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N79-24050

SPACECRAFT CHARGING STANDARD*

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SUMMARY

A preliminary Spacecraft Charging Standard has been generated as one of the key activities in the cooperative NASA/AF Spacecraft Charging Investigation. The document was initially generated as a "baseline specification" and has undergone careful review by the spacecraft charging community including the Air Force, NASA, private industry, government labs, universities, and other agencies. The document will be formalized into a Military Standard for Spacecraft Charging when updated to include SCATHA spaceflight data.

The format of this paper is identical to that of the Spacecraft Charging Standard except that Appendix A: Spacecraft Charging Phenomenon Background has been omitted in order to limit the length of the paper. The complete text, including the appendix is available through the authors. Comments on this document would be appreciated and may be sent directly to Dr. A. B. Holman at SAI. Pertinent information will be incorporated directly into the next update of the standard.

1.0 SCOPE

1.1 This standard establishes the spacecraft charging (SCC) protection requirements for space vehicles which are to operate in the magnetospheric plasma environment.

1.2 The environment can cause differential charging of space vehicle elements which can result in discharges, with resultant propagation of electromagnetic interference (EMI), material degradations, and enhanced contamination effects.

2.0 REFERENCED DOCUMENTS

2.1 Issues of Documents

The following documents of the issue in effect on date of invitation for bids or request for proposal, form a part of this standard to the extent specified herein:

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* Work supported through contract F04701-77-C-0166 with SAMSO.

STANDARDS

Military

MIL-STD-1541 (USAF) Electromagnetic Compatibility Requirements for Space Systems

2.2 Other Publications

The following documents form a part of this standard to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or request for proposal shall apply.

NASA TM X-73446 - Provisional Specification for Satellite Time in a Geomagnetic Substorm Environment

AFML-TR-76-233 - Conductive Coatings for Satellites

AFGL-TR-77-0288 - Modeling of the Geosynchronous Orbit Plasma Environment - Part 1

NASA (To be Published) - Design Guidelines for Spacecraft Charging Monograph

NASA CR-135259 - NASCAP User's Manual

3.0 DEFINITIONS

3.1 Definitions that Apply to this Standard

The terms used in this standard are either defined in MIL-STD-1541 or listed in the following paragraphs.

3.1.1 Backscattering

The deflection of particles or radiation by scattering processes through an angle greater than 95° with respect to the original direction of motion.

3.1.2 Dielectric-To-Metal Spark

A spark discharge between two electrodes, one of which is a dielectric charge retaining surface and the other is a conductive (metal) electrode in the vicinity of the dielectric. A dielectric material will typically accumulate charge when irradiated by electrons or ions or under certain conditions when placed in a plasma environment.

3.1.3 Differential Charging

The act of charging neighboring space vehicle surfaces to differing potentials by the combined effects of space plasma charging, photoemission, secondary emission and backscatter.

3.1.4 Faraday Cage

An electromagnetically shielded enclosure. The term generally refers to a conductive metallic structur , package, or mesh which attenuates electromagnetic interference to specified levels on the interior.

3.1.5 Flash-Over Spark

A spark characterized by a current path that travels along the surface of the material and generally around an edge to close the path to the other electrode.

3.1.6 Geomagnetic Substorm Activity

The conditions near geosynchronous altitude during the injection of solar storm particles into the earth's magnetic field, including disturbances in the dipole field and increased plasma energies and current densities.

3.1.7 Magnetospheric Plasma

The space plasma environment constituent in the magnetosphere. This is an electrically neutral collection of electrons and positive ions (primarily protons) with densities near geosynchronous altitude on the order of one particle/cm^3.

