Engineering Notes

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Where Do Negatively Biased Solar Arrays Arc?

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Introduction

THE ionospheric plasma, with densities up to several 10^6 cm^{-3} and thermal energies of the order of fractions of an electron volt, may provide a hostile environment for solar arrays operating at elevated voltages. The resulting failure modes may adversely influence or terminate their long-term functioning in orbit. Here, the effects of one such failure mode, namely the arcing of negatively biased solar arrays, will be considered.

If the layout of the solar cell strings or the firing of ion thrusters[1] produce predominantly positive potentials, as seen in the undisturbed plasma environment, then the electrons will basically determine the features of the interaction. The location of primary interest is clearly close to the biased interconnectors and the adjacent dielectric cover glasses (typically coated with the antireflection material MgF2).[2] Sheath formation around the interconnectors and surface charging of the dielectrics compete with each other to eventually generate strong electric fields at this interface. In this location the electric fields are sufficiently strong to allow for secondary emission.[3] Potential lenses[4] focus most of the primary particles toward the interconnector and cover glass edge. Thus, a current balance between impacting primary plasma electrons and emitted secondary electrons is established. These secondary particles contribute to enhanced leakage current. Electric fields at this location scale inversely with the degree of secondary emission.[5]

Negative potentials, rather than positive potentials, are, however, characteristic of the standard operation of solar arrays. The array voltage (with respect to the plasma chamber ground) adjusts to give a zero net current flow of plasma particles to the panel. Under such conditions, more than 90% of the solar array area is expected to be below plasma ground.[6] Arcing in this potential configuration is the dominant process that jeopardizes the operation of solar arrays. It is generally assumed that the electric fields near the negatively biased interconnector provide a triggering mechanism for anomalous processes in the interaction.[7] Based on a model for the cover glass/conductor interface, arcing can be understood as the breakdown of gas that is emitted under electron bombardment from the cover glass on the solar cells.[7]

The aim of this Note is to present experimental results from interaction experiments on negatively biased solar array modules that display new arcing features. The experiments were performed at a defined plasma density and with test samples only in the negative voltage range. Any degradation effect on the test sample is then related to this specific voltage regime.

Experimental Setup

A plasma with typical low-Earth orbit (LEO) plasma parameters was simulated in a large vacuum tank.[2] Plasma densities ranging from 10^4 to 5×10^6 cm^{-3} and temperatures between 0.1 and 1 eV can be generated by the plasma source. Plasma density gradients near the source decrease rapidly toward the center of the vacuum tank, where the plasma is basically uniform. Three different test samples consisting of 10 solar cells connected in series were tested. Sample 1 used 2×4 cm^2 solar cells. Sample 2 was identical to sample 1, except that the interconnectors were insulated by epoxy resin. Sample 3 consisted of 5×5 cm^2 solar cells. The test samples were exposed to the plasma environment, and a defined negative voltage was switched on. The actual circuit layout of our measurements has been described elsewhere.[2] Briefly, we established a current loop between the solar array test sample, the simulated LEO plasma, and the chamber ground. The measurement of the plasma current drawn by the biased test sample identified any anomaly resulting from the interaction. Simultaneously, the test sample was photographed from outside the vacuum tank through one of the windows. The picture was taken with a long exposure time of 30 s, which corresponded to the duration of the experiment. Thus, we were able to document all events during this time interval. Finally, the test sample was visually examined following the experiment.

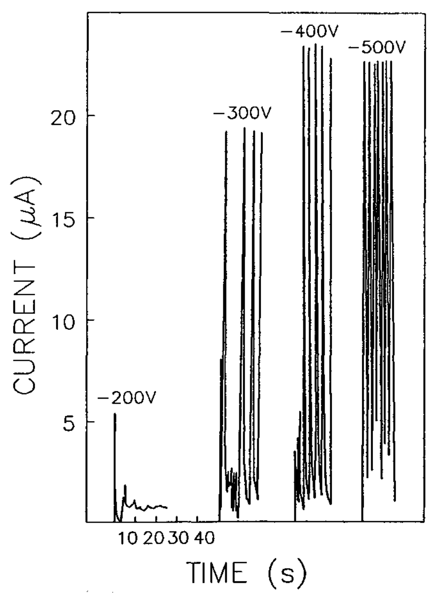

Fig. 1 Arc discharges as seen by a current vs time diagram for different applied voltages.

