METRIC

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LOW EARTH ORBIT SPACECRAFT CHARGING DESIGN STANDARD

DOCUMENT HISTORY LOG

Status	Document Revision	Change Number	Approval Date	Description
Interim			2006-09-11	Interim Release
Baseline			2007-06-03	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.
Revision	A		2016-02-01	The original intent of "musts" and "wills" used in section 4 was to reflect requirements; changed to "shall" statements to conform to Agency policy for indicating requirements. Section 4.1.6 has been combined with section 4.1.2; section 4.1.6 provided direction on how to minimize parasitic currents, where section 4.1.2 was stating the requirement. Added or modified template boilerplate text. Moved applicable document AFWAL-TR-88-4143, Volume 2, to Appendix B, References; and deleted

DOCUMENT HISTORY LOG (Continued)

Status	Document Revision	Change Number	Approval Date	Description
Revision	A		2016-02-01	Continued section 5, moving all references to Appendix B. Numbered requirements and added Requirements Compliance Matrix in Appendix A. Corrected formatting errors.
Revalidation	A	1	2021-11-17	Revalidated—This NASA Technical Standard was reviewed and only editorial/administrative changes to conform to the current template resulted.

FOREWORD

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

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and Facilities, and applicable technical requirements may be cited in contract, program, and other Agency documents. It may also apply to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center [FFRDC]), other contractors, recipients of grants and cooperative agreements, and parties to other agreements only to the extent specified or referenced in applicable contracts, grants, or agreements.

This NASA Technical Standard provides a design standard for high-voltage spacecraft power systems (> 55 volts) that must operate in the plasma environment associated with low Earth orbit (LEO) at latitudes less than 50 degrees latitude.

Requests for information should be submitted via “Feedback” at https://standards.nasa.gov. Requests for changes to this NASA Technical Standard should be submitted via Marshall Space Flight Center (MSFC) Form 4657, Change Request for a NASA Engineering Standard.

Original Signed By	**February 1, 2016**
Ralph R. Roe, Jr. NASA Chief Engineer	Approval Date

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LOW EARTH ORBIT SPACECRAFT CHARGING DESIGN STANDARD

1. SCOPE

This NASA Technical 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 NASA Technical Standard is to provide a design standard for spacecraft electrical power systems using voltages greater than 55 volts that operate in the low Earth orbit (LEO) plasma environment encountered in altitudes up to 2000 kilometers (km) and latitudes 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 primary reasons. The first reason is to save launch weight. For the same power level, higher voltages enable use of smaller diameter 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 smaller 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.

The second reason to use a high voltage power system is that some spacecraft functions require them. For example, electric propulsion uses voltages from about 300 V (Hall thrusters) to about 1000 V (ion thrusters). A low-voltage power system would require conversion of substantial power to high voltages 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. If the high-voltage function is electric propulsion, such a system is called a direct-drive electric propulsion system.

Because of these and other reasons, spacecraft designers and manufacturers are increasingly employing high voltage power systems, but with the advantages comes a higher risk of spacecraft charging. The presence of high voltage solar arrays and exposed electrical conductors that carry high voltages can directly exacerbate the spacecraft charging process in LEO, potentially resulting in undesirable electrical arcing, power drain and disruptions, and contamination of spacecraft surfaces and coatings all of which contribute to the damage 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 is useful to space mission personnel including project managers, solar array designers, and system engineers.

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

1.2 Applicability

This NASA Technical Standard is applicable to spacecraft electrical power systems using voltages greater than 55 volts that operate in the LEO plasma environment encountered in altitudes up to 2000 kilometers (km) and latitudes between -50 and +50 degrees. Specifically excluded are spacecraft that encounter GEO charging conditions that do not (often) encounter energetic electrons within the auroral ovals, 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 and internal charging will be a concern.** However, it is not in the purview of this document to deal with those two topics. For direction on designing spacecraft to survive the conditions in GEO and in the Van Allen belts, one should reference NASA-HDBK-4002A, Mitigating In-Space Charging Effects-A Guideline.

Some of the design standards for LEO are at variance with good design practice for GEO spacecraft. For example, in GEO one would use materials on the external surface of the spacecraft with low electrical resistance that are all bonded together. This prevents external charging and the potential for electrostatic discharge. In LEO, if you make external materials conductive, then more current is collected from the plasma increasing the parasitic currents in the system and changing the system floating potential. If the spacecraft will fly in both LEO and GEO conditions, be careful to use design solutions that are applicable in both environmental regimes (see NASA-HDBK-4002A).