3.1.8 Maxwellian Energy Distribution

An energy distribution based on Maxwell-Boltzmann statistics and applicable in a general form to the space plasma environment. The energy distribution has the integral form

$$\phi\,(>E) = N\sqrt{\frac{8kT}{\pi m}}\left(1 + \frac{E}{kT}\right) \exp(-\,E/kT)$$

where

$\phi\,(>E)$ = integral flux at energies greater than E (particles/cm^2 sec)

E = energy (keV)

N = total number density (particles/cm^3)

k = Boltzmann constant = 8.6×10^{-8} keV/^{0}K

T = plasma temperature (^{0}K)

m = particle mass (g)

It is interesting to note that $\sqrt{8kT/\pi m}$ is the average speed of the particles, so that the flux of all particles (setting E = 0) is found by multiplying the density by the average speed.

3.1.9 Metal-To-Metal Spark

A spark discharge between two electrodes both of which are conducting.

3.1.10 Photoemission

An effect whereby radiation of sufficiently short wavelength impinging on substances causes bound electrons to be given off with a maximum energy that varies linearly with the frequency of the radiation.

3.1.11 Primary Radiated Spark Fields

The electric and magnetic fields radiated from the spark gap.

3.1.12 Punch-Through Spark

A spark discharge through the bulk of a dielectric material. It is a bulk breakdown of the insulating strength of a dielectric separating two electrodes. The current path is through the bulk of the material, with surfaces above and below the dielectric acting as electrodes. The punch-through spark may occur in vacuum or in air.

3.1.13 Replacement Current

Current, excluding the spark gap current, in the region of the spark gap and within the material surrounding the spark gap due to the rearrangement of charge following the spark discharge.

3.1.14 Secondary Emission

An effect whereby electrons or ions, called secondary electrons or ions, are emitted from a material as a result of the collision of higher energy electrons or ions with the material. The ratio of secondary particles to incident particles can be greater than unity.

3.1.15 Space Emission Spark

A vacuum spark characterized by the ejection of current into the space surrounding an electrode. To produce a space emission spark, the electric field must be sufficiently high to ionize and vaporize the charge retaining material.

3.1.16 Spacecraft Charging (SCC)

The phenomenon where space vehicle elements and surfaces can become differentially charged to a level sufficient to cause discharges and resulting EMI. The primary effects of SCC are electrical transients and upsets, material degradation and enhanced contamination.

3.1.17 Spark Discharge

A sudden breakdown of the insulating strength of the dielectric separating two electrodes, due to the formation of ions by an intense electric field, accompanied by a pulse of electricity across the spark gap and a flash of light indicating very high temperature. In contrast to the arc discharge or glow discharge, the spark is of very short duration. It may be oscillatory, or intermittent, with several discharges taking place in quick succession.

3.1.18 Spark Discharge Current

The total current within the spark gap.

3.1.19 Spark Lag

The interval between the attainment of the sparking threshold potential and the initiation of the spark.

3.1.20 Sparking Threshold Potential

If the voltage across a spark gap is progressively raised, a spark passes when the voltage level has become sufficiently high. The lowest voltage at which the initial spark will pass is the sparking threshold potential. Note that the voltage may be increased considerably above this value without producing a spark. After one spark has passed others may follow, at different sparking potentials.

3.1.21 Vacuum Spark Discharge

A spark discharge taking place in a vacuum region with high potential gradients. The electric field may exist within a dielectric or in the vacuum region surrounding the charge retaining material. In the latter case the gradients are between the electrode and either the vacuum chamber walls or an equivalent space charge surrounding the electrode. In these cases the potential gradients must be sufficiently high to ionize and vaporize the charge retaining material. There are different types of vacuum sparks that are of considerable importance, each classified by the configuration of the electrodes or the characteristics of the current path of the spark gap. These are the dielectric-to-metal spark and the metal-to-metal spark, each with a spark gap path that is classified as a punch-through spark, a flash-over spark or a space emission spark.

