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EXPERIMENTAL RESULTS ON PLASMA INTERACTIONS WITH LARGE SURFACES AT HIGH VOLTAGES

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Abstract

Future mission concepts envision payloads requiring multikilowatt power levels. Powers of this level can be more efficiently generated using solar arrays operating in the kilovolt range. This implies that large areas of the array at high operating voltages will be exposed to the space plasma environment. The resulting interactions of these high voltage surfaces with space plasma environments can seriously impact the performance of the satellite system. This study investigates the plasma-surface interaction phenomena using relatively large samples. The tests were performed in two separate vacuum chambers, a 4.6 m diameter by 19.2 m long chamber and a 20 m diameter by 27.4 m long chamber. The generated plasma density was approximately 1×10^4 cm^{-3}. Ten solar array panels, each with areas of 1400 cm^2 were used in the tests. Nine of the solar panels were tested as a composite unit in the form of a 3x3 solar panel matrix. The results from all the tests confirmed small sample tests results: insulators were found to enhance the plasma coupling current for high positive bias and arcing was found to occur at high negative bias.

Introduction

Future missions concepts envision very large, high power systems to be orbited in either low Earth orbit or at geosynchronous altitudes. These concepts embody solar array powers of 25 kW and higher. For these high levels of power, there must be an increase in the operating voltage from the present day level if the weight and harness losses are to be minimized. Operating voltages up to 45 kV have been proposed.[1] At such high voltage and power levels, large areas of solar array with kilovolts on them will be exposed to the plasma environment. The interaction of these high voltage surfaces with the space plasma can seriously impact the performance of the power system. Therefore detailed understanding of the surface-plasma interaction phenomena are required before these systems become feasible.

Previous plasma interaction studies were limited to small samples.[2-9] Used in these studies were samples that simulated the front side and pinhole imperfections on the back side of solar arrays. In some tests small solar array panels were used. All these samples were tested by biasing them with an external power supply and measuring the plasma coupling current. Two main results were found: (1) for positive bias voltages above about 100 volts on samples that have their electrode exposed to the plasma and surrounded by an insulator, have a leakage current that is greatly increased by the insulator, and (2) for the small solar array samples that were biased negatively, arcing to the plasma occurred for high bias voltages. These arcs were observed for bias voltages as low as 300 volts. Associated with these arcs were large surges of current which sometimes tripped off the power supply. If the large current for positive bias and arcing for negative bias continue to occur for large samples, then these may be the limiting factors for the operating voltages for the high voltage solar arrays of standard construction.

The present studies involved testing relatively large samples. An array consisting of nine 37 cm x 38 cm solar panels arranged to form a 3x3 solar panel matrix was used. In addition, three other samples were tested; (1) a single solar panel that was the same size as one of the panels in the 9-panel matrix; (2) a 61-cm diameter fiberglass disk with a 3.6 cm diameter electrode in its center; and (3) a 3.6 cm diameter electrode without any surrounding insulation. Except for the plain disk sample, these samples were much larger than any of the samples previously tested. To insure that the sheath that is formed around the samples at high voltages could expand without wall interference, the same samples were tested in a large vacuum facility at NASA Lewis Research Center (LeRC) and checked in a much larger vacuum facility at NASA Johnson Space Flight Center (JSC).

The results from these tests will aid in devising scaling laws for the current collection, help in determining the sample size limitation of the LeRC facility, and also help in determining whether the current enhancement and arcing is worse for very large solar arrays.

Test Samples

A 61-cm diameter disk with a 3.6 cm diameter electrode, a 3.6 cm diameter electrode without surrounding insulation, and 10 solar panels were used in the tests. A cross-sectional view of the fiberglass disk is shown in Fig. 1(a). The electrode was made of stainless steel and gold coated on top. All the solar array panels had 0.015 cm (6-mils) microsheet over each cell. Standard silver Z-bar interconnect construction was used between the cells (fig. 1(b)). These interconnects were left bare and served as the current collection areas on the solar array panels. The solar panels were constructed to flight specifications and originally served as back-up panels or were used in qualification testing for either the Space Electric Rocket Test (SERT) II or the Space Plasma High Voltage Interaction Experiment (SPHINX) satellite. There were eight SERT II type panels each approximately 1400 cm^2, and two SPHINX type panels each consisting of approximately 1950 cm^2. The interconnect area correspond to about 10 percent of the total panel area in each case. The SERT II type consisted of 370 2x2 cm N/P solar cells and the SPHINX type consisted of 640 1x2 N/P solar cells.

