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LOW EARTH ORBIT SPACECRAFT CHARGING DESIGN STANDARD

MEASUREMENT SYSTEM IDENTIFICATION: METRIC

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DOCUMENT HISTORY LOG

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Interim		09-11-2006	Interim Release
Baseline		06-03-2007	Baseline Release. Interim Standard NASA-STD-(I)-4005 was transitioned to this standard and the handbook, NASA-HDBK-4006. 4.1.3: Changed from: "Spacecraft systems susceptible to arcing or large parasitic current drains shall be tested in a simulated LEO . . ." to "Spacecraft systems susceptible to arcing or large parasitic current drains shall be tested to ensure their function and performance in a simulated LEO . . ." 4.1.4, 2nd sentence: Change from "Spacecraft that operate a significant amount of time in LEO must use . . . to "Spacecraft that operate a significant amount of time in LEO shall use . . ." 5.1: Added information for two reference documents. Made editorial and formatting changes.

FOREWORD

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

This standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities.

This standard provides a design standard for high-voltage space power systems (> 55 volts) that must operate in the plasma environment associated with Low Earth Orbit (LEO).

Requests for information, corrections, or additions to this standard should be submitted via "Feedback" in the NASA Technical Standards System at http://standards.nasa.gov.

Original Signed By

____________________________	_____06-03-2007____
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Low Earth Orbit Spacecraft Charging Design Standard

1. SCOPE

This standard provides requirements relative to various plasma interactions that can result when a high-voltage system is operated in the Earth's ionosphere and standard practices to eliminate or mitigate such reactions.

1.1 Purpose

The purpose of this standard is to provide a design standard for high-voltage space power systems (> 55 volts (V)) that operate in the plasma environment associated with LEO (altitude from 200 and 1000 km and latitude between -50 and +50 degrees). Such power systems, particularly solar arrays, are the proximate cause of spacecraft charging in LEO; and these systems can interact with this environment in a number of ways that are potentially destructive to themselves as well as to the platform or vehicle that has deployed them.

High-voltage systems are used in space for two reasons. The first reason is to save launch weight. First of all, for the same power level, higher voltages enable use of thinner wires (lighter cabling). This is true because $P = IV$, and $V = IR$, so $P = I^2R$ (where P is power, I is current, R is resistance, and V is voltage). If I is decreased by use of higher V, then thinner wires can be used with no increase in power loss due to cabling. Of course, if one uses the same cable mass, higher voltages will enable higher efficiencies, since less power will be lost to resistance in the cables. For very large power systems, the decrease in cable mass can be substantial.

Second, some spacecraft functions require high voltages. For example, electric propulsion uses voltages from about 300 V (Hall thrusters) to about 1000 V (ion thrusters). For low-voltage power systems, conversion of substantial power to high voltages is required for these spacecraft functions to operate. The weight of the power conversion systems, power management and distribution (PMAD), can be a substantial fraction of the total power system weight in these cases. It is more efficient, and can save weight, if the high-voltage functions can be directly powered from a high-voltage solar array, for instance. If the high-voltage function is electric propulsion, we call such a system a direct-drive electric propulsion system.

Because of these and other reasons for using high voltages in space, spacecraft designers and manufacturers are using high voltages more and more. However, the use of high voltages entails risk; **in particular, spacecraft charging in LEO, in contrast to that in geosynchronous earth orbit (GEO), is caused by exposed high voltages**, and can lead to arcing, power drains, power disruptions, and loss of spacecraft coatings. Thus, system designers need a standard to show them how to mitigate the spacecraft charging effects of using high voltages in LEO. In addition to system designers, this document should be useful to project managers, solar array designers, system engineers, etc.

This document is intended as a standard for design applications and can be used as a requirements specification instrument.

1.2 Applicability

This standard is applicable to high-voltage space power systems that operate in the plasma environment associated with LEO.

