AN INVESTIGATION OF ARC DISCHARGING ON NEGATIVELY BIASED DIELECTRIC-CONDUCTOR SAMPLES IN A PLASMA*

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Proposals are now being developed for the construction of high-power photovoltaic systems for operation in low Earth orbit, where the plasma number density is about 10^3 to 10^6 per cm^3. Existing data indicate that interactions between the plasma and high-voltage surfaces of an orbiting power system will occur. In ground tests, where the applied voltage is increased negatively from ground, the array current collection shows an approximately linear rise until it terminates in arcing at greater than several hundred volts negative. This arcing may reduce the power generation efficiency and could possibly affect the low-level logic circuits of the spacecraft. Therefore it is important that the arcing phenomenon be well understood. This study is a survey of the behavior of different dielectric-conductor samples, including a solar cell module, that were biased negatively in a low-density plasma environment with the intent of defining arc discharge conditions and characteristics. Procedures and results are discussed.

INTRODUCTION

Recent proposals for the construction of large spacecraft to operate in low Earth orbit envision much greater power requirements than those of presently operating spacecraft. The employment of very large solar arrays has been suggested as a means of generating such power. These arrays may operate at higher voltages than have been previously used in order to reduce the mass of conductive materials.

Conventional solar array design exposes cell interconnects to the plasma environment of low Earth orbit, which can be as dense as 10^6 per cm^3. Ground and flight tests have shown the existence of interactions between array surfaces at high voltage and the surrounding plasma. For positive applied bias voltage a nonlinear current collection phenomenon known as "snapover" has been documented (ref. 1). For negative applied bias voltage, to be considered herein, recorded observations of solar arrays (e.g., ref. 2) include current transients and visible flashes of light, both referred to as "arcing." Although no effort to characterize these arcs in detail appears in the literature to date, there is agreement that arcs seem to occur on or near exposed metal surfaces of a solar cell array at bias voltages of -300 V or more (in this paper, "more" implies an increasing magnitude of negative voltage). If violent enough, these

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arcs could conceivably disrupt efficient power generation and low-level electronic circuit operation, as well as cause physical damage to the solar cells of an orbiting system. Therefore a thorough understanding of the arc phenomenon is vital for the successful design of large-scale photovoltaic power-generating systems.

In this investigation, dielectric-conductor samples of various configurations, including a solar cell module, were biased negatively in a plasma of known density. The test facility was a small vacuum chamber, equipped with an argon plasma source. Arcing behavior and its dependence on sample configuration, bias voltage, and plasma density were studied.

TEST FACILITY

Figure 1 shows the electrical circuit and a typical experiment configuration. The test chamber was a 46-cm-diameter by 81-cm-high steel bell jar evacuated with mechanical and oil diffusion pumps. Plasma was obtained by flowing argon gas past a hot tungsten-filament cathode located in an anode cylinder immersed in a magentic field. The source was mounted about 40 cm above the test samples and produced densities of 10^3 to 10^5 per cm^3. A 1.3-cm baffle at the exit aperture of the source diffused the emerging particles and prevented filament electrons and other particles in the source chamber from striking the samples directly. With the plasma source on, chamber pressures during testing ranged from 5×10^{-6} to 3×10^{-5} torr.

The test samples were mounted on electrically insulating rods. They were biased using two external, continuously variable voltage sources connected in series, giving an output of zero to -1000 V. Plasma characteristics data were obtained with a 1.91-cm-diameter spherical Langmuir probe connected to an automated data system. Surface potential profiles were made by using a noncontacting electrostatic potential probe. This probe senses a voltage by nulling the electric field between itself and a small area of test sample surface. The probe was mounted on a movable arm and its sensing surface was swept in a plane 2 to 5 mm above the test sample surfaces.

In the high-voltage electrical line from the voltage source, 21.1-MΩ series resistance was shunted by 0.0117-uF capacitance. Although some tests were run without the series resistance, it served to isolate the discharge process from the characteristics of the voltage source, as well as limit the current flow from the voltage source during arcing to protect the equipment. Collection current was monitored with a digital electrometer and an analog panel ammeter. A current pulse transformer detected transients in the high-voltage line between the capacitors and the sample. The transformer's output was fed to a waveform recorder, connected in turn to an oscilloscope, where the traces were photographed. Surface voltage profiles, test-sample applied bias voltage, and Langmuir probe current were recorded on a strip chart.