Nine panels, seven SERT II type and two SPHINX type, were mounted on an aluminum grating structure

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to form a 3x3 matrix of solar array panels. The panels in this matrix will be referred to by panel number as shown in Fig. 1(c). The panels were electrically isolated from the aluminum grating using 1.9 cm long ceramic isolators. A picture of the 9-panel array, the 61 cm fiberglass disk, and the single solar array panel mounted in the LeRC facility is shown in Fig. 2. Both the positive and negative terminals on each panel were brought to a terminal strip outside the vacuum chamber. This allowed any series or parallel connections or groupings of the panels to be achieved. This also allowed the current to each individual panel or to a particular group of panels to be measured.

Another solar array panel, a SERT II type, was tested singly. A comparison of the data from this panel with that of the 9-panel array shows the effect of the surrounding panels on the collection current.

Facilities

The tests were performed in two different vacuum facilities, one located at NASA LeRC and the other located at NASA JSC. The vacuum facility at LeRC was 4.6 m in diameter and 19.2 m long. The vacuum chamber at JSC was 20 m in diameter and 27.4 m long. In each facility the ambient pressure was approximately 5×10^{-6} torr. In the LeRC facility the 9-panel matrix faced axially and the single solar panel and the disk faced radially when mounted in the chamber as shown in Fig. 2. At JSC all panels, including the 9-panel matrix, faced radially toward the center of the chamber (fig. 3). These were mounted on a ring whose circumference was located about 9.1 m from the chamber floor and 3 m from the vertical side wall.

The plasma at JSC was generated from a 30 cm diameter Kaufman ion thruster using argon gas. The accelerating and decelerating grids on the thruster were left floating. Operating the thruster in this manner, the thruster was capable of generating plasma densities from 10^4 to 10^6 cm^{-3}. The source was located in the center of the floor of the chamber.

At LeRC the plasma was generated using a Pennington type discharge tube. This source was capable of generating plasma densities up to 10^5 cm^{-3}. A cross sectional view of this plasma source is shown in Fig. 4. The source was operated with an anode voltage of 50 volts. A baffle was used to spread the plasma throughout the chamber. This baffle also prevented any line of sight between the samples and cathode filament of the source. Both argon and nitrogen gases were used in this source. In both facilities Langmuir spheres were used to diagnose the plasma.

In some of the tests at JSC, a solar simulator was used in testing the 9-panel solar matrix. The simulator consisted of two circular beam carbon arcs mounted on the side wall opposite the 9-panel matrix sample. The arcs were adjusted for an intensity of one solar constant at the panel location. All panels were fully illuminated except for two small triangular shaped areas on panels number 2 and 8 in the matrix. These triangular areas were the areas left from using two circular arc lamps to illuminate the square shaped area of the 9-panel matrix. No solar simulation was used in the LeRC tests.

Procedure

All the tests except some of those with illumination at JSC were performed by externally biasing the samples. The voltage was slowly increased while the current was measured with an electrometer between the power supply and the sample. Both positive and negative biases were used in the tests. The bias voltages applied to the array were in the range ±1 kV (less if the power supply tripped). The disks were biased to ±2.5 kV. For the solar simulation tests the 9-panel matrix was tested floating, grounded, and biased with an external power supply. With illumination the 9-panel matrix had an open circuit voltage of 260 V and a short circuit current of 43 mA. This low short circuit current was probably due to two of the panels in the series not being fully illuminated.