This standard is intended for space systems that spend the majority of their time at altitudes between 200 and 1000 km (usually known as LEO applications) and at latitudes between about + and -50 degrees — that is, space systems that do not encounter GEO (geosynchronous orbit) charging conditions, that do not (often) encounter the auroral ovals of electron streams, and that do not fly through the Van Allen belts. **For the extreme radiation protection that is necessary for orbits in the Van Allen belts, exterior spacecraft charging will likely be a secondary concern**. However, internal charging will be very important. It is not in the purview of this document to deal with internal charging.

Some of the design standards for LEO are at variance with good design practice for GEO spacecraft. If your spacecraft will fly in both LEO and GEO conditions, be careful to use design solutions that are applicable in both environmental regimes.

This standard may be cited in contract, program, and other Agency documents as a technical requirement. Mandatory requirements are indicated by the word "shall." Tailoring of this standard for application to a specific program or project shall be approved by the Technical Authority for that program or project.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this standard as cited in the text of section 4. The latest issuances of cited documents shall be used unless otherwise approved by the assigned Technical Authority. The applicable documents are accessible via the NASA Technical Standards System at http://standards.nasa.gov, directly from the Standards Developing Organizations, or from other document distributors.

2.2 Government Documents

NASA-HDBK-4006	Low Earth Orbit Spacecraft Charging Design Handbook
AFWAL-TR-88-4143 Volume 2	Design Guide: Designing and Building High Voltage Power Supplies, Materials Laboratory

2.3 Non-Government Documents

None.

2.4 Order of Precedence

When this standard is applied as a requirement or imposed by contract on a program or project, the technical requirements of this standard take precedence, in the case of conflict, over the technical requirements cited in the applicable documents or referenced guidance documents.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms

AFWAL	Air Force Wright Aeronautical Laboratories
ASTM	American Society for Testing and Materials
DC Direct	Current
EMI Electrom	agnetic Interference
ESD Electrostatic	Discharge
GEO Geosynchronous	Earth Orbit
HDBK Handbook	
LEO	Low Earth Orbit (200-1000 km altitude, -50 to +50 latitude, for the purposes of this document)
NASA	National Aeronautics and Space Administration
PMAD	Power Management and Distribution

3.2 Definitions

The following definitions are based on AFWAL-TR-88-4143, Volume 2**,** *Design Guide: Designing and Building High Voltage Power Supplies, Materials Laboratory:*

Breakdown (Puncture): A disruptive discharge through an insulating medium.

Breakdown Voltage: The voltage at which the insulation between two conductors fails.

Capacitance (Capacity): That property of a system of conductors and dielectrics that permits the storage of electricity when potential difference exists between the conductors. The ratio of the charge on one of the conductors of a capacitor to the potential difference between the conductors. (There will be an equal and opposite charge on the other conductor.)

Capacitor (Condenser): A device whose primary purpose is to introduce capacitance into an electric circuit.

Cell: A single unit capable of serving as a direct current (DC) voltage source by transfer of ions in the course of a chemical reaction.

Charge: In electrostatics, the amount of electricity present upon any substance that has accumulated electric energy.

Conductivity: Reciprocal of resistivity.

Conductor: An electrical path that offers comparatively little resistance. A wire or combination of wires not insulated from each other, suitable for carrying a single electric current.

Corona: A non-self-sustaining discharge (sometimes visible) due to ionization of the gas surrounding a conductor around which exists a voltage gradient exceeding a certain critical value for a gaseous medium.

Coverglass or Coverslide: The layer (usually of glass) that covers a semiconductor solar cell or array to prevent radiation damage.

Critical Voltage (of gas): The voltage at which a gas ionizes and corona occurs, preliminary to dielectric breakdown of the gas.

Dielectric: A non-conducting material.

Dielectric Breakdown: An electrical discharge within a dielectric due to an applied electric field in excess of the dielectric strength of the material.

Dielectric Strength: The maximum electrical potential gradient (electric field) that an insulating material can withstand without rupture, usually expressed in volts per mm of thickness.