4.0 GENERAL REQUIREMENTS

4.1 Spacecraft Charging Protection Program

The contractor shall (a) conduct a spacecraft charging protection program, (b) prepare and maintain an analytical plan and (c) prepare and maintain a test plan. The intent of the program shall be to assure that the space vehicle is capable of operating in a space plasma charging environment without degradation of the specified space vehicle capability and without changes in operational modes, location or orientation. This performance must be accomplished without the benefit of external control such as commands from a ground station. The spacecraft charging protection program, the analytical plan and the test plan shall be approved by the procuring agency.

4.1.1 Performance

4.1.1.1 Electrical Systems

The contractor shall assure through analysis and/or test that all space vehicle electrical systems perform to specified capabilities when operating in a space plasma charging environment.

4.1.1.2 Materials

The contractor shall assure through analysis and/or test that all space vehicle materials which may be exposed to a space plasma charging environment will retain specified capabilities.

4.1.1.3 Contamination

The contractor shall assure through analysis and/or test that any contamination effects due to electrostatics induced by a space plasma charging environment will not degrade the performance of space vehicle surfaces or elements below specified capabilities.

4.1.2 Design

4.1.2.1 Electrical Systems

The contractor shall design all space vehicle electrical systems to perform to specified capabilities in a space plasma charging environment. This may include protective design measures compatible with MIL-STD-1541 (USAF).

4.1.2.2 Materials

The contractor shall use materials in the space vehicle design that will perform to specified capabilities in a space plasma charging environment. Any protection features incorporated to reduce material damage must not reduce material performance below specified levels.

4.1.2.3 Contamination

The contractor shall design the space vehicle to minimize the effects of contamination enhanced by a space plasma charging environment. Any contamination present must not reduce performance of space vehicle systems below specified capabilities.

5.0 DETAILED REQUIREMENTS

5.1 Performance

5.1.1 Electrical Systems

Space vehicle electrical system outage is permissible during a discharge if operation returns to normal within a telemetry main frame period after onset of the discharge. A command to the space vehicle from an external source such as a ground station is not required to be completed if a discharge occurs during transmission of the command, provided that an unintended action does not result and provided that the space vehicle is capable of receiving and executing subsequent commands and meeting specified performance. Space plasma induced electrical transients shall not affect on board digital data beyond the specified design limits. Conditions outside of specified limits for electronic equipment due to space plasma induced electrical transients shall be prohibited.

5.1.2 Materials

Thermal control surfaces, second surface mirrors, and solar cell coverslides shall not degrade in thermal or optical properties or structural integrity in a space plasma charging environment below the level required to perform to specified capabilities. Space vehicle structural elements shall not be permitted to degrade in mechanical properties in a space plasma charging environment below the level required to perform to specified capabilities.

5.1.3 Contamination

Contamination of thermal and optical space vehicle elements due to space plasma charging effects shall not degrade performance below the specified capabilities. Contamination of any other space vehicle elements or subsystems shall not reduce the operational performance of the space vehicle below its specified limits.

5.2 Design

5.2.1 Electrical Systems

Space vehicle electrical systems shall be designed such that transients induced by space plasma associated discharges do not interfere with space vehicle performance. Where practical this shall be accomplished by pulse duration discrimination. Where this is not practical, other design techniques shall be utilized such as filtering and RF shielding of selected wiring harnesses. The following design techniques shall be incorporated and made compatible to MIL-STD-1541 (USAF) specifications.

(1) All electronic boxes should consist of solid metal enclosures with no openings which permit the penetration of significant EMI.

(2) All metallic structural elements and other conductors shall incorporate sufficient common grounding to prevent metal to metal discharges.

(3) All metallized surfaces on thermal blankets shall incorporate multiple grounds to the space vehicle conducting structure.

(4) The space vehicle structure should provide a "Faraday Cage" design with a minimum of openings to prevent radiated EMI generated on the space vehicle exterior from propagating to internal locations. This may not be necessary if it can be shown by analysis and test that the "Faraday Cage" is not required.

5.2.1.1 Design Guidelines

The design guidelines present design features which will reduce the levels of discharging on the space vehicle and the effects of SCC on electrical systems. The design guidelines as presented in the "Design Guidelines for Spacecraft Charging Monograph" (NASA document to be published) should be followed wherever applicable. The monograph provides further detail on the design techniques given in Section 5.2.1.