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and Facilities and may be cited in contract, program, and other Agency documents as a technical requirement. It may also apply to the Jet Propulsion Laboratory and other contractors only to the extent specified or referenced in applicable contracts.

Verifiable requirement statements are designated by the acronym “SCR” (Spacecraft Charging Requirement), numbered, and indicated by the word “shall. This NASA Technical Standard contains 14 requirements. Explanatory or guidance text is indicated in italics beginning in section 4. To facilitate requirements selection by NASA programs and projects, a Requirements Compliance Matrix is provided in Appendix A.

1.3 Tailoring

Tailoring of the requirements in this NASA Technical Standard for application to a specific program or project is acceptable when documented in program or project requirements and formally approved by the delegated Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements.

2. APPLICABLE DOCUMENTS

2.1 General

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

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

2.1.3 Non-use of specifically designated versions will be approved by the delegated Technical Authority.

2.1.4 Applicable documents may be accessed at https://standards.nasa.gov obtained directly from the Standards Developing Body or other document distributors, or information for obtaining the document is provided.

2.1.5 References are provided in Appendix B.

2.2 Government Documents

National Aeronautics and Space Administration (NASA)

NPR 7120.5	NASA Space Flight Program and Project Management Requirements
NASA-HDBK-4006	Low Earth Orbit Spacecraft Charging Design Handbook

2.3 Non-Government Documents

None.

2.4 Order of Precedence

2.4.1 The requirements and standard practices established in this NASA Technical Standard do not supersede or waive existing requirements and standard practices found in other Agency documentation.

2.4.2 Conflicts between this NASA Technical Standard and other requirements documents will be resolved by the delegated Technical Authority.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

AFWAL	Air Force Wright Aeronautical Laboratories
cm	centimeter(s)
dc	direct current
DWV	dielectric withstand voltage
EMI	electromagnetic interference
ESD	electrostatic discharge
FFRDC	Federally Funded Research and Development Center
GEO	geosynchronous Earth orbit
HDBK	Handbook
km	kilometer(s)
LEO	low Earth orbit
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirements
PMAD	power management and distribution
RC	resistor-capacitor
SCR	spacecraft charging requirement
SI	Système Internationale or metric system of measurement
STD	standard
V	volt(s)

3.2 Definitions

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

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

Bulk Resistivity: A material property that refers to the material’s ability to oppose the flow electrical charge through the material. The SI units are Ohm-cm. A designer must be careful not to use values of bulk resistivity for materials where water absorption in the material is the major charge carrier.

Capacitance: That property of a system of conductors and dielectrics that permits the storage of electrical charge in dielectric materials when potential differences exist between the conductors. The value is expressed as the absolute ratio of the stored electrical charge to the potential differences between the conductors.

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: The fundamental conserved property of certain subatomic particles that determines their interaction with electromagnetic fields. Electric charge is quantized in integer multiples of individual small units called the elementary charge, e, approximately equal to 1.602×10−19 coulombs.

Conductivity: A constitutive parameter (σ) of a material that represents the measure of the material to conduct electrical current in the direction of an externally applied electric field. Conductivity is the reciprocal of bulk 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 material that exhibits a high electrical resistivity together with a high electrical breakdown level, such that electrical current does not flow under operational conditions. The term is generally interchangeable with the term insulator.

Dielectric Breakdown: A sudden increase in electric current flow within a dielectric caused by an applied electric field exhibiting a magnitude in excess of the dielectric strength of the material.

Dielectric Strength: The maximum electrical electric field that a dielectric material can withstand without breakdown, usually expressed in volts per mm of thickness. May also be referred to as dielectric withstand voltage (DWV).

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 travels 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.

Float: A term used to describe a power or signal system whose reference or return is isolated from primary power or signal systems reference or return.

Gradient: A vector derivative of a scalar field producing a vector field with the magnitude of the maximum rate of change of the scalar field, pointing in the direction of the maximum change of the scalar field.

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 that exhibits a high electrical resistivity together with a high electrical breakdown level, such that electrical current does not flow under operational conditions. The term is generally interchangeable with the term dielectric.

Ion: An atom or molecule which has gained or lost one or more of its valence electrons, giving it a net positive or negative electrical charge. An ion may be formed when a molecule of gas is stressed electrically beyond its critical voltage.

Paschen Discharge: The result of application of the voltage necessary to initiate a discharge or electric arc between two conductors in a gas as a function of pressure and gap length.

Permeability: The magnetic constitutive parameter (μ) of a material, a measure of the capacity of the material to store kinetic energy and to align with and magnetize along an externally applied magnetic field.