PROCEDURE

After the plasma source was allowed to stabilize and the plasma data were obtained, voltage was applied to a sample in 50- to 100-V increments, with a 3- to 10-min waiting period at each voltage. One to 2 min were generally required for collection current stabilization, although completely stable conditions were not reached in some solar cell array tests. Tests were also conducted by setting the bias voltage at a fixed value for an extended period of time. The longest test duration at a constant applied bias voltage with constant test conditions was 8 hr.

TEST SAMPLES

The samples tested are illustrated in figure 2. The disk/pinhole sample (fig. 2(a)) was a 10-cm-diameter fiberglass disk with a centered 5-cm-diameter electrode. The disk and electrode were completely covered with 0.0127-mm-thick Kapton insulation, except for a 0.8-mm-diameter "pinhole" in the center exposing the electrode. Tests were also conducted with wire strands inserted between the Kapton and the electrode and extending 5 to 10 mm beyond the disk's surface.

A four-solar-cell module (fig. 2(b)) of 2-cm by 4-cm cells was tested with the array output leads shorted together. Two separate tests were conducted with Kapton tape masking all but a small section of the cells and exposed interconnects.

Also examined was a 0.4-mm-base-diameter tapered tungsten pin protruding from a 10-cm-diameter fiberglass disk (fig. 2(c)). The disk covered a 5-cm-diameter, centered, concave electrode. The pin, attached to the electrode, extended through a 0.7-mm-diameter hole in the fiberglass to about 0.8 mm above the disk's surface. Thus metal touched dielectric only on the underside of the fiberglass at the edges of the concave electrode. The back side of the sample was covered with Kapton tape to prevent current collection on the rear surface. The same sample was also tested with a 3-cm by 2-cm piece of Kapton tape on the fiberglass surface. The tape was pierced by the pin so that the pin was in contact with the tape.

Finally, a 5-mm-diameter coaxial cable (RG 58B/U) was cut (fig. 2(d)) with the ground shielding stripped 1.5 cm away from the exposed surface to expose the copper center-conductor and surrounding insulation.

DISCUSSION AND RESULTS FOR INDIVIDUAL SAMPLES

Disk/Pinhole

Current collection rose linearly with voltage but rarely terminated in arcing for the plain pinhole sample. The few arcs that did occur were attributed to dust particles inside the hole. With the wire strands in place, arcs occurred regularly at an applied bias of about -500 V or more and were seen near or in the pinhole but not at the strand tips. The observations might suggest that sharp or discontinuous surfaces and close proximity of dielectric are requirements for arc discharging.

Solar Cell Array

In tests of the fully exposed (unmasked) solar array, arcing occurred at -300 V or more, and arcs were seen on all interconnects, although they tended to occur more frequently toward the outer edges of the array. The exposed area of the second masking test, located on an edge of the array, arced more often than the first, although the exposed metal area was roughly the same (fig. 2(b)).

During long constant-applied-bias-voltage tests, the discharge rate of the fully exposed array segment decreased with time (fig. 3). Perhaps arcs were blunting metal edges, rendering them less likely sites for future arcing. The arc rate appeared to reach some nonzero equilibrium value. However, longer tests are needed to determine this conclusively. The rapid decrease and subsequent rise in arc rate from about 20 to 75 min (fig. 3) may be the result of varying plasma characteristics early in the test.

Visible damage to the solar cell array as a result of arcing (fig. 4) appeared to be limited to a roughening of interconnect surfaces, mostly concentrated in spots near interconnect edges and protrusions. In addition, coloration of the interconnect surfaces occurred along the length of several interconnects. The coloration may be the result of vacuum pump oil contamination, although this is not certain. It is not known to what extent a film of oil might affect the test results.

With the 21.1-MΩ current-limiting series resistance removed, arcs were much brighter, exhibited larger peak currents, and were longer in duration. Damage to the interconnect surfaces was much more extensive and included regions where metal appeared to have melted and then resolidified (fig. 5). Coloration occurred and was also more pronounced and extensive than after tests with the large resistance in place.

