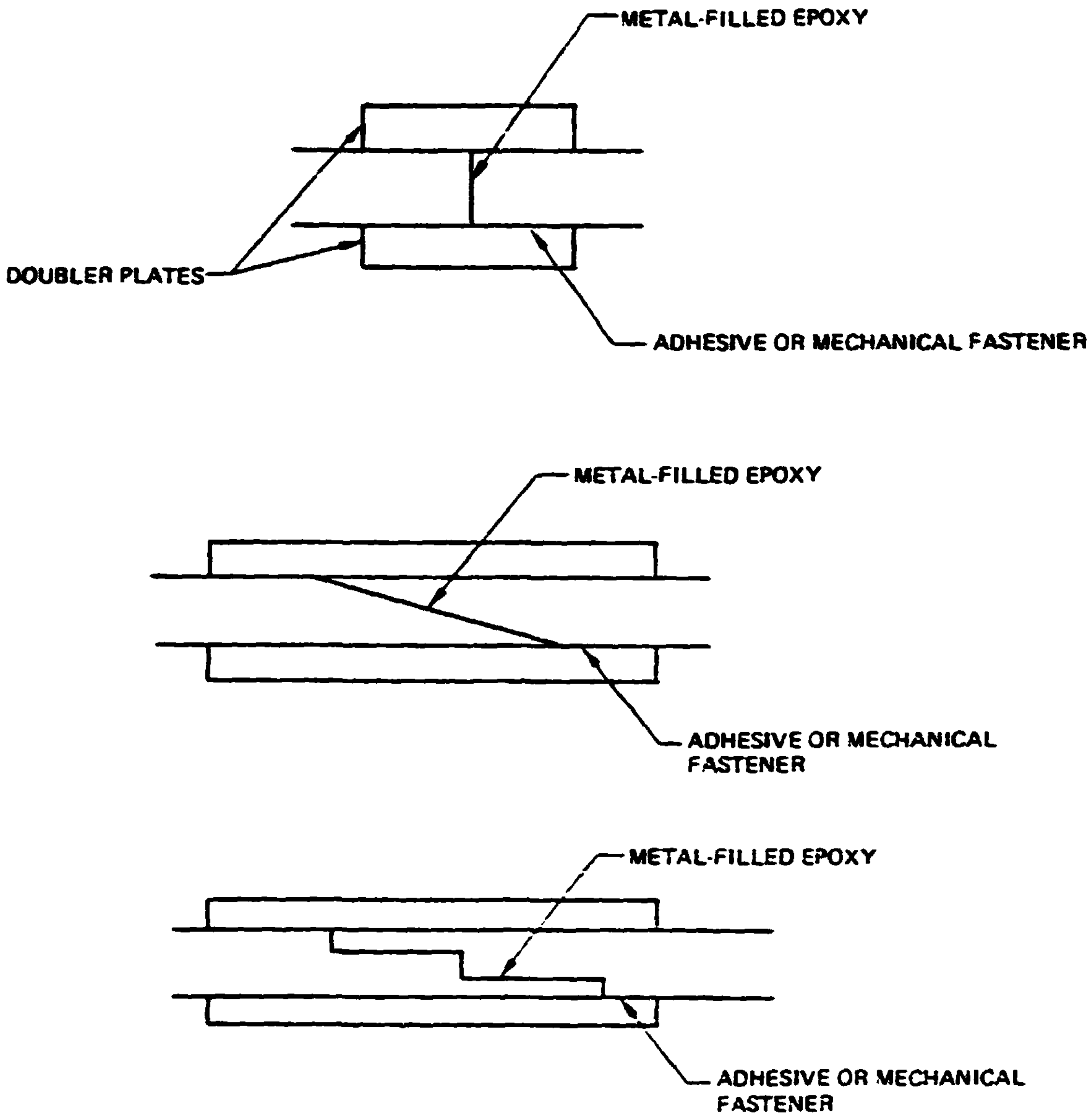

Figure 5.1-3: Butt, Scarf, and Stepped-Lap Joints

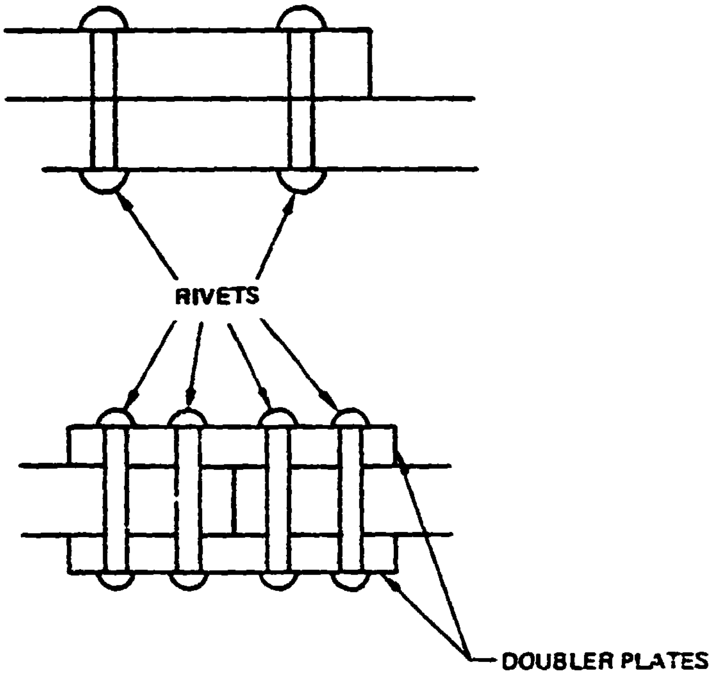

Figure 5.1-4: Mechanically Fastened Joints

composites to metal structural components. In a truss structure to be assembled in space, composite members will be connected at the ends using metal quick-connect fasteners as in figure 5.2-1. In this case, the cut end of the composite member would be fitted prior to launch into a socket in the connector. Electrical conductivity would be provided by metal-filled epoxy at the end of the composite member and structural strength by adhesive or mechanical bonding. The same type of joint could be used to bond a composite member into a fixed metal socket in a metal structure. Another application of composite-to-metal bonding is in the joining of composite panels through a stepped-lap metal splice. This joint is shown in figure 5.2-2 using metal screen for electrical conduction. The same joint may be fabricated without the screen with a resistivity about an order of magnitude more than that of the screen joint; a ground fault current in this joint, though, will tend to vaporize the joint adhesive and may cause rupture or delamination at the joint. Composite members may also be bolted or riveted directly to metal structure with a resistivity of about two orders of magnitude greater than that of a screen joint.

5.3 Surface Treatment

In some cases the current-carrying capability of the composite structure will not be adequate, as in ground fault protection. In such instances, treatments such as aluminum foil or screen bonded to the surface of aluminum arc-plasma sprayed in an inert gas environment, will increase current carrying capability. These treatments whould be used in the vicinity of high-voltage power conductors to provide a conductive surface for the attachment of ground fault areas. The surface area of the treatment should be such that the current density at the edge will not damage the composite structure. Surface treatments should also be used when EMI shielding greater than that afforded by the composite structure alone is required (figure 5.3-1).

An assessment of the six recommended joint concepts is shown in Table 5.3.-1. Metal connectors are recommended for large space structures. Although the initial cost is high, the fabrication time in space

