PLASMA INTERACTIONS WITH SOLAR ARRAYS AT HIGH VOLTAGES

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SUMMARY

The problems associated with operating solar arrays at high positive and negative voltages have been investigated at Lewis for several years. These studies have shown that, for arrays biased positively with respect to plasma potential, plasma coupling currents to the array are greatly enhanced by the insulators surrounding current collection points. For arrays biased negatively, arcing occurs at threshold voltages that depend on the plasma densities. This current enhancement and arcing were verified both in ground and space testing for small arrays (~100 cm^2). Extension of these results to the larger arrays proposed for future missions becomes difficult to verify in ground tests because the sheath generated around a larger surface may extend to the vacuum chamber wall. Scaling laws are therefore required. Scaling from small laboratory-size arrays to large kilowatt and gigawatt power arrays is not reasonable. So the approach taken in this preliminary investigation is to obtain results and devise scaling laws for arrays that can be tested in ground-based space simulation facilities. This report presents preliminary results for tests conducted on solar arrays with areas ranging from approximately 100 to 13 700 cm^2 in a plasma density of roughly 1×10^4 electron/cm^3. The plasma coupling current for the small array (~100 cm^2) did not scale linearly to current for the larger arrays.

INTRODUCTION

The problems associated with operating solar arrays in the kilovolt range have been investigated extensively for several years (refs. 1 to 9). Most of these investigations were carried out on small arrays in relatively small vacuum chambers. Future satellites will require kilowatts to gigawatts of power, necessitating solar arrays of meters to kilometers in length. These arrays will operate at much higher voltages than present arrays. Operating voltages to 45 kilovolts have been proposed (ref. 10). At such high voltage and power levels, large areas of the solar array operating at kilovolts will be exposed to the plasma environment. The interaction of these high-voltage surfaces with the ambient plasma must be understood before these large arrays become operational.

Testing of small arrays in plasma environments has revealed that, if the array is biased positively with respect to the plasma, the electron current coupling the ambient plasma to the array is tens to hundreds of times larger than would be calculated from simple probe theory. If the array is biased negatively with respect to the plasma, blowoff arc discharges cause large current surges in the array harness. Testing for these interaction phenomena on full-scale kilowatt and gigawatt power arrays is impossible in present laboratory plasma simulation facilities. Scaling laws are therefore required.

Scaling from small laboratory-size arrays to large kilowatt and gigawatt power arrays is not reasonable. Thus the approach taken at the Lewis Research Center is to devise scaling laws from arrays that can be tested in ground simulation facilities and then to substantiate these results, where possible, with flight data.

This report presents preliminary results for tests conducted on solar arrays with areas of approximately 100, 400, 800, 1200, 1600, 2000, and 13 700 square centimeters in a plasma density of roughly 1×10^4 electrons/cm^3. The array was externally biased in steps to ±1 kilovolt. Four 400-square-centimeter arrays that can be operated independently or in combination to give areas of 400, 800, 1200, or 1600 square centimeters are scheduled to be tested on a flight in mid-1982.

EXPERIMENTAL SAMPLES

All the arrays had 2- by 2-centimeter solar cells with 6-mil-thick fused silica glass covering each individual solar cell. The conventional Z-bar interconnections were left uncovered. The interconnections served as the electrodes for collecting charges from the plasma. They represented approximately 5 percent of the total array area. The 100-square-centimeter array consisted of 24 solar cells arranged as a 6- by 4-cell matrix. The 2000-square-centimeter array consisted of 414 solar cells arranged in a 23- by 18-cell matrix. Three columns (18 cells in each column) were removed from another similar 2000-square-centimeter array to form four independent array segments of 400 square centimeters each. The 400-, 800-, 1200-, and 1600-square-centimeter arrays were combinations of these segments. The approximately 13 700-square-centimeter array was formed by arranging seven 1400-square-centimeter solar array panels and two 2000-square-centimeter solar array panels to give one large 3- by 3-matrix solar array panel. This array was tested as a single unit.

PROCEDURE

All the solar panels except the 13 700-square-centimeter array were tested in a 2.4-meter-diameter by 3-meter-long vacuum chamber. The 13 700-square-centimeter solar array was tested in the 20-meter-diameter by 27.4-meter-long vacuum chamber at the NASA Johnson Space Flight Center, as well as in a 4.6-meter-diameter by 19.2-meter-long vacuum chamber at the NASA Lewis Research Center. A more detailed description of the 13 700-square-centimeter solar array tests is given in reference 9.