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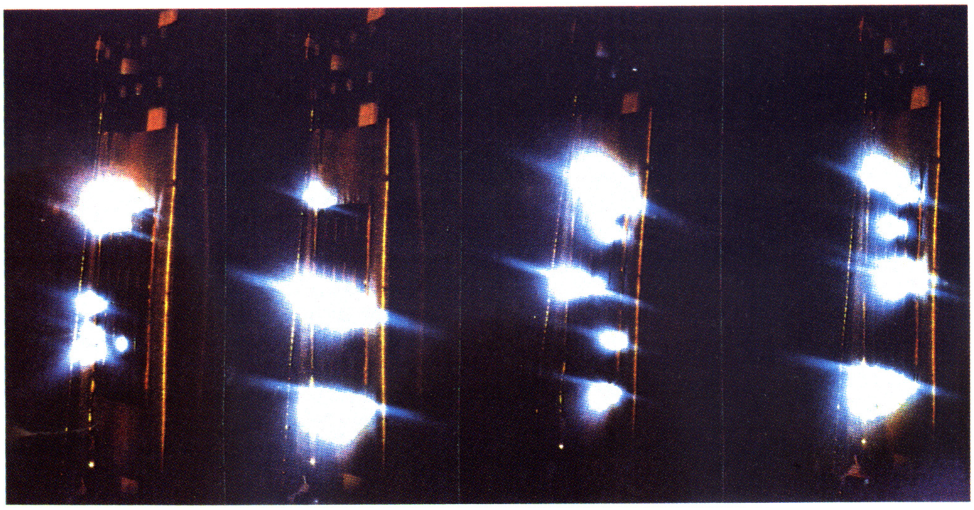

Fig. 2a Arcing observed on the front side of the test sample; applied voltages are −300 V (far left panel), −400 V (middle left panel), −500 V (middle right panel), and −600 V (far right panel).

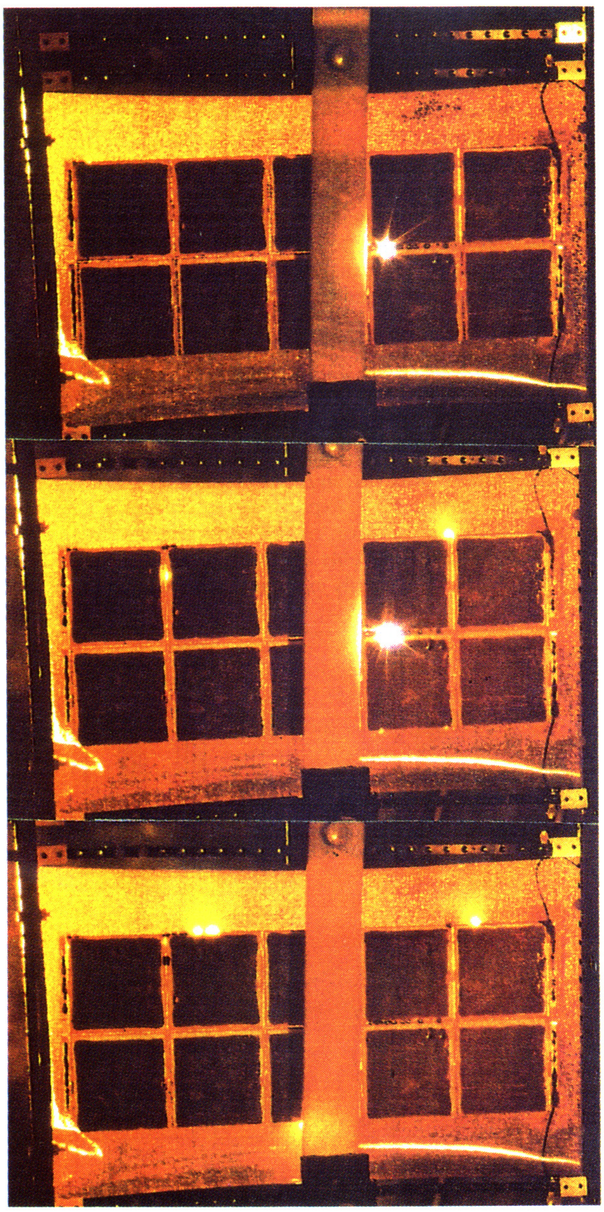

Fig. 2b Arcing observed on the rear side of the test sample at −300 V (top panel), −400 V (middle panel), and −500 V (bottom panel).

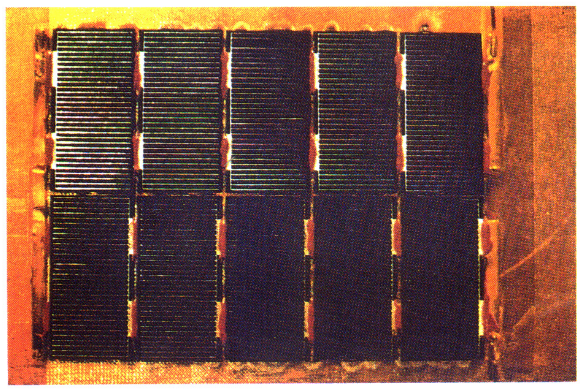

Fig. 3 Test sample after operation in the ion mode; carbonized spots are clearly visible predominantly along the solar cell edges.

