The New NASA-STD-4005 and NASA-HDBK-4006, Essentials for Direct-Drive Solar Electric Propulsion

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Abstract: High voltage solar arrays are necessary for direct-drive solar electric propulsion, which has many advantages, including simplicity and high efficiency. Even when direct-drive is not used, the use of high voltage solar arrays leads to power transmission and conversion efficiencies in electric propulsion Power Management and Distribution. Nevertheless, high voltage solar arrays may lead to temporary power disruptions, through primary electrostatic discharges, and may permanently damage arrays through permanent sustained discharges between array strings. Design guidance is needed to prevent these solar array discharges, and to prevent high power drains through coupling between the electric propulsion devices and the high voltage solar arrays. While most electric propulsion systems may operate outside of Low Earth Orbit, the plasmas produced by their thrusters may interact with the high voltage solar arrays in many ways similarly to Low Earth Orbit plasmas. A brief description of previous experiences with high voltage electric propulsion systems is given in this paper. There are two new official NASA documents available free through the NASA Standards website to help in designing and testing high voltage solar arrays for electric propulsion. They are NASA-STD-4005, the Low Earth Orbit Spacecraft Charging Design Standard, and NASA-HDBK-4006, the Low Earth Orbit Spacecraft Charging Design Handbook. Taken together, they can educate the high voltage array designer in the engineering and science of spacecraft charging in the presence of dense plasmas and provide techniques for designing and testing high voltage solar arrays to prevent electrical discharges and power drains. A description of these two companion documents are given in this paper – their range of applicability, an overview of their organization, how to use them, and the essential role of testing in high voltage solar array design and construction. Also, the relationship of these new standards documents to the previous spacecraft charging documents will be discussed, such as NASA TP-2361 (the Design Guidelines for Assessing and Controlling Spacecraft Charging Effects), and NASA-HDBK-4002 (Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects). Finally, a list of do's and don'ts for high voltage solar array designers will be given, along with information on how to obtain copies of NASA-STD-4005 and NASA-HDBK-4006.

I. Introduction

THE space environment in Low Earth Orbit (LEO) is significantly different from that in geosynchronous orbit (GEO), and an increasing number of LEO satellites are being flown. Many of the interactions leading to spacecraft charging in LEO are completely different from those in GEO environments. However, for lack of a NASA standards document on LEO spacecraft charging, many spacecraft manufacturers still use the 1984

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Spacecraft Charging Guidelines of Purvis, Garrett, Whittlesey, and Stevens[1], intended only for GEO satellites, to design LEO spacecraft. This unfortunate state of events is being changed. The new NASA-STD-4005 Low Earth Orbit Spacecraft Charging Design Standard and the NASA-HDBK-4006 Low Earth Orbit Spacecraft Charging Design Handbook have now been officially released.

II. Previous Experience With High Voltage Electric Propulsion in Space

Many electric propulsion experiments in space have used relatively low-voltage solar arrays, or have devised special grounding schemes, to mitigate the effects of high voltages. Witness the early SERT II mission (one of the missions developed by Dr. Harold Kaufman)[2], that operated in space from 1970 to 1991, and which had a center-tapped grounding scheme on the solar arrays so it could achieve high voltages without making the spacecraft float highly negative of the LEO plasma in which it operated. Perhaps the best known example of a high-voltage solar electric propulsion spacecraft was Deep Space 1, with 100 V arrays. 100 volts may not sound like a high voltage, but in LEO plasmas such voltages have led to arcing on solar arrays and can even lead to the disastrous so-called sustained arcing, whereby the solar array arcs become powered by the array itself, and which often lead to complete loss of one or more strings of the solar array[3]. Because of the threat of sustained arcing on the power bus on the Deep Space 1 solar arrays, wherein the outgoing and return traces were exposed and closely spaced together, one of the two solar arrays was even removed from the spacecraft buildup before launch and modified to prevent arcing. Such is the importance of proper spacecraft design in the dense plasma of LEO.

However, proper spacecraft design to prevent arcing in LEO plasmas is not just a LEO concern. Electric propulsion plumes on GEO and interplanetary spacecraft produce LEO-type plasmas that may interact with the solar arrays in undesirable ways. Vayner et al[4] have shown that dense arcjet plumes may interact with solar arrays to produce arcing, especially when the arcjet is turned on. It is expected that other electric propulsion plumes, such as those from Hall thrusters and ion thrusters, will also behave in this way.