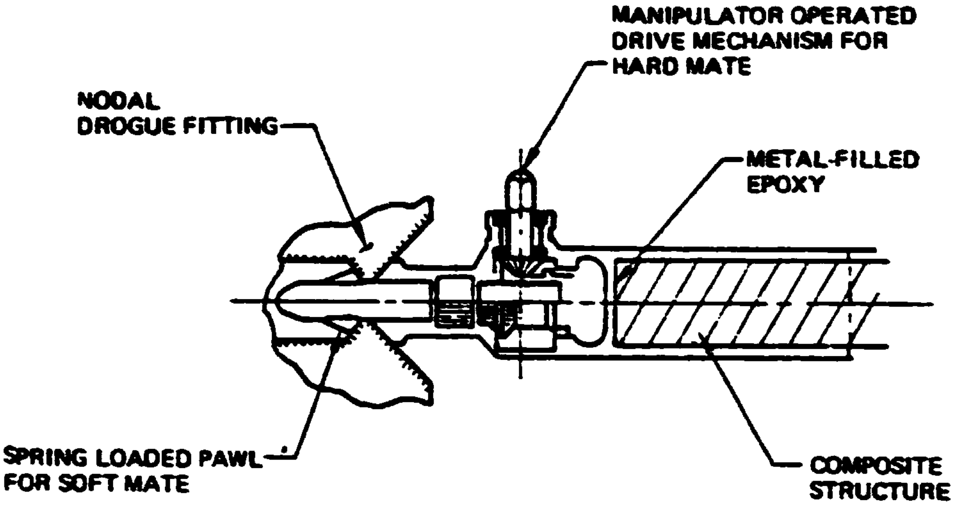

Figure 5.2-1: Metal Connector

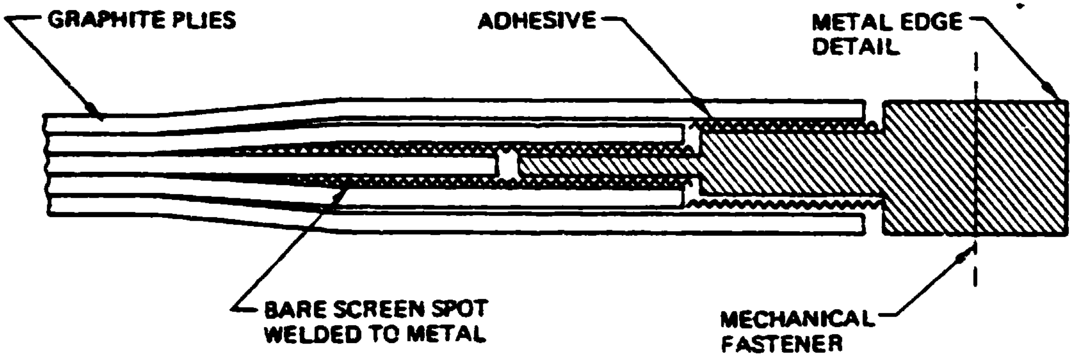

Figure 5.2-2: Center Screen Stepped Lap Composite to Metal Joint

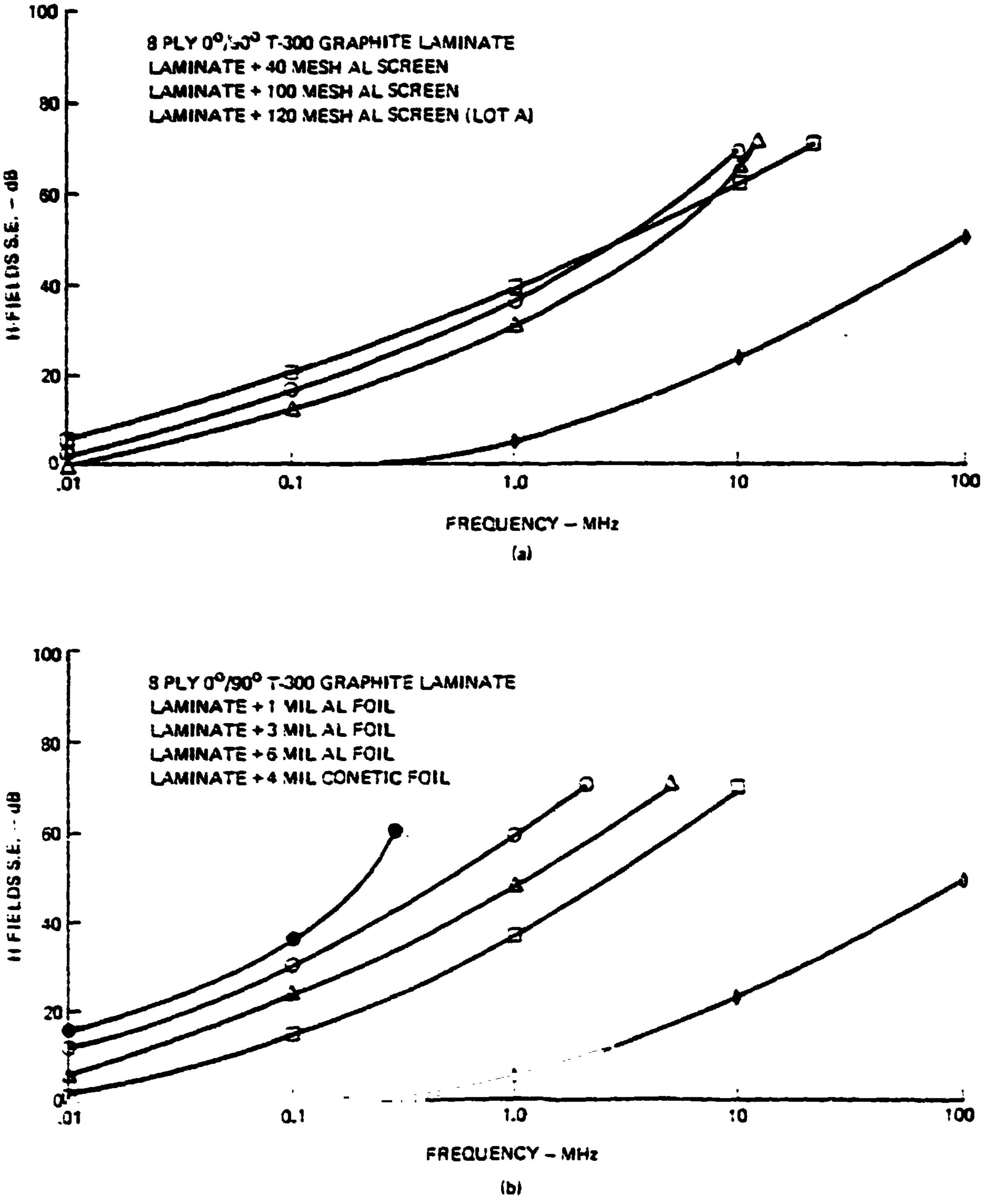

Figure 5.3-1: Measured H-Field S.E. of Coated 8 Ply Graphite Laminates

able 5.3-1 BONDING/GROUNDING CONCEPT ASSESSMENT

Joint	Advantages	Disadvantages
Screen (Fig. 5.1-1)	• Good electrical conductor	• Difficult to fabricate in space • Requires individual component layup • Requires doublers for mechanical strength
Screen (Fig. 5.1-2)	• Good Electrical conduction • Inherent mechanical strength • Can be fabricated in space with pre-launch preparation	• Requires individual component layup
Metal-filled epoxy (Fig. 5.1-3)	• Good Electrical conduction • Can be used on cut ends of continuously formed members	• Difficult to fabricate in space • Requires doublers for mechanical strength
Mechanical Fasteners (Fig. 5.1-4)	• Inherent mechanical strength • Can be fabricated in space • Components may be joined at positions other than ends • Allows use of continuously formed members	• Poor electrical conduction
Metal Connectors (Fig. 5.2-1)	• Good electrical conduction • Inherent mechanical strength for truss structures • Easily fabricated in space with pre-launch preparation • Can be used on cut ends of continuously formed members	• Requires expensive and heavy connectors • Limited to truss structures
Metal Splice (Fig. 5.2-2)	• Good electrical conduction • Inherent mechanical strength for joining panels	• Cannot be fabricated in space • Requires individual component layup • Requires expensive machined splices

may make this system the most cost effective. The second best method is a screen technique shown in figure 5.1-2. The metal splice (figure 5.2-2) mechanical fastener (figure 5.1-4), and metal filled epoxy (figure 5.1-3) need much improvement or research and development before they can be considered as applicable for assembly in space.

6.0 STATIC DRAIN

To support the use of graphite-epoxy composite structures in space, joints must be developed to provide electrical conduction between composite structural members for static drain and for a fault current return path. The static drain path is necessary because the effect of vehicle charging can be detrimental where the conducting sections of the vehicle are not bonded together. For example, consider a vehicle that is charged triboelectrically on the forward surfaces and discharged through corona from the skirt at the aft end. If the forward section is