SEP/HV Arrays and Spacecraft Interactions

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Solar Electric Propulsion (SEP) High Voltage Arrays and Spacecraft Interactions

- Solar Arrays operate in plasma – not in a vacuum
- High Voltage Solar Array – Plasma Interactions have been studied for decades
  - Cells at negative potentials arc
  - Cells at positive potentials collect current
- High Voltage solar array arcing has caused on-orbit failures
  - Reproduced in the lab
  - Preventative measures have been implemented
- Electric Thruster Plume interactions
  - Conventional: Electrically Isolated Power Processing Unit (PPU)
  - Advanced Technology: Direct Drive

If you understand how plasma interacts with solar arrays, operating at the voltages needed for Hall thruster Direct Drive isn’t that difficult.
**Direct-Drive**

Matches a 300-V solar array with a 300-V Hall thruster

Conventional System (heavy, expensive, difficult to develop)

- 160 to 300-V Solar Array
- Power Processor Unit
- Discharge Power Supply
- 300-V Hall Thruster

Direct-Drive System (potentially lighter, cheaper, easier)

- 300-V Solar Array
- Power Processor Unit
- 300-V Hall Thruster

Direct-Drive:
- Improves the power system efficiency from ~92% to ~99%
- Reduces the PPU mass by 70%
- Reduces the radiator mass by 80%
- Reduces the solar array mass, propellant mass, tankage mass, and structure mass

300-kW SEP Vehicle for Crew Transport in Deep Space
SEP Direct Drive Concept Originated at NASA/GRC (nee NASA/Lewis Research Center) in the 1970’s

- **Direct Drive for Ion Thrusters**

- **Direct Drive for Hall Thrusters**

**Figure 9. SunLine direct-drive of T-100 HET.**
“Experimental Investigation of a Direct-Drive Hall Thruster and Solar Array System at Power Levels up to 10 kW”

- Talk by Steve Snyder tomorrow - Tuesday 5:00 PM
- “Hall thruster control and operation is shown to be simple and no different than for operation on conventional power supplies.”

Fig. 1. The National Direct-Drive Testbed Solar Array.
High Voltage Solar Arrays Needed for Direct Drive

- Previous in-flight array experience below 170V, most below 100V
Solar Arrays Float Negative in a Plasma

- Solar array cells generate voltage wrt low side (low side often S/C ground)
- Current flows through the plasma
  - positive conductors collect electrons
  - negative conductors collect ions
- Electron current density $\gg$ ion current density
  - Plasma quasi neutral
    \[ n_e \approx n_i = n \]
  - Ion & electron current densities
    \[ j_e \approx n v_e \quad j_i \approx n v_i \]
  - Electron velocities $\gg$ Ion velocities
    \[ v_e \gg v_i \quad |j_e| \gg |j_i| \]
- Net current $= 0$
  \[ I_e + I_i = 0 \quad A^+ j_e + A^- j_i = 0 \]
- Negative area $\gg$ Positive area
  \[ A^- = A^+ \frac{|j_e|}{j_i} \gg A^+ \]
**International Space Station Solar Arrays Collect Little Electron Current**

- ISS PCU is a hollow cathode connected to S/C ground (array low side)
- ISS 160V Arrays
  - ISS solar array wing consists of two retractable "blankets" of solar cells with a mast between them.
  - Wing 34 meters long x 12 meters wide
  - ISS had 2 wings (max ~65 kW) when the PCU data was taken
- Ionosphere plasma currents less than 1 mA per string

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**Figure 11. Comparison of string current calculated using EWB, and March 29 DTO data.**

Positive potentials

No arcing

Parasitic current losses is the issue

Negative potentials

Solar array arcing is the issue is
Steep Gradients Cause Negative Potential Arcing

Both ions and electrons generate secondary electrons
- Electron generated secondary electrons smooth potential gradients
- Ion generated secondary electrons steepen potential gradients

“snap over”

Figure 14. - Typical surface voltage profiles solar array segment.

Figure 15. - Arcing on solar cells array sample (cell side) 2x6 cm wraparound cells on Kapton.
Metal-Dielectric-Plasma Triple Point

- Positive potential on metal
  - Electrons strike dielectric and generate secondary electrons
  - Result: enhanced collection & reduced edge fields

- Negative potential on metal
  - Ions strike dielectric and generate secondary electrons
  - Result: enhanced edge fields & arcing


Data: N. J. Stevens, et al., AIAA 78-672
Plasma Collection for “Solar Power Satellites” with Kilovolt Solar Arrays

Plasma Collection by High-Voltage Spacecraft at Low Earth Orbit

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D. E. Parks,‡ and P. G. Snee‡
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A computer model of the three-dimensional sheath formation and plasma current collection by high-voltage spacecraft has been developed. By using new space charge density and plasma collection algorithms, it is practical to perform calculations for large, complex spacecraft. The model uses objects and geometries compatible with the NASA Charging Analyzers Program (NASCAP). Results indicate that ion focusing observed in the laboratory during high-voltage collection experiments is probably due to voltage gradients on the collecting surfaces.