5.2.2 Materials

Materials used in the space vehicle design shall be selected to minimize differential charging and discharge effects from a space plasma charging environment while maintaining specified performance capabilities. All dielectric materials used on exposed surfaces should be tested or analyzed to determine their discharge characteristics in a space plasma charging environment. Surfaces located internal to the outer space vehicle structure should be shielded from the space plasma environment by eliminating openings in the structure. Design guidelines as presented in the "Design Guidelines for Spacecraft Charging Monograph" (NASA document to be published) should be followed for materials applications.

5.2.3 Contamination

Space vehicle design shall incorporate techniques which minimize outgassing and other sources of contamination. Exposed surfaces which are most susceptible to effects of enhanced contamination due to space plasma charging shall be identified and protected where necessary.

6.0 SYSTEM ANALYSIS REQUIREMENTS

6.1 Spacecraft Charging Analysis Plan

The contractor shall prepare and maintain an analytical plan for SCC. The plan shall be subject to approval by the procuring agency. The contractor shall implement the plan to analyze the space vehicle for the effects of SCC. The analysis plan should complement the test plan and the analysis should generate data useful to identifying susceptible design areas and quantifying representative test levels. Analysis procedures as presented in the "Design Guidelines for Spacecraft Charging Monograph" (NASA document to be published) should be followed where applicable.

6.2 Analysis Concepts

Analysis of the SCC phenomena is based on four primary modeling areas:

(1) Space plasma environment modeling

(2) Sheath/charging modeling

(3) Discharge modeling

(4) EMI/coupling modeling

Models are being developed and will be available for use in analytical treatments of SCC effects on space vehicles. The contractor shall utilize these models or others suitable to the procuring agency in analyzing the space vehicle performance susceptibility to electrical effects, material degradations, and contamination effects due to SCC.

6.2.1 Space Plasma Environment Models

Space plasma environment models (see Appendix A) shall be used to determine the plasma environment at the space vehicle. This includes estimating frequencies of occurrence and duration of exposure of all space vehicle surfaces to the various environment constituents and estimating the energy levels and current densities of the constituents.

6.2.2 Sheath/Charging Models

Sheath/charging models (see Appendix A) shall be used to determine the extremes of differential charging levels for space vehicle elements and exposed surfaces. This requires input from the environment models and application to the specific space vehicle geometries (including illumination effects), with the incorporation of the characteristic material properties.

6.2.3 Discharge Models

Discharge models shall be applied for the extremes in differential charging levels as calculated from the sheath/charging models for representative space vehicle geometries. Estimates of extremes of radiated EMI (external and internal to the space vehicle) and structural current levels shall be generated by the analysis.

6.2.4 EMI/Coupling Models

EMI/coupling models shall be applied for the extremes in radiated EMI and structural current as calculated from the discharge model for representative space vehicle geometries. Estimates of extremes of characteristics of electrical transients shall be generated by the analysis.

6.3 Analysis Procedures

Analysis shall be performed to determine extremes of SCC effects in the area of electrical transients. In addition, models should be applied where applicable to determine material degradation and contamination effects. In general the SCC phenomena models shall be utilized to estimate worst case extremes of effects on the specific space vehicle. If these extremes present conditions which would result in degraded space vehicle performance (below specified levels), then more detailed use of the phenomena models should be performed as a second iteration of the analysis. This less conservative approach will provide more realistic estimates of SCC effects than the worst case extremes, but at the added expense of the more detailed analytical modeling treatment.

6.3.1 Electrical Transients

The procedure for analyzing the space vehicle for electrical transients induced by SCC follows.

(1) Determine the frequency of occurrence and duration of periods of space plasma charging using the environment models for the particular orbit and mission of the space vehicle. Generate environment inputs for (2).