not electrically connected to the aft section, charge acquired on the forward section cannot flow to the aft section unless the potential difference between the sections becomes large enough for a spark discharge to occur. These spark discharges can be quite energetic, since the capacitance between the sections may be several thousand picofarads and the sparkover voltage may be several kilovolts. Furthermore, the spark discharge will seek the easiest electrical path between the sections. If there is some electrical wiring routed across this gap, it is possible that the spark will travel through a shorter gap from the section to the wiring, through the wiring, and then through another short spark gap to the aft section. This, of course, would put a tremendous noise pulse on any data line. Also, there is the possibility that these spark discharges could fire electro-explosive devices.

7.0 EVA ACTIVITY AND TOOLING REQUIREMENTS

High viscosity epoxies may be used to bond the malfunctioning structural grounding system. It would be necessary to use a carbon on metallic filled epoxy for the bonding material to assure a low resistance bond between the two bonded members.

Bonding in space will be a tedious, dirty job. First, the structural members to be bonded should be abraided with an abrasive material. During this procedure, much dust (particulates) will be created. A special tool should be designed to collect the particulate, otherwise the particulates will float onto the surface of the spacecraft and eventually deposit (adhere) onto a polarized member, such as a high voltage conductor or insulator. This could result in arc-overs and system failures. An electrostatic precipitator device must be designed to collect the particulates from the abrasive action.

After the abrasion of the structure is completed, the high viscosity epoxy has to be applied to both surfaces which are to be bonded. The epoxy must be applied with a special gun and spreader to keep the epoxy on the two members. Otherwise the outgassing will tend to spew some of the epoxy on adjacent members, into space, and on the crew members. A minor amount will attach to the spacecraft and crew members regardless of the precautionary action taken by the crew member. Finally, the two structural members must be joined and held in place until the epoxy cures. The clamps should be capable of remaining fastened to decrease crew member time allocation to the project. A post-cure visual inspection and joint resistance reading should be taken after the epoxy cures.