Results and Discussion

Positive Bias

Disk experiments. The plasma coupling current as a function of positive applied voltage for the 61-cm diameter fiberglass disk is shown in Fig. 5. Two tests are shown for the LeRC facility, one with argon plasma and the other with nitrogen plasma. As can be seen the type of gas makes no discernable difference. The JSC tests were run only in an argon plasma. From Fig. 5 it is seen that there is a large variation in the data for voltages below 200 V. In both the LeRC tests, the coupling currents were approximately an order of magnitude lower than JSC test data in the low voltage range. Although this difference is rather large, no significance can be placed on it since differences of this magnitude have also been observed between different runs at LeRC.

The large increase in current seen for voltages between 100 and 500 volts is due to the insulator surrounding the electrode (area effect).[3-5] In order to see clearly the effect of the insulator, the plain disk and the 61 cm diameter samples results are shown in Fig. 6. In addition, the ground test data for the kapton disk experiment for the PIX satellite[2] are also shown on this figure. The kapton disk sample was of the same type construction as the fiberglass disk except for a sheet of 0.0127 cm thick kapton was used to cover the top of the fiberglass substrate. The kapton disk was 20.3 cm in diameter with a gold coated electrode the same size as those in the present tests. From this figure, it is seen that the kapton disk and the fiberglass disk results are very close at the high voltages. The current collected is approximately 6.5 times higher than those for the plain disk in this voltage range. A simple probe calculation indicates that the effective electrode area for the disks with insulation is about 310 cm^2. Thus the dominant effect of the surrounding insulator on current collection apparently occurs within a radius of approximately 10 cm or a distance of 8.2 cm beyond the electrode. Also from Figs. 5 and 6, it is noticed that after the current has made its jump, it varies approximately linearly with voltage thereafter. According to probe theory this type of variation occurs for constant probe areas. This implies that for the fiberglass disk and kapton disk samples, after the current has made its jump the effective current collection area remain constant with voltage.

For voltages below 100 volts the plain disk results are higher than the fiberglass and the kapton disks results. This agrees with previously found results that insulators suppress electron current collection at low voltages.

Single solar array panel. The electrodes for the solar panels are the interconnecting tabs between each solar cell. Therefore surrounding the electrodes are the insulating cover glass of each solar cell. The plasma coupling current-voltage characteristics for the single solar panel is shown in Fig. 7. A large variation in the data from run to run for voltages below 100 V are observed for this sample also. Factors causing the large irreproducibility in the data in this voltage range have not been investigated. It is known that the surrounding insulator causes a suppression in electron collection. The same insulator causes an enhancement of the current at higher voltages as can be seen from the steep rise in current for voltages between 100 and 300 volts. At higher voltages, the current rises linearly with voltage indicating the whole array is collecting current as a solid electrode.

In the JSC tests, an unusual phenomenon occurred. When the voltage was raised above 400 V, an oscillating glow type discharge occurred between the panel and the surrounding plasma. The current increased by a factor of hundred or more and was very unstable. This caused the power supply to trip off and so the test was terminated. This type of discharge has not been observed in the LeRC facility.

Nine panel solar array matrix. The current voltage characteristics for the 9-panel array is shown in Fig. 8 for tests performed at LeRC and JSC. The current increases rather steeply, with voltage up to a voltage of approximately 200 V. Above 200 V the increase is more gradual and is less than linear. This less than linear increase in current is as expected since for this size panel the current collection is beginning to approach that for an infinite plane. For an infinite plane the current is constant since the current is at most the thermal flux hitting the sheath boundary.

In the JSC chamber the 9-panel array also went into a glow discharge mode at voltages above 200 volts. In this mode a bright glow appeared over all nine panels and the current was larger than the 20 mA limit of the power supply. This type of discharge was observed for all positive bias run in the JSCS chamber but was never observed in the LeRC chamber. In order to rule out the possibility that the pressure in the vicinity of the panel was much higher in the JSC chamber than in the LeRC chamber, argon gas was bled into LeRC chamber to increase the pressure to approximately 8×10^{-5} torr. Testing at this pressure still did not produce the discharges. The cause of these discharges remain unexplained.