III. Scope, Purpose and Applicability of the NASA-STD-4005 Standard and NASA-HDBK-4006 Handbook

The NASA-STD-4005 standard and NASA-HDBK-4006 handbook present an overview of the current understanding of the various plasma interactions that can result when a high voltage system is operated in the Earth’s dense LEO plasma, references common design practices that have exacerbated plasma interactions in the past, and recommends standard practices to eliminate or mitigate such reactions. The purpose of the standard and handbook is to provide a design standard for *high-voltage space power systems* (>55 volts) 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 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 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.

Secondly, 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[5]. 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 plasmas. In addition to system designers, NASA-STD-4005 and NASA-HDBK-4006 should be useful to project managers, electric propulsion and solar array designers, system engineers, etc.

The NASA-STD-4005 standard and the NASA-HDBK-4006 handbook are applicable to high-voltage space power systems that operate in the plasma environment associated with LEO. As was stated before, they are 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 NASA-STD-4005 and NASA-HDBK-4006 to deal with internal charging*. For internal charging problems, one would do well to access NASA-HDBK-4002 (Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects).

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, care must be taken to use design solutions that are applicable in both environmental regimes.

IV. The Requirements Section

There are sections on acronyms and definitions, defining all of the specific terms used in the Standard, that take up about 4 pages. Then comes the meat of the standard. Section 4 of the NASA-STD-4005 Standard is the Requirements Section. Here, all of the LEO requirements are given and references are given to the Appendices in NASA-HDBK-4006, the Handbook, based largely on the Ferguson and Hillard (2003) LEO Spacecraft Charging Design Guidelines[6]. The main requirement is to prevent arcing. All of the types of arcing due to spacecraft charging are listed.

Quoting from the standard,

> *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:*
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> *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).*

Strategies to prevent arcing are given, and techniques are detailed to implement the strategies. Secondly, prevention of large parasitic currents to the power system is emphasized. Strategies and techniques are given. Throughout NASA-STD-4005, the importance of testing is emphasized. Many of the thresholds for arcing are poorly known, and if the strategy to prevent arcing is to keep voltages lower than the appropriate threshold, testing must be used to determine those thresholds and to guarantee that flight articles do not arc. Thus, testing is listed as a requirement. The requirements section is about 6 pages long.

V. NASA-HDBK-4006, The Handbook

As stated before, the Requirements Section of NASA-STD-4005 has many references to the Appendices of NASA-HDBK-4006, the Low Earth Orbit Spacecraft Charging Design Handbook. Based on the Ferguson and Hillard (2003) Low Earth Orbit Spacecraft Charging Design Guidelines[6], the NASA-HDBK-4006 Handbook has been updated and revised to serve as an explanatory supplement to the NASA-STD-4005 standard. It has 6 main subsections, in addition to the document reference section. The main subsections are:

APPENDIX A. OVERVIEW OF PLASMA INTERACTIONS,
APPENDIX B. ENVIRONMENTS,
APPENDIX C. PLASMA INTERACTIONS,
APPENDIX D. MITIGATION TECHNIQUES,
APPENDIX E. MODELING, and
APPENDIX F. TESTING.

In each section, a comprehensive description/review of the topic is given, with many references. The Handbook is intended as a description of the state-of-the-art in LEO spacecraft charging, and is fully 63 pages long.

NASA-STD-4005 and NASA-HDBK-4006, the Low Earth Orbit Spacecraft Charging Design Standard and Handbook, are published and distributed in hardcopy and as searchable electronic files. NASA-STD-4005 and NASA-HDBK-4006 may be obtained through the NASA Technical Standards Program, which has the website *http://standards.nasa.gov/*.

VI. Do's and Don'ts

1. Do read NASA-STD-4005 and NASA-HDBK-4006.
2. Don't run solar array strings next to each other with differential voltages of more than about 55 V without taking measures to prevent sustained discharges from occurring.
3. Do arrange your electric propulsion devices so that there is no direct plume impingement on the solar arrays.
4. Don't just model the plume and space plasma interactions, test them!
5. Do feel free to use direct-drive if you have followed the NASA-STD-4005 requirements.
6. Don't neglect to inform your insurance companies that you are NASA-STD-4005 compliant.
7. Do use encapsulation on the solar array conductors and cell edges if you can afford the weight penalty.
8. Don't allow Paschen discharge or dielectric breakdown to occur.
9. Do model your spacecraft floating potential with and without the thruster(s) operating.
10. Don't forget – the gain in specific impulse is worth the effort to use electric propulsion, and the gain in PMAD efficiency is worth the effort to use direct-drive and high voltage arrays.

Conclusions

Because of the threat of sustained arcing on high voltage solar arrays and the efficiencies of using direct-drive electric propulsion, NASA-STD-4005 and NASA-HDBK-4006 are essentials for those interested in designing, building, and operating direct-drive solar electric propulsion systems in space. The two new official NASA documents are freely available on the NASA Technical Standards Program website.

References

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