Permittivity: The electrical constitutive parameter (ε) of a material, a measure of the capacity of the material to store potential energy and to align with and polarize along an externally applied electric field.

Plasma: Plasma is the fourth state of matter. A plasma is a typically neutral gas within which some or all of its constituent atoms are split up into electrons and ions, able to move independently of each other. Plasma may be strongly influenced by electrostatic and electromagnetic fields and forces, leading to very complex and interesting behavior.

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 of change of energy when work is done. Power is obtained in watts if work is expressed in joules and time is expressed 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.

Resistor-Capacitor (RC) Time Constant: Time constant obtained by multiplying resistance by capacitance.

Resistivity (specific insulation resistance): The electrical resistance between opposite faces of a 1-centimeter (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 measure of electrical potential difference between two points. Voltage provides the motive force in response to which electrical current will flow when a conductor is located 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

4.1.1.1 [SCR 1] Arcs on spacecraft in LEO **shall** be prevented because of their potentially disastrous consequences (see NASA-HDBK-4006, Appendix C, section C.1.2.3).

4.1.1.2 [SCR 2] 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

[SCR 3] Large parasitic current drains to the LEO plasma can lead to power losses and **shall** be minimized.

a. Large parasitic plasma currents can be reduced using one or more of the following methods:

  (1) Control the maximum solar array positive potential to below the snapover potential (which shall be determined by testing; see NASA-HDBK-4006, Appendix C, section C.1.1.4.3). This control can be achieved by one or more of the following:

    A. Using power system voltages less than the snapover voltage (snapover potential has been measured to 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).

      i. When applying the encapsulation, care should be taken to eliminate trapped air which could possibly crease at Paschen discharge.

- 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 emission yields (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).*

4.1.3 Simulated LEO Plasma Environment Test

[SCR 4] 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

[SCR 5] Spacecraft that operate a significant amount of time in LEO **shall** use arc prevention and mitigation techniques appropriate for the LEO environment. *The techniques used to prevent and mitigate arcing in LEO are not the same as those used to mitigate GEO arcing. For design guidelines to prevent spacecraft charging in GEO, use NASA-HDBK-4002A.*

4.1.5 Arc Prevention

a. [SCR 6] Solar array or power system trigger arcs **shall** be prevented using one or more of the following methods (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 shall be determined by testing). *This task can be achieved by one or more of the following:*

  - A. *Using power system voltages lower than the threshold voltage.*
  - 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 more of the following*:

A. *Limiting power system voltages to below the trigger arc threshold (which shall 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 (see NASA-HDBK-4006, Appendix D, section D.2.3) and avoid creating Paschen discharge conditions. *Elimination can be achieved by one or more 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.*

i. [SCR 7] Openings in vented 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. [SCR 8] Sustained solar array arcs **shall** be prevented with one or more 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 4.1.5.a above).

(2) Limit the differential potentials of adjacent solar array strings, cells, or power traces to below the sustained arcing threshold (which shall 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 the following methods:*

  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.*

    i. [SCR 9] The arcing thresholds for geometries intended to mitigate sustained arcing **shall** 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 shall 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. [SCR 10] Dielectric breakdown of structure surface coatings **shall** be prevented with one or more of the following methods (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 shall be determined by testing) for the dielectric material. *This task can be achieved by one of the following methods:*

  A. *Limiting the power system voltage to below the snapover voltage (which shall 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. [SCR 11] Paschen discharges **shall** be prevented with one or more 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 can be achieved by one or all of the following methods:*

  A. Using very low power system voltages.

  B. Encapsulating exposed electron-collecting conductors (be careful not to create 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 methods:*

  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 sulfur hexafluoride (SF_6).

  E. Using only spacecraft materials that have low outgassing properties in enclosed spaces.

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

a. [SCR 12] If arcs cannot be prevented, the impact of the arcs **shall** be limited in one or more of the following ways:

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

  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 and will not contaminate sensitive surfaces nor 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).

4.1.7 Testing

4.1.7.1 [SCR 13] Compliance with the LEO spacecraft charging standards in section 4.1, General LEO Standard Requirements **shall** always be verified by testing.