In order to see the voltage profile across the panel, a Treck electrostatic surface voltage probe was swept across panels 2, 5, and 8 at a distance about 0.3 cm from the cell surfaces. The voltage sweep was made in both the LeRC and the JSC chambers. At the low voltages, that is, before the current makes its jump, the voltage is limited only to the interconnecting tabs between solar cells. The profile is similar to that shown in Fig. 9 for negative bias except that the peaks are positive. At the high voltages, that is, after the current jump, the whole array is essentially at the applied voltage or slightly below it. A positive voltage trace obtained in the LeRC chamber when the array is at 500 volts is also shown in Fig. 9. As can be seen, the whole array is approximately 50 volts below the applied 500 volts. The large current at the high voltages are, therefore, caused by the whole array surface attracting electrons.

The 9-panel array was also tested under an illumination of one solar constant generated using the carbon arc solar simulator in the JSC facility. With all panels in series, an open circuit voltage of 260 volts and a short circuit current of 43 mA was measured. The sequence of the series connection was 1-2-3-6-5-4-7-8-9 with panel 9 being the low end. The current flowing through each panel of the series when the 9-panel array was floating and grounded are shown in Fig. 10. Also shown in the figure for the floating case are the value of the voltage with respect to ground on the high voltage side of each panel. It is seen that the zero voltage point is located somewhere in panel 2. Parts of the 9-panel array float up to 45 volts positive and 203 volts negative with respect to ground. This agrees with the statement generally assumed that most of a floating array in space would be negative with respect to plasma potential. When the array is grounded, approximately 12 mA of current is passing through the array. This is comparable to the current collected at 300 volts with an external voltage power supply.

The 9-panel array was also biased with an external power supply connected to panel 9. The results are shown in Fig. 11. Also shown in Fig. 11 are the results for the panel in the dark. With illumination, discharging occurred above a bias of 100 volts, causing the power supply to trip off. Since the solar array itself generates over 200 volts, the voltage for this discharge is over 300 volts which is comparable to the value observed in the dark. Comparing the results with illumination with those obtained in the dark shows that the insulator area effect is active with the internal generated voltage of the array.

Negative Bias

Disk experiment. The coupling currents versus applied voltage for both disk experiments are shown in Fig. 12. As can be seen the current is almost linear, with voltage for both the plain disk and the 61-cm diameter fiberglass disk. The plain disk current is about a factor of three higher than the fiberglass disk current. This implies that the large fiberglass insulator surrounding the electrode tends to suppress the ion current to the electrode. This result was not observed in previous tests with smaller samples.

Solar array experiments. The coupling currents versus applied voltage for the solar array experiments are shown in Fig. 13. For the single array arcing occurred for voltages higher than 150 volts and for the 9-panel array arcing occurred for voltages higher than 250 volts. These arcs are point blowoff type discharges. Electrons seem to be blown off into the plasma at different points on the array. During arcing there was always a steep rise in current and it was very unstable.

From Fig. 13 it is also noticed that the coupling current for the 9-panel array rises more gradually than that for the single panel array. This is probably because this large size array tends to collect like an infinite plane.

The surface voltage trace for a negative bias of 500 volts on the 9-panel array is shown in Fig. 9. Unlike the case for positive bias at this voltage level, only the interconnecting tabs are at the applied voltage. The solar cell coverslides remain essentially at zero volts.

Concluding Remarks

Three samples were tested in a plasma of approximately 1×10^4 el/cm^3 in this investigation; (1) a single solar panel of approximately 1400 cm^2, (2) a matrix of nine single panels each consisting of approximately 1400 cm^2, and (3) a 61 cm diameter fiberglass disk with a 3.6 cm diameter electrode in its center. Each of these samples was biased positive and negative to 1 kV or until arcing occurred.

For positive bias, all three samples with insulators showed that the insulator strongly increases the electron current. For all of these samples, there was a steep rise in current for voltages between 100 and 500 volts. Above 500 volts, the current increase was dependent on the size of the sample. For the disk and single array experiments, the current rose almost linearly with voltages above 500 volts. For the 9-panel array the current was tending toward that expected for an infinite plane, that is, the current increased less than linearly with voltage. Also for positive bias, the disk experiment showed that most of the influence of the insulator was limited to a distance less than 10 cm from the edge of the electrode.