The plasma was generated by bleeding argon gas into a 5-centimeter-diameter by 7-centimeter-long discharge chamber. The argon was ionized by electrons emitted from a hot tungstun filament. The emitted electrons were accelerated through a potential of 50 volts that was applied between the filament and the cylindrical anode. The ionized argon and the electrons formed in the discharge chamber exited through an 1.3-centimeter-diameter orifice at one end of chamber. A sketch of this plasma source is shown in figure 1. These charged particles formed the plasma for the tests. Plasma densities of 10^2 to 10^6 electrons/cm^3 are possible at the testing location with this source.

In the tests the solar arrays were biased with an external power supply. The small voltage generated by the array had a negligible effect on the plasma coupling current since the vacuum chamber was dark during the tests. The plasma coupling current to the arrays was measured with an electrometer between the power supply and the array while the voltage was slowly increased. A sketch of the test setup is shown in figure 2. Both positive and negative bias were used. The maximum voltages were ±1 kilovolt, or less if the sample arced.

DIAGNOSTICS

The current-voltage (I-V) characteristics of the two spheres (1.9 cm and 1.27 cm diam) were used to determine the plasma parameters. The voltage was varied from -100 volts to 100 volts. Assuming the gas was Maxwellian, the current in the electron repulsion region of the I-V characteristic is given by (ref. 11)

$$I = Aen\left(\frac{kT}{2\pi m}\right)^{1/2} e^{-\left|\frac{eV}{kT}\right|} \tag{1}$$

where A is the area of the sphere, n is the electron density, k is Boltzmann's constant, T is the temperature, m is the electron mass, e is the electronic charge, and V is the applied voltage. From equation (1) the temperature T is found to be (ref. 11)

$$T = \frac{k}{e}\,\frac{V_2 - V_1}{\ln I_1/I_2}$$

where I_1,V_1 and I_2,V_2 are two current-voltage points in the repulsion region.

The plasma density was found by using the electron saturation region of the I-V characteristic. Assuming the gas was Maxwellian outside the sheath and collisionless within the sheath, the current is (ref. 11)

$$I = \frac{1}{2}\,neA\left(\frac{2kT}{\pi m}\right)^{1/2}\left(1 + \frac{eV}{kT}\right)$$

so that after taking the derivative, the equation can be solved for the electron density to give

$$n = \frac{(2\pi mkT)^{1/2}}{e^2A}\,\frac{dI}{dV}$$

This equation was used to determine the density of the plasma.

RESULTS AND DISCUSSION

The plasma coupling current as a function of applied positive voltage for the 100-square-centimeter array is shown in figure 3. The data in this figure show a comparison of flight results with laboratory results. The flight data were obtained from the Plasma Interaction Experiment (PIX) satellite that was launched in March 1978. In addition to the solar array experiment, there were two disk experiments on this flight, a Kapton disk and a plain disk. The Kapton disk consisted of a 1.4-centimeter-diameter gold-coated metal electrode mounted on a 20-centimeter diameter 5-mil-thick sheet of Kapton. The plain disk has the same size gold-coated electrode without the Kapton sheet. More details of the experiments are given in reference 6. In this figure the ground-based data agree well with the flight results.

Figure 4 shows the flight and ground-based results for these same three experiments when they are negatively biased. Again the ground-based data agree well with the flight results. The arc discharges for the solar array are typical for solar arrays negatively biased in a plasma. For this array, arcing occurred at a bias voltage of -700 volts. This is the highest voltage achieved with any of the solar arrays when negatively biased. Figures 3 and 4 show that ground-based facilities can be used to reliably simulate the plasma interaction on small arrays in space.

Figure 5 shows the 13 700-square-centimeter array. This array was formed from nine single panels. The panels were mounted on a aluminum grating structure by using 1.9-centimeter-long ceramic isolators. Each panel could be biased individually or in combination. Figure 6 shows the total plasma current when all panels were biased at the same positive voltage. For comparison the data for a single 2000-square-centimeter panel are also shown in this figure. If the coupling current scaled linearly with area, the nine-panel array current would be approximately seven times larger than the single-panel current. As can be seen from this figure, the nine-panel array current is much higher than this at the low voltages and lower than this at the high voltages. Both panels were tested in the same plasma environment.