Electrode: A conductor, not necessarily metal, through which a current enters or leaves an electrolytic cell, arc, furnace, vacuum tube, gaseous discharge tube, or any conductor of the nonmetallic class.

Electron: A stable elementary, negatively charged particle that circles around the center or nucleus in an atom.

Electrostatic Discharge: A sudden and large increase in current through an insulation medium due to the complete failure of the medium under the electrostatic stress.

Encapsulating: Enclosing an article in an envelope of plastic or other sealant.

Gradient: Rate of increase or decrease of a variable parameter.

Insulation: Material having a high resistance to the flow of electric current to prevent leakage of current from a conductor.

Insulation Resistance: The ratio of the applied voltage to the total current between two electrodes in contact with a specific insulator.

Insulator: A material of such low electrical conductivity that the flow of current through it can usually be neglected.

Ion: An electrified portion of matter of sub-atomic, atomic, or molecular dimensions such as is formed when a molecule of gas loses an electron (when the gas is stressed electrically beyond the critical voltage) or when a neutral atom or group of atoms in a fluid loses or gains one or more electrons.

Paschen Discharge: Breakdown of neutral gas in a high electric field.

Plasma: A gaseous body of ions and electrons of sufficiently low density that considerable charge separation is possible. Because of the mobility of charge, a plasma is normally neutral and free of electric field in its interior, just like a metallic conductor.

Plastic: High polymeric substances, including both natural and synthetic products, but excluding the rubbers, that are capable of flowing under heat and pressure at one time or another.

Polymer: A compound formed by polymerization that results in the chemical union of monomers or the continued reaction between lower molecular weight polymers.

Potential: The work per unit charge required to bring any charge to the point from an infinite distance.

Power: The time rate at which work is done. Power is obtained in watts if work is expressed in joules and time is in seconds.

Pressure: Force per unit area. Absolute pressure is measured with respect to zero pressure. Gauge pressure is measured with respect to atmospheric pressure.

RC Time Constant: Time constant obtained by multiplying resistance by capacitance.

Resistivity (specific insulation resistance): The electrical resistance between opposite faces of a 1-cm cube of an insulating material, commonly expressed in ohm-centimeters. Sometimes called volume resistivity.

Sizzle Arc: A sustained electric discharge due to dielectric breakdown.

Snapover: The phenomenon caused by secondary electron emission that can lead to electron collection on insulating surfaces in an electric field.

Solar Array: Solar cells connected in series and/or parallel to generate power. Often the sole power source for a spacecraft.

Solar Cell: A photovoltaic device used to convert the energy in light to electrical energy.

String Voltage: The voltage of a single series-connected solar array segment. Often this is the power system voltage.

Surge: A transient variation in the current and/or potential at a point in the circuit.

Sustained Arc: An electrical discharge that lasts much longer than the usual capacitance-discharging arc (on the order of 1 millisecond or longer).

Trigger Arc: An electrical discharge of one type that triggers a discharge of another type.

Triple-point (triple-junction): A point where a plasma, a high-voltage conductor, and an insulator come together. At such a point, the electric field is often at a maximum, and plasma-arcing is more likely.

Voltage: The term most often used in place of electromotive force, potential difference, or voltage drop to designate electric pressure that exists between two points and is capable of producing a flow of current when a closed circuit is connected between the two points.

Wire: A metallic conductor of round, square, or rectangular cross-section that can be either bare or insulated.

4. REQUIREMENTS

4.1 General LEO Standard Requirements

4.1.1 Arcs on Spacecraft in LEO

Arcs on spacecraft in LEO must be prevented because of their potentially disastrous consequences (see NASA-HDBK-4006, appendix C, section C.1.2.3). The four types of arcs which shall be prevented are as follows:

a. Solar array or power system trigger arcs (see NASA-HDBK-4006, appendix C, section C.1.2).

b. Sustained solar array arcs (see NASA-HDBK-4006, appendix C, section C.1.2.3.1).

c. Dielectric breakdown of structure surface coatings (can also become sustained, see NASA-HDBK-4006, appendix C, section C.1.2.3.1).

d. Paschen discharges (see NASA-HDBK-4006, appendix B, section B.2, and appendix D, section D.2.3)

4.1.2 Large Parasitic Current Drains

Large parasitic current drains to the LEO plasma can lead to power losses and will be prevented. Steps will be taken to limit their effects if they cannot be prevented.