Tungsten Pin/Disk

No arcing was observed with the plain pin/disk sample. However, with the Kapton in place, energetic discharges occurred at applied bias of -800 V or more. The difference in behavior with and without the Kapton (arcing versus no arcing) could be due to the differing dielectric properties of fiberglass and Kapton. Yet, based on aforementioned observations of the disk/pinhole sample, it is more likely that the dielectric must be very close to or actually touching an exposed conductor for arcing to occur. The intensity of the arcs and the high threshold voltage for the pin/disk, relative to those of the other samples tested, suggest that the sample configuration and the type of conductive material used play some role in the discharge mechanism.

Cable End

The cable end arced at applied bias of -400 V or more. Since the total insulation area was much less on this sample than on others, it can be deduced that a large dielectric area is not a requirement for arc discharging. Further exploration is needed to determine the nature of dielectric area dependence.

GENERAL ARC CHARACTERISTICS

Some general statements can be made concerning the discharge phenomena observed on all of the samples that arced when tested.

Arc Events

The observed discharges appeared to be blue point flashes that seemed to occur individually. The time between arc events was measured to be as short as 1 sec or less. Often, current collection appeared to be stable right up to the point of discharge, with stable collection resuming shortly afterward. This was excepted in certain cases of a high arcing rate (of the order of 1 arc/sec) when the steady state collection current was not well defined.

There was an approximately linear increase in collection current as the bias voltage was increased negatively, and discharges began to occur at some definite threshold voltage. As shown in figure 6, steady-state collection was measurable and continued to rise linearly at applied bias voltages greater than or equal to the arcing threshold voltage. The difference in the slopes of the masked solar cell array and pin/disk curves represents the difference in available collection area (exposed metal area) of the two samples.

Threshold Voltage

Each sample that arced did so at a slightly different initial threshold voltage, ranging from -300 V for the fully exposed solar cell array to -800 V for the tungsten pin/disk sample. In all cases the threshold voltage became more negative as the total arcing experience accumulated. For example, a sample with an initial threshold for arcing of -500-V applied bias, which was biased at -800 V for some time, would later exhibit arcs rarely, if at all, at -500 V. The data were not conclusive as to the effect of plasma density on threshold voltage, in part because of this variance in threshold voltage with accumulation of arcing.

Duration and Peak Current

Oscilloscope traces of current pulses were recorded during arc events on various samples. The traces (fig. 7) represent negative charge leaving the capacitors in the electrical system during an arc event. The arc duration was about 10 - 30 μsec with the 21.1-MΩ resistance in series, and greater than 1 msec without the resistance. Arc peak current was generally 0.5 to 2 A with the resistance, and about 40 A or more without it. The fact that arc peak current decreased with series resistance may indicate a cutoff point at which the available current would not be enough to sustain arcing.

Arc Rate

The arc rate increased with applied voltage and plasma density for the fully exposed solar array (fig. 8). This behavior was characteristic of all of the samples that arced. The arc rate decreased with time during long tests of the fully exposed solar cell module (fig. 3). This trend was also indicated during shorter tests of other samples. As stated earlier, longer tests are needed to determine conclusively whether the arc rate does indeed reach some nonzero equilibrium value.

Surface Voltage Profiles

Strip-chart records of typical surface potential profiles were obtained by sweeping the electrostatic probe (fig. 9). Characteristics of these profiles include large voltage readings over exposed metal regions and lower potential readings over dielectric areas. During the electrostatic probe's sweep, discharges would often occur as the probe moved over an exposed metal region. This behavior suggests that the probe could have induced some discharges. It is thought that localized solar cell arcs affect the surface potentials of the rest of an array (ref. 3). The potential profiles made in this investigation indicate that the test-sample response time to an arc event was probably shorter than the response times of the electrostatic probe and the strip chart.

In addition, the results show that arcs can occur not only on solar cell arrays, but also on other surfaces with exposed metal that are biased at high voltages in a plasma.

SUGGESTIONS FOR FURTHER STUDY

More data are needed to clarify the relationships of arc rate and threshold voltage to bias voltage and plasma density. Surface potentials and plasma behavior should be examined more closely. It must be discovered to what extent arcs physically affect the dielectric-conductor surfaces and current-voltage characteristics of a given test sample. A metal plate placed some distance above a test sample surface might show if and how much metal or dielectric is vaporized. Finally, since arcing is an optical as well as electrical phenomenon, spectral analysis of the discharges could provide valuable insights into arc mechanism and composition.