Results

Experiments with all three test samples showed arcing effects for negative voltages. Typical current vs time plots are shown in Fig. 1 for sample 1. The curves show the current variation for different sample voltages. The equilibrium current value scales with the voltage and the density. Arcing is superimposed on the equilibrium value. It is identified by a sharp and transient increase in the current drain to the plasma. Arcing is an arbitrary process that occurs on a statistical basis. The experiments show that the occurrence frequency of arcing for a defined voltage is related to the magnitude of the applied voltage and the ambient plasma density. Long duration tests may even see arcing at lower voltages (e.g., −100 V) with a reduced occurrence frequency, but this requires verification by further tests.

Figure 2a is a photograph of test sample 2. The picture was taken through a side window of the plasma tank. Successive voltages of −300, −400, −500, and −600 V were applied to the side of the sample, which is directly exposed to the plasma stream. Using an exposure time of half a minute, all light flashes that occurred during the performance of the experiment for a fixed voltage were photographed. The current transients shown in Fig. 1 are always related to a single light flash at a certain location on the test sample. We never observed more than one arc at the same location. The photograph of sample 3 in Fig. 2b was taken from another window of the plasma facility. In this figure, we show the rear side of test sample 3. We note localized arc discharges at the solar cell edges. The occurrence frequency, however, is significantly reduced compared to that shown in Fig. 2a.

Figure 3 shows test sample 2 after testing. Note the dark spots on the Kapton substrate along the cell periphery. Carbonization spots accumulate with each arc discharge. These spots are more pronounced for the insulated interconnectors than for the exposed silver bus bars. Thus, our experiments emphasize the reduced importance of the fields around the interconnectors. The generation of new arc centers gradually leads to a continuous degradation of the Kapton. With the associated carbonization, the initial insulation property of the substrate is lost. Hence, a typical resistance measured between the interconnector and a carbonized and, thus, the conductive Kapton spot is less than 100 Ω. Hence, the long-term exposure of solar arrays under such conditions will lead to permanent short circuits and, eventually, a complete solar array power loss.

Summary

The results of our ground tests indicate a new failure mode in the negative voltage range. Our experiments showed local arcing at solar cell edges, and, hence, they differ substantially from other experiments, where arcing was observed near the interconnectors.[1,8] In our experiments, only three arcing events were identified close to the interconnectors. Since these locations also involved a part of the solar cell edge, the influence of the corresponding interconnectors on the arcing is uncertain.

The characteristics of arcing, as observed in our experiments, can be summarized as follows.

1) Arc discharges were mainly observed between the solar cell edge region and the Kapton foil starting at voltages of −200 V.

2) Within the duration of our experiments (30 s), there is a voltage and density dependent threshold for arcing.

3) Arc discharges only occur once at a given location.

4) With the onset of arcing, the whole test sample becomes more susceptible to arcing at lower voltages.

5) There is no information on arcing effects under long-term exposure conditions (longer than 30 s). However, our tests suggest the possibility of arcing for lower applied voltages with a reduced frequency.

An understanding of the interaction processes leading to arcing is far from complete. More experimental and theoretical work is needed. Experimentally, the long-term behavior at lower voltages (−150, −100 V) should be studied. High-time resolution measurements of the current transients related to arcing will allow the study of the structures of these processes in more detail.

Quantitative theoretical studies of negatively biased solar arrays in the LEO plasma environment are required. For a comprehensive picture of arcing phenomena, the electric fields in two regions on the solar array are of interest: 1) the negatively biased interconnector and the dielectric cover glasses (coated with MgF_2) of the adjacent solar cells and 2) the solar cell edge region involving the solar cell with cover glass material, the antireflection coating MgF_2, the semiconductive material, the biased metallic grid fingers, and the Kapton foil.

The capability of particle-in-cell simulations to elucidate array-plasma interactions has been shown for the positive voltage range.[3,4] Similar model calculations can be designed for negatively biased arrays. They require an appropriate formulation of the relevant electrical boundary conditions and the particle environment. For the actual case, it will also be necessary to systematically study the influence of secondary particle populations on the electric field distribution.

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Experimental Base Pressure Histories with Nonsteady Discrete Bleed Rates

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Nomenclature

D_N = nozzle diameter
D_S = shroud diameter
L = shroud length
M = nozzle exit Mach number
P_b = base pressure
P_0 = nozzle stagnation pressure
t = time
V_b = base additional volume

Introduction

INTERNAL and external base flows have been studied and reported extensively in the literature over the last 50 years, particularly at transonic and supersonic speeds. However, the vast majority of these studies involve steady conditions, either upstream of the separation point or at the base region.

There are flow situations in which unsteady conditions prevail, for example, nonsteady plume-wall interactions during

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