In the large vacuum chamber at JSC for positive biases on the solar array samples, a glow type discharge occurred over the arrays. This discharge was not observed in the smaller chamber at LeRC and could not be initiated by increasing the pressure of argon in the smaller chamber. This phenomenon needs to be investigated further to see whether it is real for space conditions or is peculiar only to some ground facilities.

For negative bias, the most serious phenomenon observed was blowoff type arc discharge occurring on the solar arrays. These arcs have been observed for all size solar arrays. The arcs are not peculiar to facility size or type of gas used to generate the plasma. However, in the voltage range where arcs did not occur, the current was low, varied linearly with voltage, and may be retarded rather than enhanced by the insulator. Therefore, solar arrays operating in this voltage range should not experience any adverse effects.

Current collected by a solar array that is generating its own voltage under illumination is similar to that for an array using an external power supply. This implies that if the physical configuration of an array could be simulated, then reliable plasma testing could be carried out using external power supplies.

Finally, except for the glow type discharges for positively biased solar arrays, the results show that 15-foot diameter chambers are adequate for testing samples of one square meter at voltages up to 1 kV.

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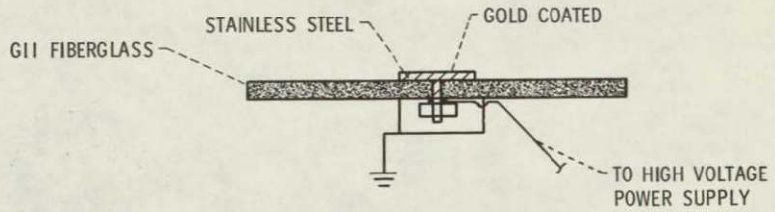
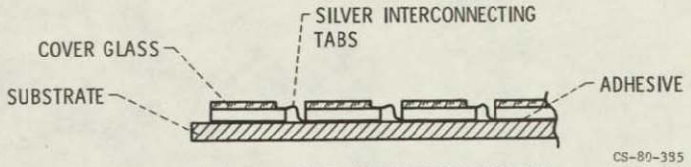


(a) 61 cm DIAMETER FIBERGLASS DISK.



(b) TYPICAL SOLAR ARRAY CONSTRUCTION.

1	2	3
4	6	5
7	8	9

(c) PANEL NUMBERING
FOR NINE-PANEL
SOLAR ARRAY MATRIX.

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Figure 1. - Typical solar array construction.

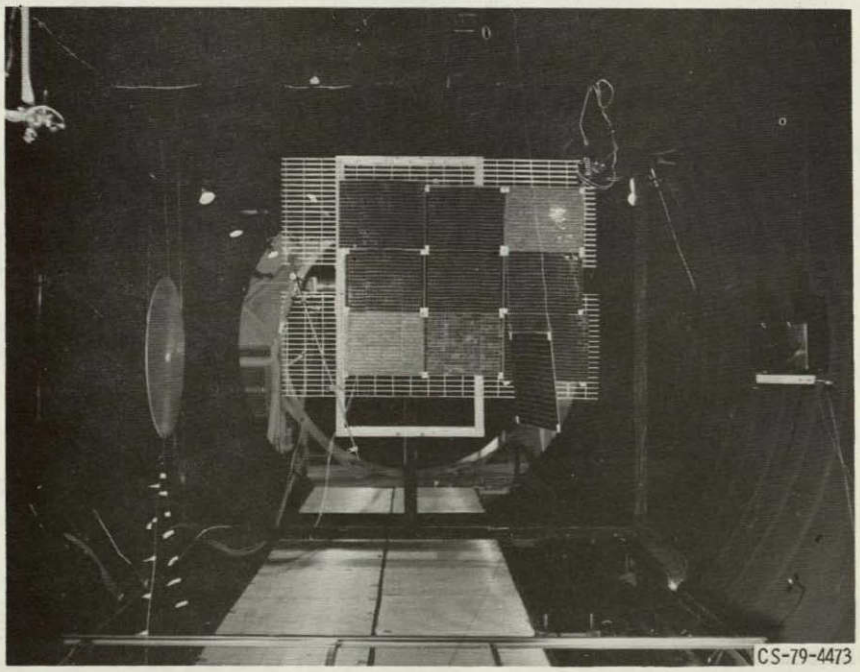

Figure 2. - Experimental set-up in Lewis Research facility (LeRC).