(2) Determine extremes of differential charging levels for the space vehicle elements and surfaces based on sheath/charging model analysis. Determine capacitance of the space vehicle material configurations and for locations susceptible to charging (including capacitances within thermal blankets and between thermal blankets and other structural surfaces). Determine the charge and voltage levels of the capacitors.

(3) Determine extremes in amplitudes, frequencies and general characteristics of discharges on the space vehicle based on discharge model analyses and material test results. Determine most likely discharge locations.

(4) Determine extremes in radiated EMI and current injection into the space vehicle structure for the expected discharges.

(5) Use a coupling model in detail to determine the frequency of occurrence and characteristics of induced transients in all space vehicle electrical systems, including wiring harnesses, circuits, and components.

(6) Determine the effect of these electrical transients on space vehicle performance.

6.3.2 Material Degradation

The procedure for analyzing the space vehicle for material degradations caused by electrostatic discharge follows. This should be followed where applicable.

(1) Determine the frequency of occurrence and duration of space plasma charging using the environment models for the particular orbit and mission of the space vehicle. Generate environment inputs for (2).

(2) Determine extremes of differential charging levels for exposed space vehicle surfaces based on sheath/charging model analysis.

(3) Determine the locations, frequencies and energy content of discharges from these surfaces based on the discharge model analysis.

(4) Determine the mission integrated effect of these discharges on the thermal, optical, and mechanical properties of the exposed materials.

(5) Determine the effect of degradation in any of the material properties on space vehicle performance.

6.3.3 Contamination

The procedure for analyzing the space vehicle for effects of contamination caused by SCC follows. This should be followed where applicable.

(1) Determine the frequency of occurrence and duration of space plasma charging using the environment models for the particular orbit and mission of the space vehicle. Generate environment inputs for (2).

(2) Determine characteristic profiles of fields and potential distributions exterior to the space vehicle and surface charge distributions on the space vehicle from the sheath/charging model analysis.

(3) Estimate the characteristics of the outgassing products, propulsion system gases, and discharge sputtered material from the space vehicle.

(4) Determine extremes in radiated EMI and current injection into the space vehicle structure for the expected discharges.

(5) Determine the effect on space vehicle performance of thermal or optical degradation of the material surface properties due to this contamination (including degradation of this contamination).

7.0 SYSTEM TEST REQUIREMENTS

7.1 Spacecraft Charging Test Plan

The contractor shall prepare and maintain a test plan for SCC. The plan shall be subject to approval by the procuring agency. This plan shall include but not be limited to the following:

(a) Measurement instruments and test equipment

(b) Test conditions

(c) Test methods

(d) Test analysis and verification

The test plan should be complementary to the SCC analysis plan (see Section 6.1). The contractor shall implement the plan to test the space vehicle susceptibility to the effects of SCC. Test procedures as presented in the "Design Guidelines for Spacecraft Charging Monograph" (NASA document to be published) should be followed where applicable.

7.2 Measurement and Test Instruments

7.2.1 Measurement Instruments

The equipment used to monitor space vehicle susceptibility to SCC caused transients shall be capable of measuring signals with adequate accuracy to a level of 6 dB below the unit, subsystem, or system requirements. These instruments should provide adequate bandwidth and proper time response to meet the test measurement requirements.

Measured signals shall be permanently recorded for later analysis as needed. Use shall be made of wideband oscilloscopes, spectrum analyzers, wideband transient detectors, circuit monitors, recorders, current meters and probes, wideband RF detectors and/or other instrumentation capable of monitoring unit, subsystem or system performance. The equipment used in this testing shall have the approval of the procuring agency and be fully described in the applicable test plan.

Measuring techniques and instrumentation accuracies shall be discussed in the test plan. Any peculiarities in operation, performance, or output in the measuring instruments shall be also discussed in the test plan.

All space vehicle telemetry equipment, aerospace ground equipment, and EMC test equipment (see MIL-STD-1541 (USAF)) used in these tests shall be described in the test plan. Any specially designed SCC measuring equipment shall also be described in the test plan.