4.1.3 Simulated LEO Plasma Environment Test

Spacecraft systems susceptible to arcing or large parasitic current drains shall be tested to ensure their function and performance in a simulated LEO plasma environment under simulated (worst-case) operational conditions before flight.

4.1.4 LEO versus GEO Charging

Prevention and mitigation techniques appropriate in the prevention of arcing in GEO cannot be the same as those for LEO spacecraft. Spacecraft that operate a significant amount of time in LEO shall use arc prevention and mitigation techniques appropriate for the LEO environment.

4.1.5 Arc Prevention Techniques

a. Solar array or power system trigger arcs may be prevented with any or all of the following (see NASA-HDBK-4006, appendix D, section D.2.4.2):

(1) Limit the potential of possible arc-sites to a voltage lower than the trigger arc threshold (which must be determined by testing). This task can be achieved by all or one of the following:

A. Using power system voltages lower than the threshold.
B. Limiting electron collection to solar arrays by using welded-through interconnects (see NASA-HDBK-4006, appendix C, section C.1.1.1) or closely spaced coverslides (see NASA-HDBK-4006, appendix C, section C.1.1.4.1).
C. Encapsulating exposed electron-collecting conductors (see NASA-HDBK-4006, appendix D, section D.2.3, but be careful of creating Paschen discharge conditions).
D. Using a plasma contactor with a grounded neutralizer (see NASA-HDBK-4006, appendix D, section D.2.2).

(2) Limit the electric fields of potential arc-sites. This task can be achieved by one or all of the following:

A. Limiting power system voltages to below the trigger arc threshold (which must be determined by testing).
B. Using (slightly) conductive coverslides or otherwise preventing sharp triple-points (see NASA-HDBK-4006, appendix C, section C.1.2.3).
C. Using wrap-through interconnects (see NASA-HDBK-4006, appendix C, section C.1.1.1).
D. Grouting the edges of cells (see NASA-HDBK-4006, appendix D, section D.2.3).
E. Using cell coverslides with a large overhang.
F. Using thick coverslides.

(3) Eliminate arc-sites; i.e., effectively encapsulate all exposed conductors (see NASA-HDBK-4006, appendix D, section D.2.3, but be careful of creating Paschen discharge conditions). This elimination can be achieved by one or all of the following:

A. Using very large coverslides that cover an entire array segment.
B. Using concentrator arrays with fully grouted solar cells.
C. Using thin-film coatings that are thick enough to have a dielectric strength higher than (can stand-off) the full array voltage.
D. Openings in vented experiment electronics enclosures shall have smaller dimensions than the minimum Debye length expected in the LEO environment (see NASA-HDBK-4006, appendix D, section D.2.3.1).

b. Sustained solar array arcs may be prevented with any or all of the following (but see also NASA-HDBK-4006, appendix D, section D.2.4.2):

(1) Prevent all occurrences of trigger arcs (see section 4.1.5a above).
(2) Limit the differential potentials of adjacent solar array strings, cells, or power traces to below the sustained arcing threshold (which must be determined by testing). This task can be achieved by using power system string voltages lower than the sustained arcing voltage threshold and/or using string layouts that prevent adjacent cells or strings from having large differential voltages.
(3) Prevent trigger arc plasmas from reaching adjacent cells or strings. This task can be achieved by

A. Grouting the edges of cells and strings that have large differential voltages with adjacent cells or strings.
B. Erecting physical barriers to plasma movement, and/or spacing adjacent strings far from each other.
C. The arcing thresholds for geometries intended to mitigate sustained arcing must be determined by testing.