Of major concern is the comparative validity of results obtained by using a test rig containing shorted solar cell arrays that are biased with an external power supply rather than by using self-generated voltages. The difficulties that arise here are the introduction of the effects of the external supply's characteristics and the lack of the ability to examine the actual electronic behavior of the solar cells during arcing. Also, the test chamber's limited size (and the subsequent introduction of boundaries) probably affects the plasma behavior (e.g., wave propagation). However, this test setup does allow for visual and spectroscopic observation of arcs, which would probably not be possible during a simulated sunlight test because of the great intensity of ambient light in the test chamber.

CONCLUSIONS

This study confirms the results of previous studies that found that visible arcs occur on, or very near, the interconnects of solar cell arrays biased several hundred volts negative. The results show that arcing is not solely a solar array phenomenon, but that arcs can occur on other dielectric-conductor configurations as well. There are indications of geometrical, material, plasma density, and applied bias voltage dependence of the discharges. In addition, the arc behavior of a sample can be categorized by parameters that include arc rate, threshold voltage, duration, arc current, and optical intensity. Moreover, further study is required before the arc phenomenon will be adequately understood, and hence, before the limiting factors of arcing in the design of large high-power photovoltaic systems can be thoroughly assessed.

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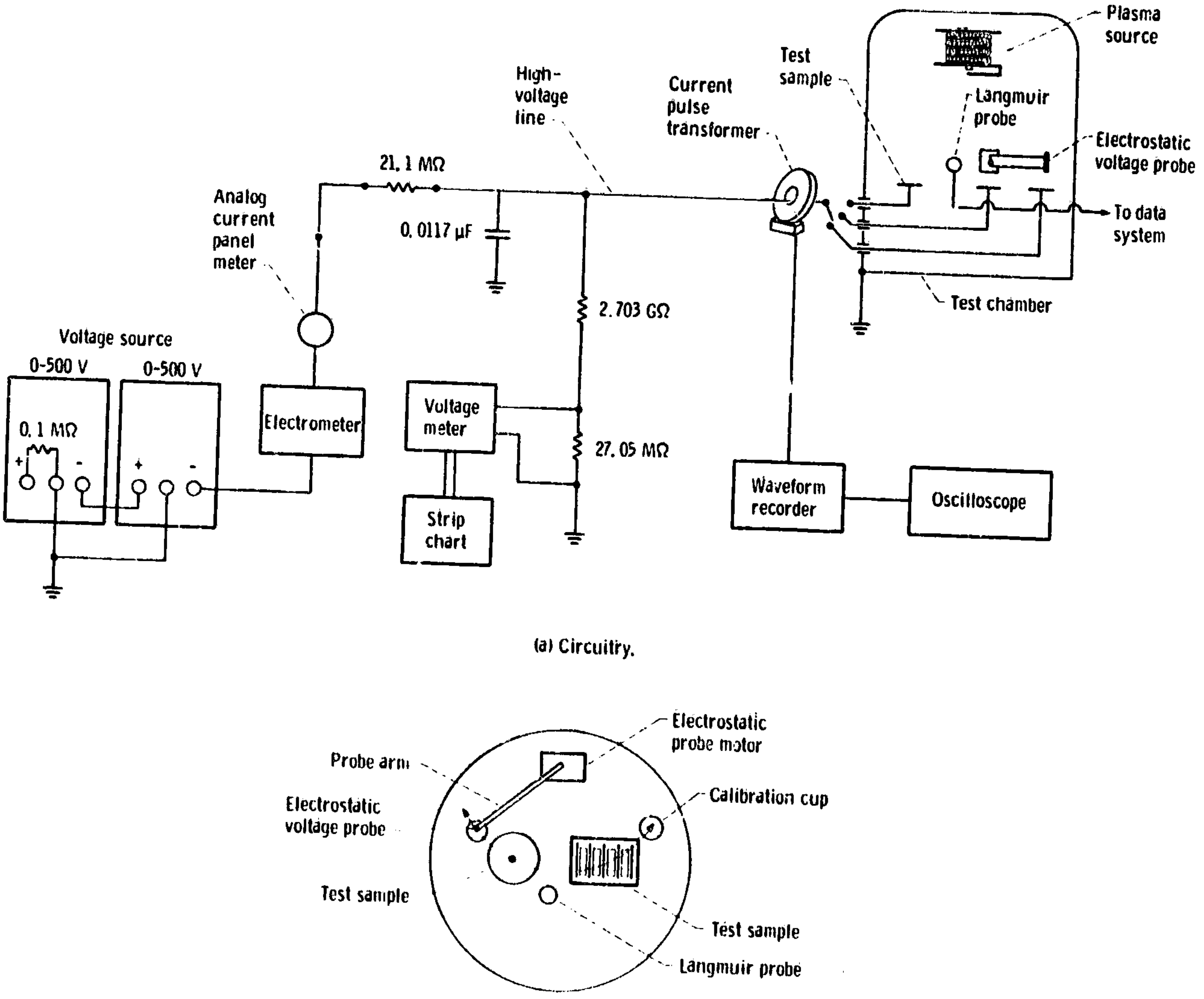
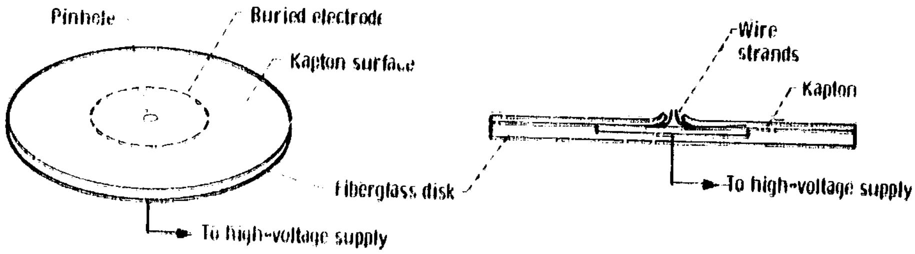