Figure 7 shows the results for negative bias on the nine-panel array and the single 2000-square-centimeter panel. As can be seen, the current for negative bias also does not scale linearly with area. However, the inception voltages for arcing on the two arrays are within 200 volts of each other. This agrees with data previously obtained in that the arcing voltage is independent of the size of the array (refs. 6 and 9). Details of the 13 700-square-centimeter solar array results are given in reference 9.

The results for positive bias on the 400- and 1600-square-centimeter arrays are given in figure 8. Above 300 volts the 1600-square-centimeter array current saturated. This indicates that the array was collecting the maximum current possible for this size facility at this plasma density. Below 300 volts the current for the 1600-square-centimeter array was approximately four times that for the 400-square-centimeter array. For these arrays the current does scale approximately linearly with area. This linear scaling was substantiated with preliminary results from the 800- and 1200-square-

centimeter arrays. The currents for these two arrays were two and three times that for the 400-square-centimeter array, respectively.

Also shown in figure 8 are data for the 100-square-centimeter array. The dashed curve shown represents four times the 100-square-centimeter array data. As can be seen, these data fall far below those for the 400-square-centimeter array. One would have expected that the small (100 cm^2) array current would follow close to spherical theory since end effects are not negligible. Since spheres collect the maximum current, it was expected that the dashed curve would fall above the 400-square-centimeter-array data. Further tests are being performed to investigate this behavior.

The results for negative bias on the 400- and 1600-square-centimeter arrays are shown in figure 9. For voltages above 100 volts for the 1600-square-centimeter array and 200 volts for the 400-square-centimeter array, arc discharges occurred. This 100 volts arc inception voltage is the lowest inception voltage that has been observed for arcing. Before arcing occurred, the current scaled approximately linearly with array area. This was also substantiated with preliminary data for the 800- and 1200-square-centimeter arrays. The current for the 100-square-centimeter array was much too low for negative bias also, as can be seen from the dashed curve in figure 10.

CONCLUDING REMARKS

The plasma coupling current as a function of applied voltage has been presented for solar arrays ranging in size from 100 to 13 700 square centimeters. For the 100-square-centimeter array, flight and laboratory data have been presented. The two results were in good agreement. This verified that ground-based facilities can be used to simulate the plasma interaction phenomenon in space for small solar arrays.

One of the objectives of this investigation was to determine whether the plasma coupling current scales linearly with array area. The 100- and 2000-square-centimeter-panel coupling currents did not scale linearly with area to the 13 700-square-centimeter array. However, the coupling current for the 400-square-centimeter panel could be scaled linearly with area to obtain the current for the 800-, 1200-, and 1600-square-centimeter panels. Since these arrays were on the same substrate, this may have contributed to the linear scaling. This result occurred for both positive and negative bias on the arrays. Continued testing is being done to further investigate this effect.

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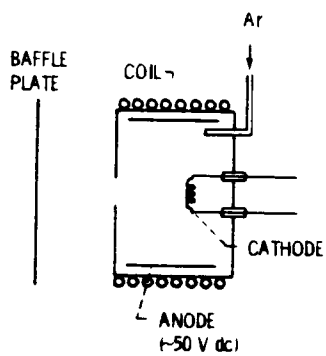


Figure 1. - Plasma-generating source.