(4) Prevent trigger arc plasmas from initiating Paschen discharge at the differential voltage between strings or cells. The Paschen minimum for most materials that can be evolved during a trigger arc can only be determined by testing. Without an extensive test program to determine these thresholds, this technique can only be implemented by using solar array materials that do not decompose under the high heat of an arc. This excludes the use of Kapton®, certain adhesives, and non-refractory metals in solar array construction.

(5) Limit currents at arc-sites to below the sustained arcing current threshold (which must be determined by testing). This goal can be achieved by one of the following:

A. Using blocking diodes in string circuits to prevent string arc-current communication.
B. Using solar cells of current output below the sustained arcing current threshold.
C. Using RC time constants in solar array strings that are much longer than trigger arc timescales.

(6) Prevent arcs from extending in duration to milliseconds or more. This task can be achieved by sensing arc occurrence and quickly (< 200 microsecond) open-circuiting strings where arcs occur (see NASA-HDBK-4006, appendix D, section D.2.4).

c. Dielectric breakdown of structure surface coatings will be prevented with any or all of the following (but see also NASA-HDBK-4006, appendix D, section D.2.4.2):

(1) Keep electric fields in the coatings below the breakdown voltage set by the dielectric strength of the coating. This limitation can be achieved by one of the following:

A. Using low power system voltages.
B. Letting the solar array float with respect to the system ground.
C. Limiting electron collection to solar arrays by using welded-through interconnects (see NASA-HDBK-4006, appendix C, section C.1.1.1) or closely spaced coverslides (see NASA-HDBK-4006, appendix C, section C.1.1.4.1).
D. Encapsulating exposed electron-collecting conductors (see NASA-HDBK-4006, appendix D, section D.2.3, but be careful of creating Paschen discharge conditions).
E. Choosing a power system grounded at or near its most positive end (see NASA-HDBK-4006, appendix D, section D.2.1).
F. Using a plasma contactor with a grounded neutralizer.
G. Using thick dielectric coatings with a high breakdown voltage.
H. Using very thin dielectric coatings with bulk resistivity low enough that the surface potential is close to the underlying conductor potential (but be careful

that the capacitance across the coating does not become great enough to exacerbate arc damage when arcs occur).

(2) Prevent sustained dielectric breakdowns (sizzle arcs) by preventing the original dielectric breakdown (see above), or by preventing the spacecraft's electron current collection from reaching the sustained arc threshold (which must be determined by testing) for the dielectric material. This task can be achieved by one of the following:

A. Limiting the power system voltage to below the snapover voltage (which must be determined by testing, see NASA-HDBK-4006, appendix C, section C.1.1.4.3).
B. Using a power system grounded at or near its most positive end (see NASA-HDBK-4006, appendix D, section D.2.1).
C. Encapsulating all exposed electron collecting conductors, or by other techniques for limiting electron current collection (see below).

d. Paschen discharges will be prevented with any or all of the following:

(1) Keep potentials of exposed conductors below the Paschen minimum for all ambient and emitted gases (see NASA-HDBK-4006, appendix D, section D.1). This goal can be achieved by one or all of the following:

A. Using very low power system voltages.
B. Encapsulating exposed electron-collecting conductors (but be careful of creating Paschen discharge conditions below the encapsulation).
C. Using a plasma contactor with a grounded neutralizer.

(2) Prevent the neutral pressure from entering the Paschen regime for the spacecraft plasma sheath dimensions. This task can be achieved by the following:

A. Placing vents and nozzles far from exposed conductors.
B. Adequately venting enclosures with exposed high-voltage differentials.
C. Venting only gases with high Paschen minimum voltages.
D. Filling pressurized enclosures with an electron-sponge gas (such as SF_6).
E. Using only spacecraft materials that have low outgassing properties in enclosed spaces.