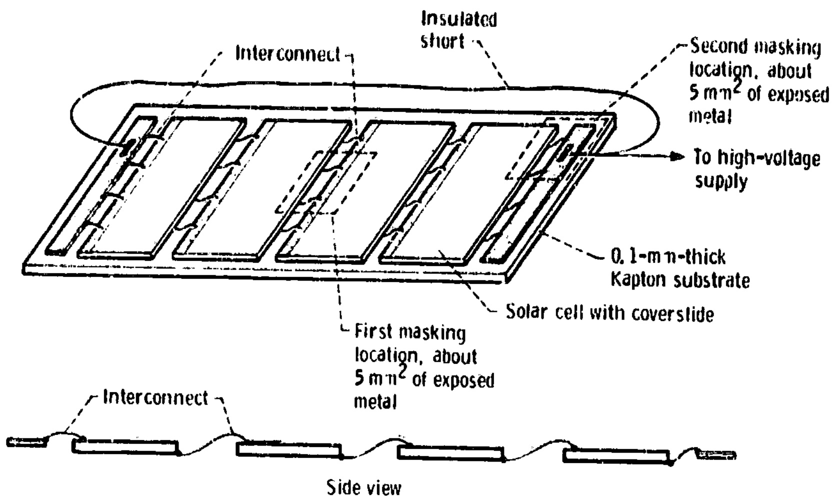
(a) Circuitry.

(b) Configuration and electrostatic probe path.

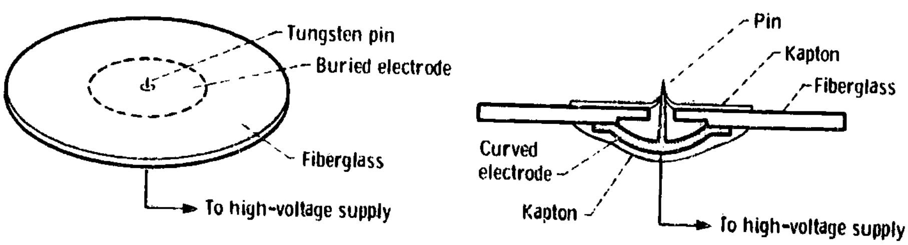
Figure 1. - Typical experiment circuitry and configuration.