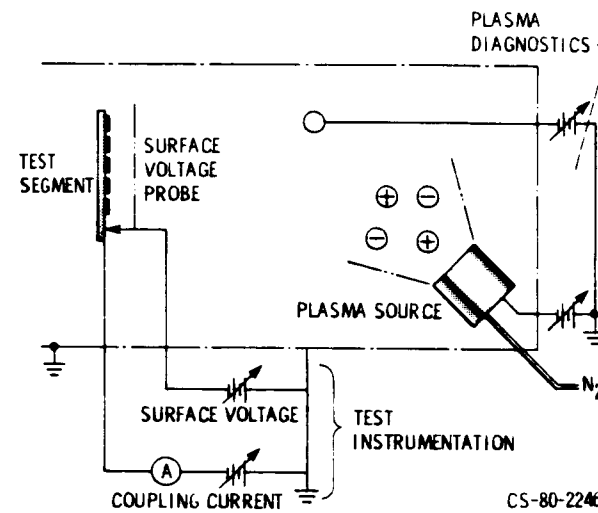
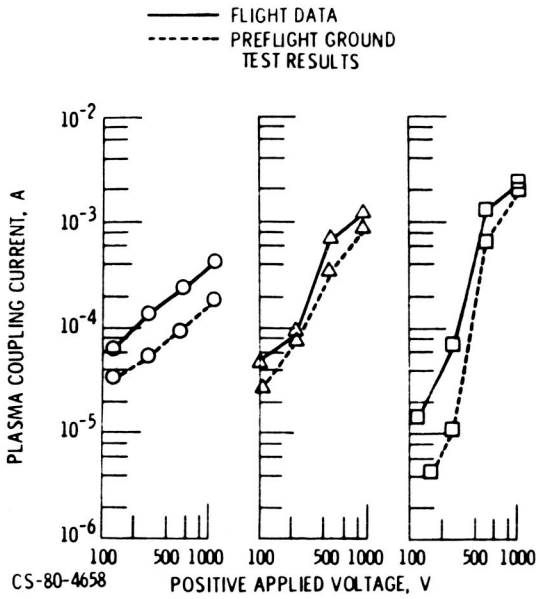
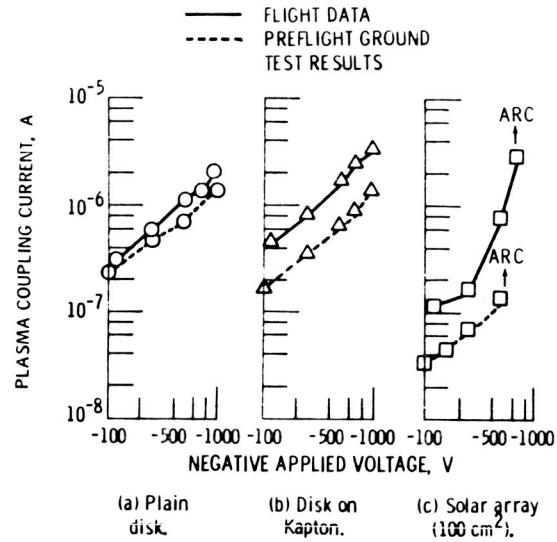


Figure 2. - Schematic diagram of test arrangement.



(a) Plain disk. (b) Disk on Kapton. (c) Solar array (100 cm^2).

Figure 3. - Adjusted flight current compared with preflight ground current as a function of applied voltage. Plasma density, n, ~$2x10^4$ electrons/cm^3.



(a) Plain disk. (b) Disk on Kapton. (c) Solar array (100 cm^2).

Figure 4. - Flight plasma current compared with preflight ground current as a function of applied voltage. Plasma density, n, ~ $2x10^4$ electrons/cm^3.

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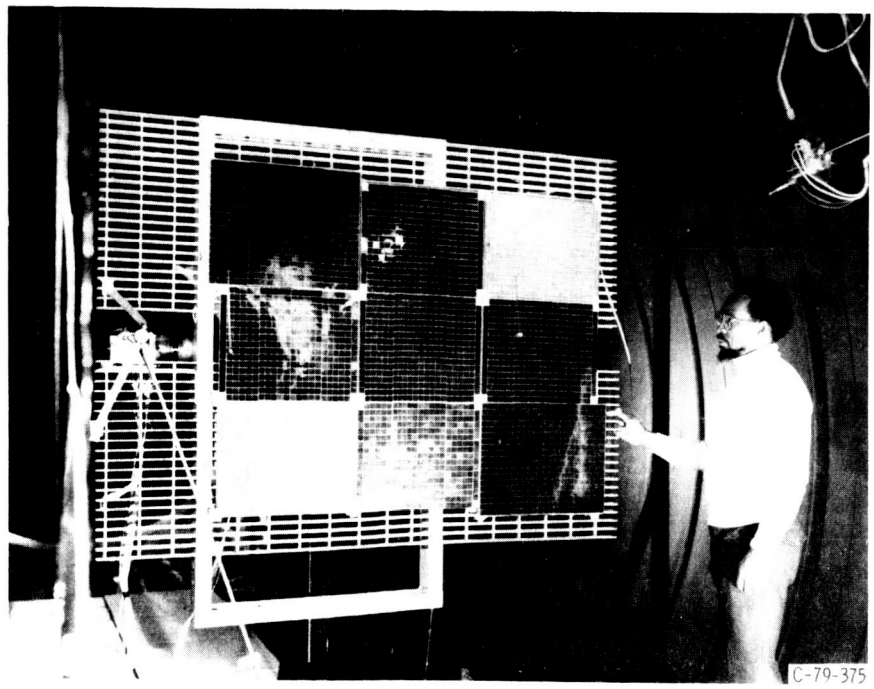

Figure 5. - 13 700-Square-centimeter array.