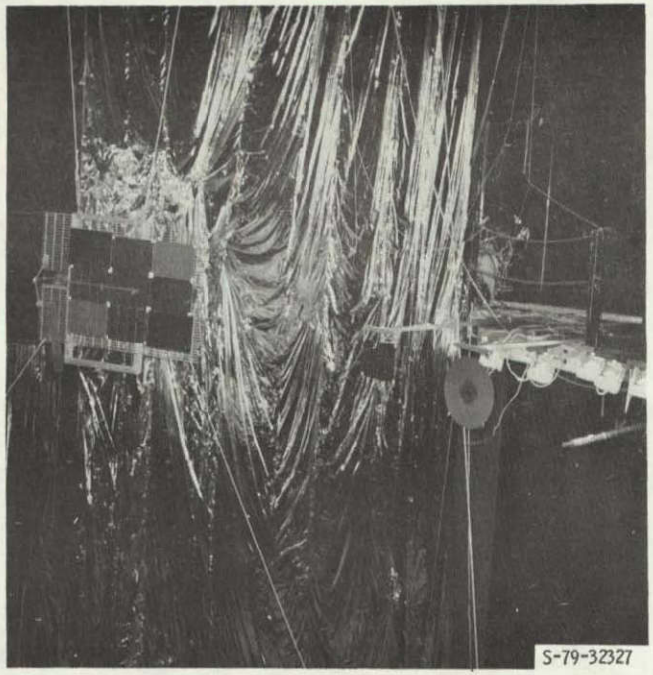

Figure 3. - Experimental setup in Johnson Spaceflight Center (JSC).

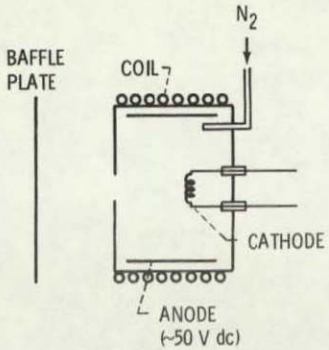

Figure 4. - Plasma generating source for LeRC facility.

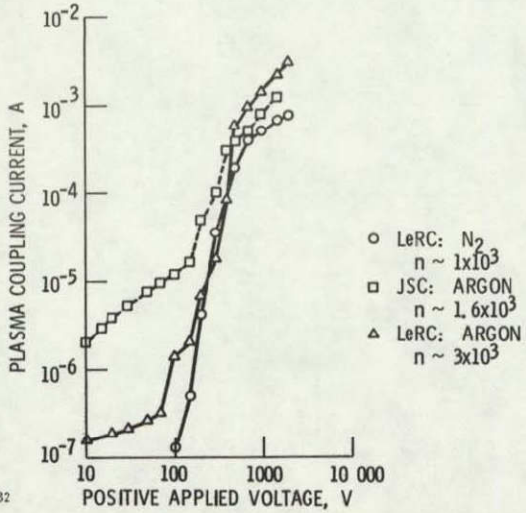

Figure 5. - Plasma coupling current versus positive applied voltage for the 61-cm fiberglass disk.

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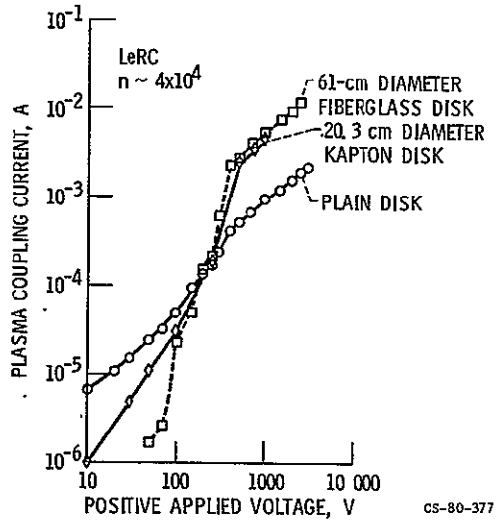

Figure 6. - Comparison of the plasma current for different disk sample as a function of positive applied voltage.