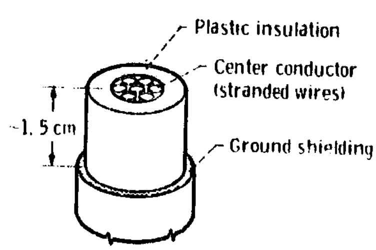
(a) Disk/pinhole.



(b) Solar cell module.



(c) Tungsten pin/disk.



(d) Cable end

Figure 2. - Test samples.

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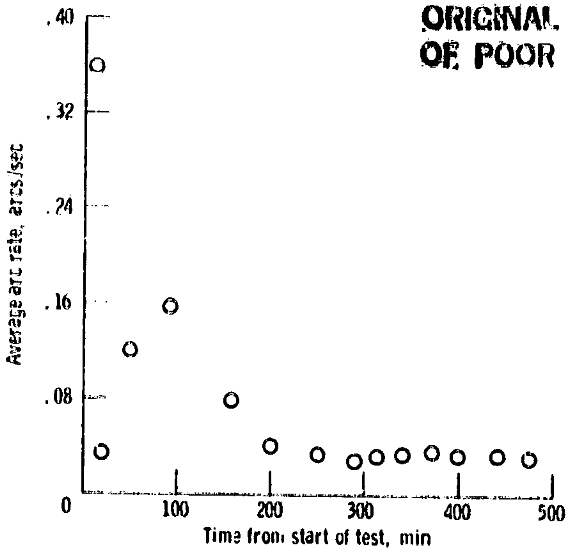
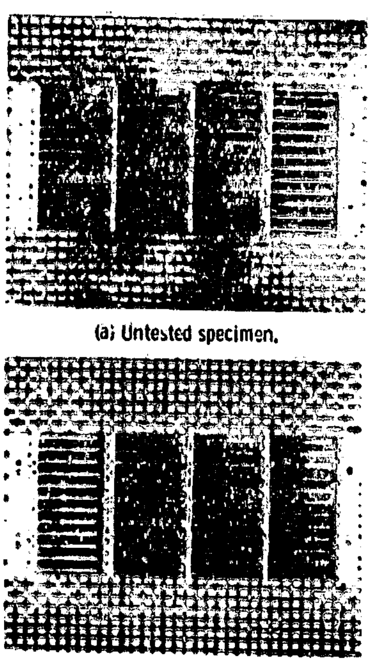


Figure 3. - Arc rate decrease during long constant-voltage test. Fully exposed solar cell module; applied bias voltage, -700 V; plasma number density, $N_e = 1.8 \times 10^5$ electrons/cm^3.



(a) Untested specimen.

(b) Tested specimen.

Figure 4. - Comparison of untested solar cell module and one that underwent extensive arcing tests without current-limiting resistance.

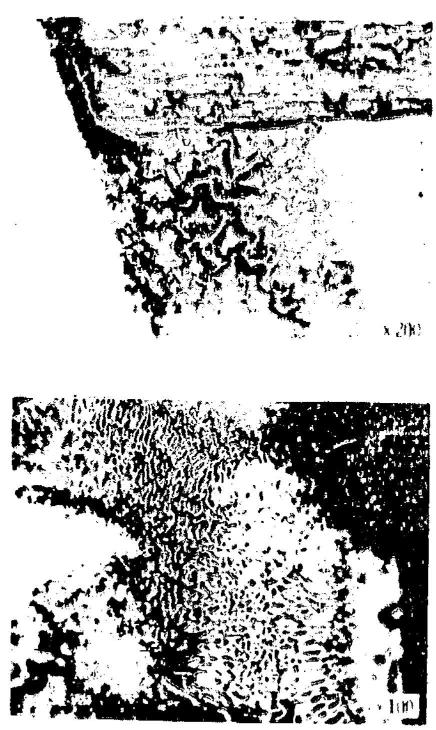


Figure 5. - Damage at two separate interconnect locations on fully exposed solar cell module after tests without current-limiting resistance.