4.1.6 Prevention of Large Parasitic Plasma Currents

a. Large parasitic plasma currents will be prevented with the following method:

(1) Control the maximum solar array positive potential to below the snapover potential (which must be determined by testing, see NASA-HDBK-4006,

appendix C, section C.1.1.4.3). This control can be achieved by any or all of the following:

A. Using power system voltages less than the snapover voltage (may be as low as 80 V).
B. Letting the solar array float with respect to the system ground.
C. Encapsulating exposed electron-collecting conductors (see NASA-HDBK-4006, appendix D, section D.2.3, but be careful of creating Paschen discharge conditions).
D. Choosing a power system grounded at or near its most positive end (see NASA-HDBK-4006, appendix D, section D.2.1).
E. Operating the solar arrays only when in their own wake (the afternoon side of the orbit).
F. Using snapover-preventive coatings with low secondary electron emissivities (see NASA-HDBK-4006, appendix C, sections C.1.1.4.1 and C.1.1.4.3).
G. Using a plasma contactor with a grounded neutralizer (see NASA-HDBK-4006, appendix D, section D.2).

4.1.7 Steps to Limit the Impact of Arcs to Sensitive Spacecraft Systems

a. If arcs cannot be prevented, the impact of the arcs shall be limited in one or all of the following ways:

(1) Limit the energy that is dissipated in a trigger arc. This task can be achieved by one or all of the following:

A. Limiting the capacitance that can be discharged in the arc (including all circuits directly connected to the arc-site).
B. Limiting the potential of an arc-site (see above).
C. Providing an RC time constant larger than the trigger arc duration for other strings or surfaces that can provide current to the arc.

(2) Prevent arc currents from traversing the human body or other circuits sensitive to power surges. This task can be achieved by using sneak-circuit analysis to make sure astronauts or sensitive circuits are not in the direct path of current flow during an arc.

(3) Prevent the arc from drawing power continuously from the solar arrays. This task can be achieved by preventing the arc from becoming a sustained arc (see above).

(4) Prevent a trigger arc from becoming a Paschen discharge. See above for techniques to prevent Paschen discharge.

(5) Limit arc-sites to material surfaces that are not sensitive to damage. This limitation can be achieved by preventing dielectric breakdown or solar array arcing on surfaces that are used for thermal control, optical surfaces, possible electromagnetic interference (EMI)-radiating surfaces, electronics enclosures, and the like. See above for techniques to prevent dielectric breakdown and/or solar array arcing on these surfaces. Arcs on surfaces that are not critical to spacecraft

systems will not contaminate sensitive surfaces, and will not radiate into sensitive electronics do not require arc prevention.

(6) Detect the occurrence of arcs and rapidly cut off current to the site when an arc occurs (see NASA-HDBK-4006, appendix D, section D.2.4).

4.1.8 Testing

4.1.8.1 Compliance with the LEO standards shall always be verified by testing. Verification of LEO space systems' performance in preventing arcing and/or large parasitic plasma currents must never be attempted solely by analysis. No substitute exists for testing in a simulated LEO environment under simulated (worst-case) operational conditions. Do not trust any analysis results exclusively. Test your particular design and have a knowledgeable space electrostatic discharge (ESD) engineer review your design at the earliest possible stage in the program, and make sure you have continuing support through launch.

4.1.8.2 See NASA-HDBK-4006, appendix F for appropriate test conditions.

5. GUIDANCE

5.1 Reference Documents

An important reference document for LEO spacecraft charging design is Ferguson and Hillard, 2003. It contains an extensive annotated bibliography that is not possible to repeat here. A good (and current) reference for test procedures is Ferguson et al., 2005. For other guidance information, see NASA-HDBK-4006.

Ferguson, D.C.; Hillard, G.B. (2003). Low Earth Orbit Spacecraft Charging Design Guidelines. NASA/TP—2003-212287.

Ferguson, D. C.; Vayner, B. V.; Galofaro, J.T.; Hillard, G. B.; Vaughn, J.; Schneider, T. (2005). "NASA GRC and MSFC Space-Plasma Arc Testing Procedures." Proceedings of the 9th Spacecraft Charging Technology Conference, Tsukuba, Japan, April 4-8, 2005.