Fig. 1 Test object for sample calculations.

Fig. 3 - High Voltage "array" test lay-out in Chamber A

Fig. 4 y-z views of electron sheath particle trajectories for cases 4-7 (left to right).

Fig. 5 x-y views of electron sheath particle trajectories for cases 4-7 (left to right).

Parasitic Current Losses Due to Solar-Electric Propulsion Generated Plasmas

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Natural-sphere propellant is a leading candidate for most upcoming space missions. Under many circumstances plasma produced by charge-exchange reactions visible in the lab are significant for materials on spacecraft. This is particularly true of low Earth orbit. In particular, the low Earth orbit ionizing losses are significant since the large electric fields lead to a large number of charge-exchange plasma ions. These results from a three-dimensional model of the plasma sheath around the solar array wing. Results of calculations for several configurations and voltage levels indicate that with kilovolt plasma power losses of -20% or more are likely, even with only one stage in operation, and that neutralizer schemes should be based on the ion-focused portion of the solar array.

Arcs that Can Damage High Voltage Solar Arrays

Mechanism for Spacecraft Charging Initiated Destruction of Solar Arrays in GEO

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Recently, there have been anomalies on geosynchronous communications satellites that have lead to failures of strings on the solar arrays. The symptoms of the failures are low impedance shorts between high and low voltage cells on a string, and shorts between high voltage cells and the array ground. All of the anomalies occurred when other, instrumented, satellites measured a charging environment. In this paper we present a theory and supporting laboratory data, which show how small, low energy, spacecraft charging arcs on solar arrays can lead to larger, sustained discharges, which permanently damage the solar arrays. While observed in GEO, this mechanism can also lead to array destruction in LEO.

EOS-AM Solar Array Arc Mitigation Design

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TRW Space and Defense

William Andiaris
Lockheed Martin Missiles and Space

David Snyder
Glen Research Center

Ira Katz
Maxwell Technologies

ABSTRACT

This paper discusses the design and test program related to retrofit the EOS-AM solar array, protecting it from a newly discovered damage mechanism that is initiated by electrostatic discharges (ESD) while in orbit.

INTRODUCTION

Solar array power loss on two commercial geosynchronous satellites has been attributed to an ESD initiated damage mechanism that is applicable to high voltage solar arrays.1 Solar arrays are known to arc on orbit. These electrostatic discharges do not contain enough energy to cause damage. When they occur susceptible to the same damage mechanism. Arc mitigation implemented to protect the solar array consists of isolation diodes, isolated passive “grounding” structures, and overvoltage protection. The EOS-AM arc mitigation design was validated through further testing at CRC. The ESD mitigation design is discussed in detail in this paper.

OVERVIEW OF ARC DAMAGE MECHANISM

In GEO, the spacecraft charging environment consists of a low temperature (a fraction of an electron volt) plasma with densities ranging from 10^5 to 10^9 particles per cm^3. The floating potential of a spacecraft in this environment is sufficient to cause damage to the solar arrays at the edges of the arrays.
Discharge Scenario

1. Spacecraft charging provides trigger arc (~300V)
2. Solar array string provides the power for surface flashover
3. Sustained surface flashover pyrolizes the kapton
4. Permanent low impedance path across string

Solar Cells charge in response to space environment

Spacecraft Charging Causes a small arc to occur in the gap between cells.

The spacecraft charging arc triggers a sustained discharge driven by the array string current and voltage

Solar Cell - Coverslip
E field > 4 x 10⁶ V/m

Small Discharge Starts in Gap Between Cells
Discharge Generates a Plasma Cloud

Plasma Cloud Provides Low Impedance Path Across String

Design of Tests Conducted at NASA/LeRC

- Chamber Environment
  - Low density, ionosphere like plasma density ~ \(10^{11} \text{ m}^{-3}\)
  - Pressure < \(10^{-6} \text{ Torr}\)

- Solar Array Supply (SAS)
  - Purpose: Simulate the current generation capabilities of a string

- Charging Bias Supply (CBS)
  - Purpose: Simulate the sunlight charging of the array
  - Parameters: \(0 - 1000\text{V}\)
    - Capacitor to simulate wing capacitance
    - Positive terminal attached to tank ground
    - \(10\text{K}\Omega\) current limiting resistor

- Diagnostics
  - Current on the SAS supply
  - Current on the CBS supply
  - Low level TV with time stamp
  - Transient pulse monitor

- Test Procedure
  - Step from \(-200\text{V}\) to \(-1000\text{V}\) in \(50\text{V}\) steps
  - Dwell the order of an hour at each step to allow differential to develop

Example Test Data - Array Sustained Discharge

Photo from EOS-AM1 testing

Terminology

- primary discharge (blow-off + flashover)
- non-sustained arc (NSA)
- temporary sustained arc (TSA)
- permanent sustained arc (PSA)

Graph with labels:
- Trigger Arc Current
- Solar Array Current
Failure Thresholds

Figure 14. Measured GaAs Coupon Failure Threshold

Figure 15. Measured Si Coupon Failure Threshold

SS/L Corrective Actions

1. All solar array panels were rewired so that the voltage between adjacent cells is 50 V or less.

2. An RTV barrier, was inserted in all gaps between cells of differing voltages, and for a width of at least 10 mm in the crossing gaps between series cells.