4.1.7.2 [SCR 14] Verification of LEO space systems’ performance in preventing arcing and/or large parasitic plasma currents **shall** never be attempted solely by analysis. *No substitute exists for testing in a simulated LEO environment under simulated (worst-case) operational conditions. Test the particular design, have a knowledgeable spacecraft electrostatic discharge (ESD) engineer review the design at the earliest possible stage in the program, and ensure continuing support is provided through launch. (See NASA-HDBK-4006, Appendix F, for appropriate test conditions.)*

APPENDIX A

REQUIREMENTS COMPLIANCE MATRIX

A.1 Purpose

Due to the complexity and uniqueness of space flight, it is unlikely that all of the requirements in a NASA technical standard will apply. The Requirements Compliance Matrix below contains this NASA Technical Standard's technical authority requirements and may be used by programs and projects to indicate requirements that are applicable or not applicable. Follow the process for tailoring in section 1.3 in this NASA Technical Standard. Enter "Yes" in the "Applicable" column if the requirement is applicable to the program or project or "No" if the requirement is not applicable to the program or project. The "Comments" column may be used to provide specific instructions on how to apply the requirement or to specify proposed tailoring.

NASA-STD-4005A w/Change 1

Section	Description	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.1.1.1	Arcs on Spacecraft in LEO	[SCR 1] Arcs on spacecraft in LEO **shall** be prevented because of their potentially disastrous consequences (see NASA-HDBK-4006, Appendix C, section C.1.2.3).		
4.1.1.2	Arcs on Spacecraft in LEO	[SCR 2] 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).		

NASA-STD-4005A w/Change 1				
Section	Description	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		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	[SCR 3] Large parasitic current drains to the LEO plasma can lead to power losses and **shall** be minimized.		
4.1.3	Simulated LEO Plasma Environment Test	[SCR 4] 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	[SCR 5] 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	a. [SCR 6] Solar array or power system trigger arcs **shall** be prevented using one or more of the following methods (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 shall be determined by testing). (2) Limit the electric fields of potential arc-sites. (3) Eliminate arc-sites (see NASA-HDBK-4006, Appendix D, section D.2.3) and avoid creating Paschen discharge conditions.		
4.1.5	Arc Prevention	i. [SCR 7] Openings in vented electronics enclosures **shall** have smaller dimensions than the minimum Debye length		

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Section	Description	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		expected in the LEO environment (see NASA-HDBK-4006, Appendix D, section D.2.3.1).		
4.1.5	Arc Prevention	b. [SCR 8] Sustained solar array arcs **shall** be prevented with one or more 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 4.1.5.a above). (2) Limit the differential potentials of adjacent solar array strings, cells, or power traces to below the sustained arcing threshold (which shall be determined by testing). (3) Prevent trigger arc plasmas from reaching adjacent cells or strings.		
		i. [SCR 9] The arcing thresholds for geometries intended to mitigate sustained arcing **shall** be determined by testing.		
4.1.5	Arc Prevention	(4) Prevent trigger arc plasmas from initiating Paschen discharge at the differential voltage between strings or cells. (5) Limit currents at arc-sites to below the sustained arcing current threshold (which shall be determined by testing). (6) Prevent arcs from extending in duration to milliseconds or more.		

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Section	Description	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.1.5	Arc Prevention	c. [SCR 10] Dielectric breakdown of structure surface coatings **shall** be prevented with one or more of the following methods (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. (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 shall be determined by testing) for the dielectric material.		
4.1.5	Arc Prevention	d. [SCR 11] Paschen discharges **shall** be prevented with one or more 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). (2) Prevent the neutral pressure from entering the Paschen regime for the spacecraft plasma sheath dimensions.		
4.1.6	Steps to Limit the Impact of Arcs to Sensitive Spacecraft Systems	a. [SCR 12] If arcs cannot be prevented, the impact of the arcs **shall** be limited in one or more of the following ways: (1) Limit the energy that is dissipated in a trigger arc. (2) Prevent arc currents from traversing the human body or other circuits sensitive to power surges.		

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Section	Description	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		(3) Prevent the arc from drawing power continuously from the solar arrays. (4) Prevent a trigger arc from becoming a Paschen discharge. (5) Limit arc-sites to material surfaces that are not sensitive to damage. (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).		
4.1.7.1	Testing	[SCR 13] Compliance with the LEO spacecraft charging standards in section 4.1, General LEO Standard Requirements **shall** always be verified by testing.		
4.1.7.2	Testing	[SCR 14] Verification of LEO space systems' performance in preventing arcing and/or large parasitic plasma currents **shall** never be attempted solely by analysis.		

APPENDIX B

REFERENCES

B.1 PURPOSE

This Appendix provides guidance made available in the reference documents listed below.

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

B.2 REFERENCE DOCUMENTS

AFWAL-TR-88-4143, Volume 2, Design Guide: Designing and Building High Voltage Power Supplies, Materials Laboratory.

ANSI/AIAA S-115-2013, Low Earth Orbit Spacecraft Charging Design Standard Requirement and Associated Handbook.

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.