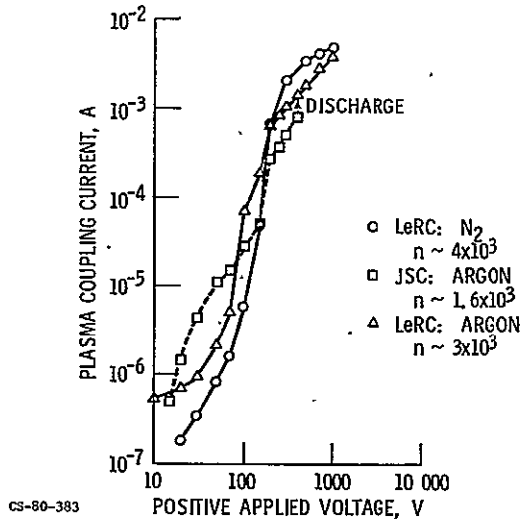

Figure 7. - Plasma coupling current as a function of positive applied voltage for the single panel array.

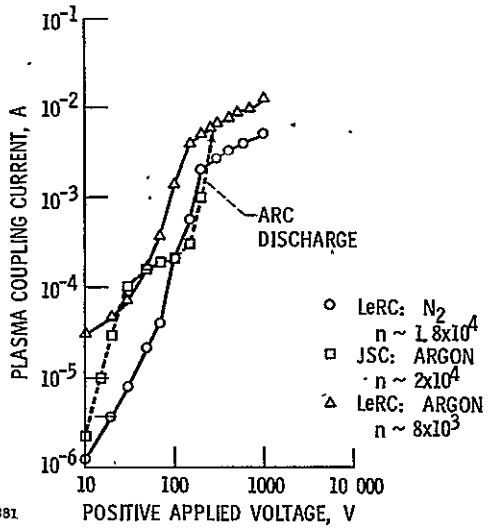

Figure 8. - Plasma coupling current as a function of applied positive voltage for the nine-panel solar array.

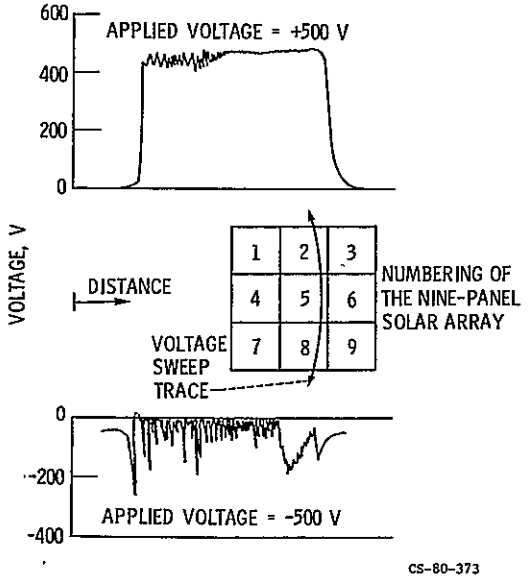

Figure 9. - Typical surface voltage profiles across three solar panels in the nine-panel solar matrix.