3. Each string is isolated by diodes, limiting the current available to an arc.

Effectiveness of the RTV Barrier

**Figure 16.** GaAs Coupon Failure Threshold with RTV Barrier Installed

**Figure 16.** Si Coupon Failure Threshold with RTV Barrier Installed

Testing Embodied in ISO Standard

Introduction to ISO-11221, Space Systems – Space Solar Panels – Spacecraft Charging Induced Electrostatic Discharge Test Methods

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Laboratory of Spacecraft Environment Interaction Engineering
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September 22, 2010
11th Spacecraft Charging Technology Conference, Albuquerque, NM, USA

Introduction

- Papers on GEO satellite accidents
- 7th SCTC (ESA-ESTEC, 2001)
  - Difference of test methods
  - Values of external capacitance
  - How to test, plasma or beam?
- 8th SCTC (Huntsville, 2003)
  - Round-robin discussion on standardization

Test facility

- If it can be confirmed that the probability of a transition from a primary discharge to a secondary arc does not depend upon the method of primary discharge inception, any method can be used to cause primary discharges, irrespective of the anticipated charging situation in orbit.
- The test shall take place under vacuum in a test chamber with a pressure that guarantees the physical state of a collisionless plasma if a low energy plasma is used, or lower than $3 \times 10^{-6}$ Pa if other triggering methods such as an energetic electron beam, UV ray, laser pulse, etc., are used.
Current Flow in EP Thruster Plasma Plumes

- Electrons and ions from the thruster plume plasma and can be collected by exposed potentials on the solar array

Two grounding schemes

1. **EP System Electrically Isolated** from Spacecraft
   - Ground through a resistor
   - e.g. NASA’s Dawn Spacecraft
   - Current through the plasma changes “Neutralizer Cathode Common” voltage

2. **Direct Drive**
   - “Cathode Common” tied to the low side of the array
   - Hall thruster anode tied to array high side
   - “Parasitic” currents flow through the plume
   - Reduced arcing!
Plasma Currents on the Dawn Spacecraft

- Neutralizer common floating potential ~40 V
- Resistor 1.4 MΩ
  Current ~ 30 μA
- Solar Array Area 35 m²
EPIC: Integrated Computer Modules for the Assessment of Electric Propulsion –Spacecraft Interactions

Sputter Yield curves for typical S/C materials
Material-specific interactions, time dependence, 3-D effects all within EPIC’s capabilities.

Sputter Yield curves for typical S/C materials

Erosion Thickness (Å)
Recent Studies of HV – Solar Array Interactions included Electron Collection and the Effects of On-Orbit Aging


- Gaps in RTV ~ 250 μm x 25 μm

Empirically-reduced dependence of non-dimensional electron collection \( \overline{J}_c \) as a function of nondimensional collection potential \( \chi \), based on averaged data from the TECSTAR coupon tests.


Fig. 6. Magnified image of a section of the area between strings on coupon A. The image reveals that the RTV contact with the cell edges is reduced and gaps have been created that allow for arc formation.
Parasitic Currents

• Solar cell
  e.g. Spectrolab XTJ
  Current density $J_{\text{load}}$ min avg = 17.14 mA/cm$^2$ = 171 A/m$^2$
  $V_{\text{load}}$ = 2.310 V

• String voltage
  $V_{\text{string}}$ = 300V
  Packing fraction $f_{\text{pack}}$ = 0.8
  current density $J_{\text{string}}$ = 1 A/m$^2$

• Environment plasma Current densities

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<td>Hall (10m)</td>
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<td>2</td>
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• Current collected by a Gap in Grout 250 μm x 25 μm $\sim$ 0.5 μA

\[ j_{\text{string}} = f_{\text{pack}} \frac{J_{\text{cell}} V_{\text{cell}}}{V_{\text{load}}} \approx 1 \text{ A/m}^2 \]
SEP/HV Arrays and Spacecraft Interactions

- High Voltage Solar Array – Plasma Interactions have been studied for decades
  - Cells at negative potentials arc
  - Cells at positive potentials collect current

- Solar Arrays have successfully flown with voltages as high as 160 V

- Two approaches to Solar Electric Propulsion system designs
  - Conventional: Isolated electrically from solar array
  - Direct Drive: Cathode common connected to low side of the solar array
    - Advantages: Simpler & More efficient
    - Disadvantage: Requires higher voltage arrays

- Electric Propulsion Plasma Plumes interact with solar arrays
  - Currents collected by the arrays have been small
  - Higher voltage arrays will collect more current
  - Measures, such a grouting with RTV will limit current losses