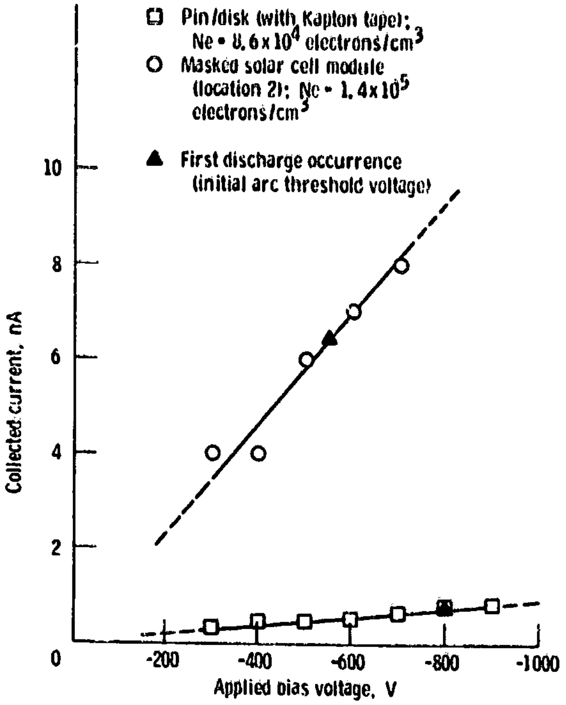
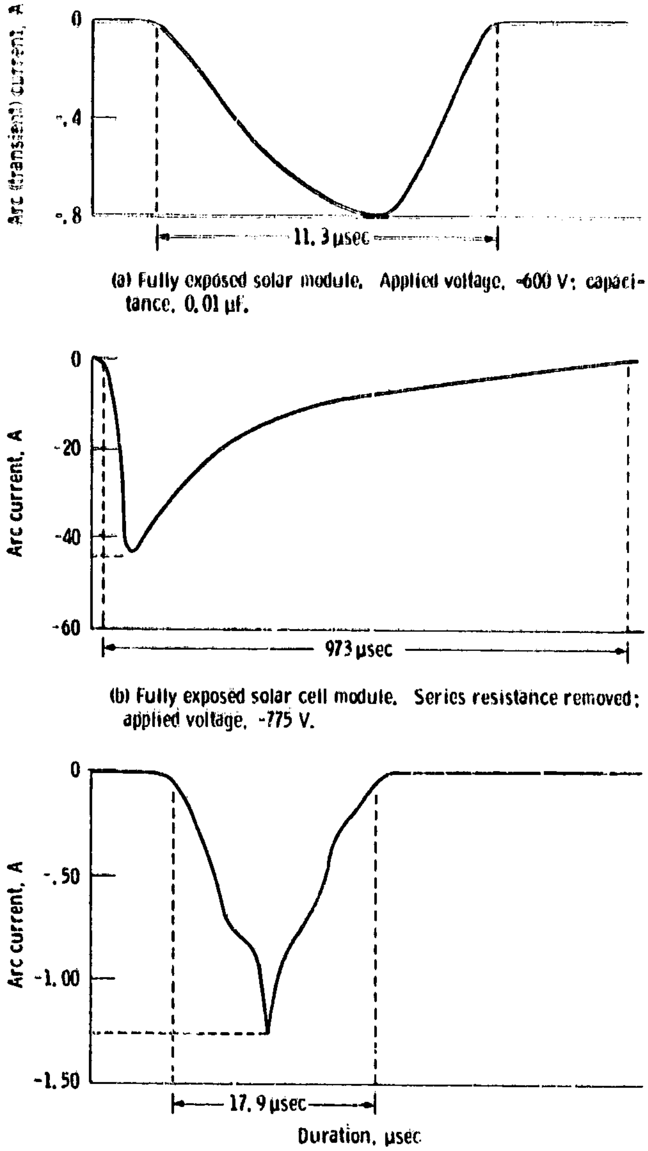


Figure 6. - Linear rise of collected current with applied bias. Voltage thresholds (initial arcs) are indicated.