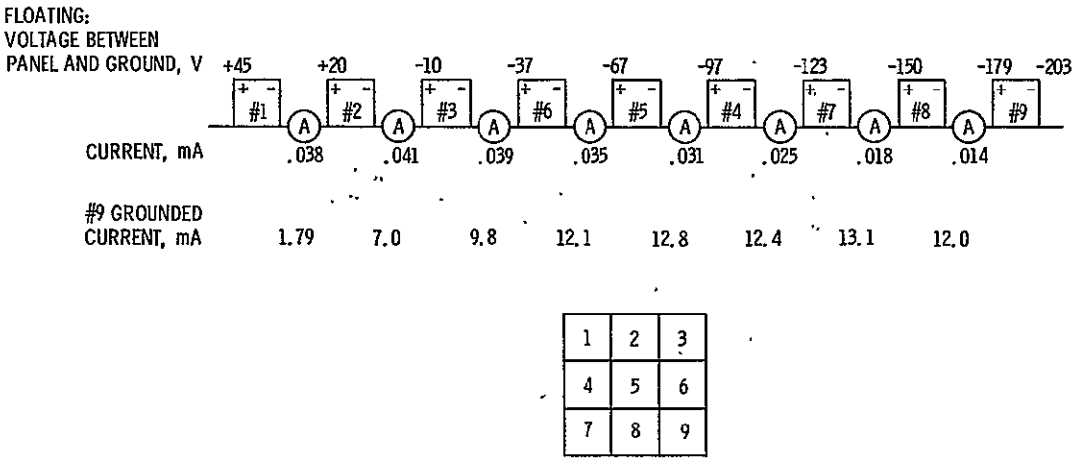

Figure 10. - Current passing between each solar panel of the nine-panel matrix when fully illuminated, floating, and grounded.

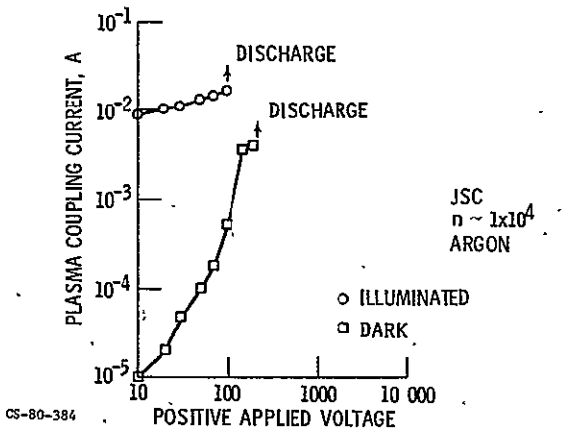

Figure 11. - Plasma coupling current as a function of applied voltage for the nine-panel array in dark and fully illuminated.

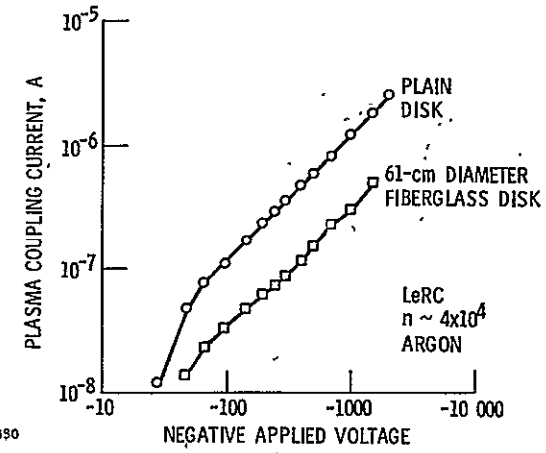

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Figure 12. - Plasma coupling current as a function of negative applied voltage for the disks samples.

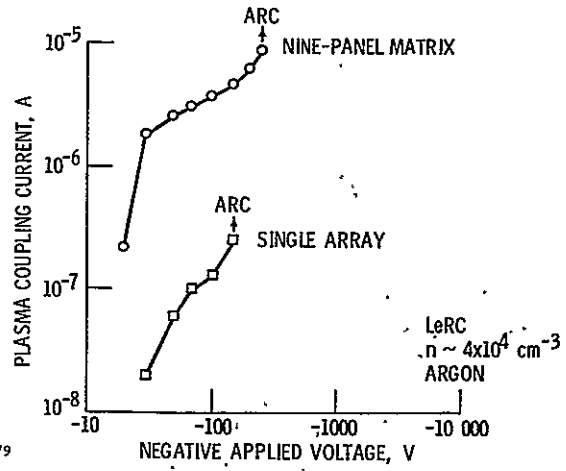

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Figure 13. - Plasma coupling current as a function of negative applied voltage for the solar array samples.

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