8.0 TEST PLAN

The objectives of the test plan are to evaluate developmental, new concept grounds and bonds for the LSST program where many structures will be fabricated of carbon fiber/epoxy materials. Developmental grounding systems shall be capable of being manually, automatically, or remotely, prepared and installed in space.

8.1 Scope

Grounding/Bonding conceptual designs shall be assessed for operation in a space system environment. Those systems which meet the mechanical, electrical, and environmental requirements, automatic and remote operation in space, and astronaut control and EVA time, shall be selected for design and test evaluation.

One structural member with a bonded ground shield shall be designed fabricated and tested, complete with electrical and mechanical design, fabrication, and test procedures and drawing. This is to evaluate the grounding under high-voltage/high-current conductors.

A structural joint with the bonded/grounding system integrated into the fabricated structure shall be designed, fabricated, and tested, complete with electrical and mechanical design fabrication and test procedures and drawings.

The two ground/bonded assemblies shall be demonstrated to operate in a simulated space environment. Bonding of the joint shall be demonstrated.

8.2 Technical Requirements/Tasks

Conceptual designs and designs from a literature survey of space program documentation of government and industry shall be evaluated for future development.

Automatic and manual operation in space with and without astronaut assistance shall be considered. EVA expended time per bonded ground joint shall be minimized during docking and undocking exercises to allow the astronaut to attend to high priority docking duties.

Weight, volume, and positive connection to produce a minimum resistance ground joint shall be evaluated as a function of cost for the qualification and acceptance test evaluation and operation in space.

Two grounding concepts shall be selected for development and demonstration.

A metal-covered structural member concept to simulate a structure with a high voltage line overhead shall be developed.

a. Metal shield 0.125 cm thick
b. Short circuit current 50 K amperes
c. to ground
d. graphite epoxy structure

An aluminum to graphite-epoxy joint with an embedded screen or two graphite epoxy members with embedded screens to reduce joint resistance shall be developed

a. Screen to reduce joint resistance to that of solid structure
b. Impulse current to 50 K amperes
c. Short circuit voltage to 2,500 volts

The two ground/bond concept drawings, manufacturing procedures, processes, and test procedures shall be detailed to show compatibility with the spacecraft environment and spacecraft electrical systems.

Preparation and assembly jigs and fixtures, and evaluation test fixtures shall be part of the deliverable items for the demonstration model.

A test procedure for the acceptance qualification shall be supplied along with a specification for all parts, materials, and tests for the demonstration models.

The structural members and tools shall be tested for automatic and manual operation. Zero gravity conditions may be simulated by assembling the joints in the free-floating mode under water.

9.0 CONCLUSIONS

Data and conceptual designs generated during the program clearly indicate that grounding and bonding can be accomplished in space using either manual or automatic joining of the structural members. More design and analytical work, however, are necessary to define the close tolerances demanded by the precision structures of the antennae and electrical/electronic cul-de-sacs.

This concluding section first reproduces the significant results and conclusions drawn from the work accomplished. This is followed by recommendations for future applications.

9.1 Observations

On reviewing the study results, several observations can be made.

1. A screen or metal mesh should be embedded into the graphite fiber-epoxy joints to increase electrical conductivity across the joint.
2. A multiple exposed screen with a mechanically fastened stepped lap joint has the best electrical and mechanical characteristics and can be joined in space by automatic or manually operated equipment.
3. EVA activity can be minimized by using the exposed screen joints
4. A metal sheet must be bonded to the structure members where high-voltage/high-current lines pass over the structure to protect against short circuits and arcs.
5. Cul-de-sacs and electronic members must be bonded to a metal clad structure to achieve good electrical conductivity.

9.2 Recommendations

The following areas have been identified as having significant payoff potential to warrant futher work on grounding and bonding for LSST systems.

1. Investigate and analyze circulating currents in structures generated by ground returns on the solar array.
2. Evaluate and analyze metal clad thickness (minimum) on structure under high-voltage/high-current lines to withstand short circuits and arcs.
3. Determine the length and spacing of metal screens on metal strips for the joints as a function of line voltage and current capacity.
4. Select and evaluate new joint clamping mechanisms other than bolts.
5. Analyze and evaluate precipatation devices and the effect of structure shape on spacecraft charging.

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