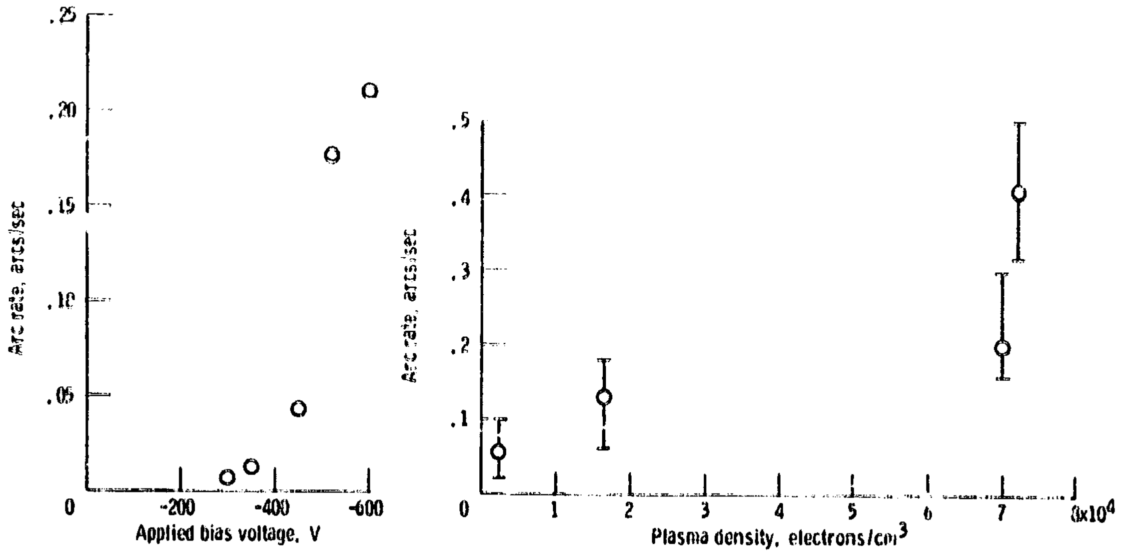


(a) Fully exposed solar module. Applied voltage, -600 V; capacitance, 0.01 μF.

(b) Fully exposed solar cell module. Series resistance removed; applied voltage, -775 V.

(c) Tungsten pin/disk with Kapton tape. Applied voltage, -800 V, capacitance, 0.01 μF.

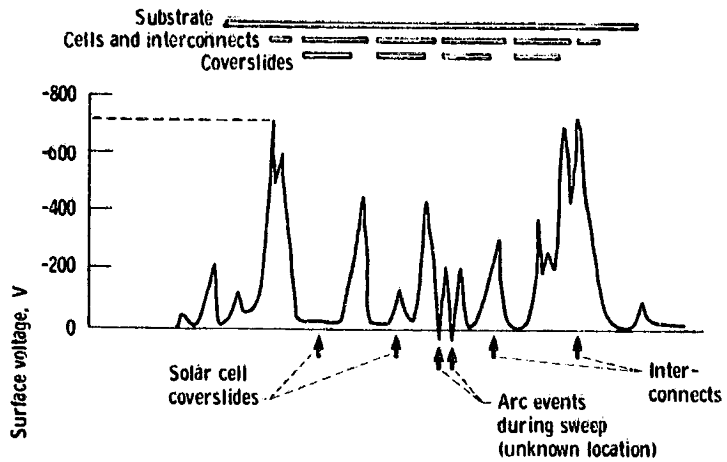
Figure 7. - Illustrations of oscilloscope traces recorded during arc events, showing peak current and duration of arcs.



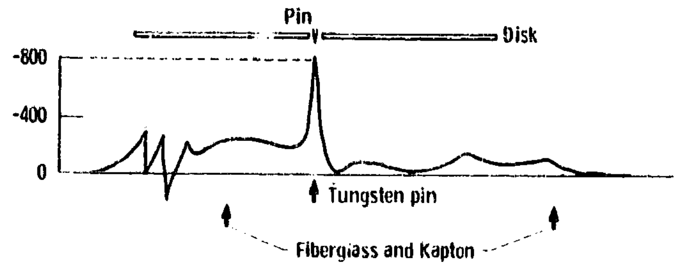
(a) With applied bias voltage. Ne = 1.64×10^5 electrons/cm³.

(b) With plasma density. Constant applied bias voltage, -6?? V.

Figure 8. - Arc rate increase for fully exposed solar cell module.



(a) Fully exposed solar cell (five interconnects and four cells).



(b) Pin/disk with Kapton tape.

Figure 9. - Surface voltage profiles made with sweeping electrostatic probe. Exposed metal regions at high voltages; dielectric at lower potentials.