7.2.2 Test Equipment

Special equipment used to simulate SCC effects on units, subsystems, or systems shall be described in the test plan. They should be calibrated within specified limits. This test equipment should include devices to

(1) Induce charge density levels of up to 10^{-3} coulombs/m^2 on the exposed surfaces of the space vehicle structure

(2) Insulate the space vehicle from all surrounding grounds during periods of testing

(3) Directly inject currents of up to 300 amperes into the space vehicle structure at selected critical test points. Lower levels may be shown adequate through analysis

(4) Generate EMI with specified intensity and characteristics at selected critical test points external to the space vehicle

(5) Deliver an electrical pulse of specified energy at selected critical test points

This equipment, its operation and its use for SCC testing shall be approved by the procuring agency before any testing of the space vehicle is started.

7.3 Test [illegible]tions

7.3.1 [illegible]/Subsystem Test Conditions

The test conditions for units and subsystems should follow the procedure outlined in "Design Guidelines for Spacecraft Charging Monograph" (NASA document to be published). Test conditions must be tailored to each individual unit or subsystem.

7.3.2 System Test Conditions

System level ambient environment testing shall be performed on a qualification model vehicle, if available, or on a flight model vehicle, if a qualification model is not available. System level testing shall be conducted in a manner that will minimize risk to the space vehicle. System level tests shall simulate, to the extent possible, the conditions expected in space. Currents and voltages induced in space vehicle structural elements and electrical systems shall not exceed by more than a factor of 2 the extremes expected in space.

7.4 Test Methods

7.4.1 Unit/Subsystem Test Method

Each unit and subsystem shall be tested for spacecraft charging susceptibility. As a minimum testing shall be performed for radiated EMI. Each unit and subsystem shall perform within specified levels during and after the testing.

7.4.2 System Test Method

System level testing shall consist of monitoring selected circuits and general space vehicle health signals while conducting the following tests:

(1) Inject current into the space vehicle structure at selected critical test points. Test levels should be determined by analysis.

(2) Induce charge flow in the space vehicle by using the space vehicle structure as one plate of a capacitor and charging and discharging the other plate of the capacitor (a test plate mounted at selected critical test points). Test levels should be determined by analysis.

(3) Create radiated EMI in the same manner as that for the unit/subsystem tests.

Critical test points shall be chosen by analysis as those locations most likely to experience discharges in space. The magnitude of the discharge should be less than double but at least equal to the expected levels estimated by the analysis. Engineering model or qualification model systems should be subjected to this full level testing. To avoid electrical stressing of flight equipment, flight vehicle systems may be subjected to lower level (1% to 10%) testing if supportive analysis is performed to assure system performance to specified capabilities in the SCC 100% threat environment.

The magnitudes of the capacitance for (2) above and the voltages at discharge shall be representative of levels estimated in the analysis.

7.5 Test Analysis and Verification

The measurements recorded during the SCC tests shall be analyzed and used to verify that the space vehicle performs to specified levels. Transients shall be shown to be below upset levels for all critical circuits and components in electrical systems. Thresholds for upsets of space vehicle critical circuits and components may be measured at the unit level or calculated analytically. The method chosen is subject to approval by the procuring agency. Protective features shall be incorporated for all electrical systems to correct any performance below specified levels. The effectiveness of the protective features shall be demonstrated by further test and analysis.

7.6 Material Degradation Tests

All materials used on exposed surfaces in the space vehicle design should be characterized for their performance in a space plasma charging environment. This information may be obtained from the literature, e.g. the "Design Guidelines for Spacecraft Charging Monograph" (to be published by NASA) or from material tests for new materials. Life cycle testing should be incorporated where applicable and where considered necessary. All materials are subject to approval by the procuring agency.

APPENDIX A: SPACECRAFT CHARGING PHENOMENON BACKGROUND (Available upon request).