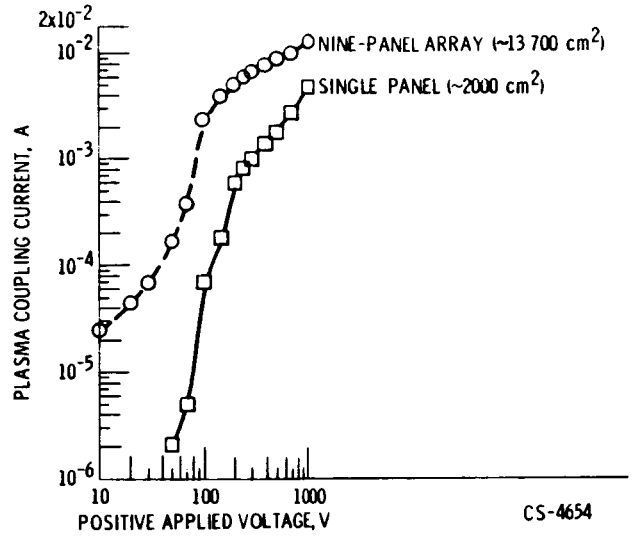

Figure 6. - Plasma coupling current as a function of positive applied voltage for 13 700- and 2000-cm^2 arrays. Plasma density, n, $8x10^3$ electrons/cm^3.

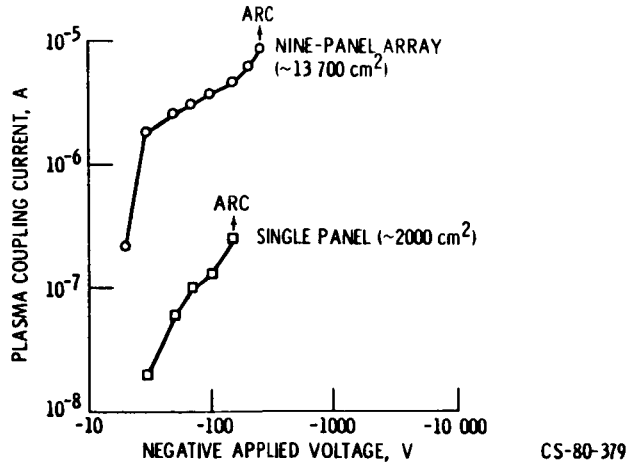

Figure 7. - Plasma coupling current as a function of negative applied voltage for 13 700- and 2000-cm^2 solar arrays. Plasma density, n, ~$4x10^4$ electrons/cm^3.

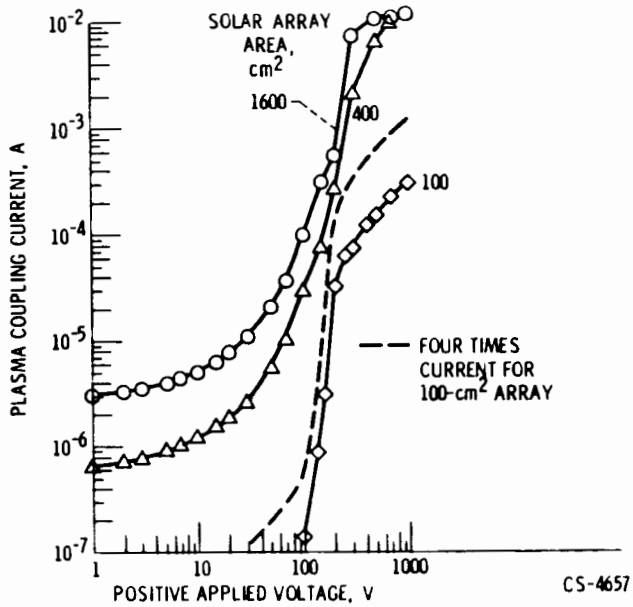

Figure 8. - Plasma coupling current as a function of positive applied voltage for 100-, 400-, and 1600-cm^2 arrays. Plasma density, n, ~9.3x10^3 electrons/cm^3.

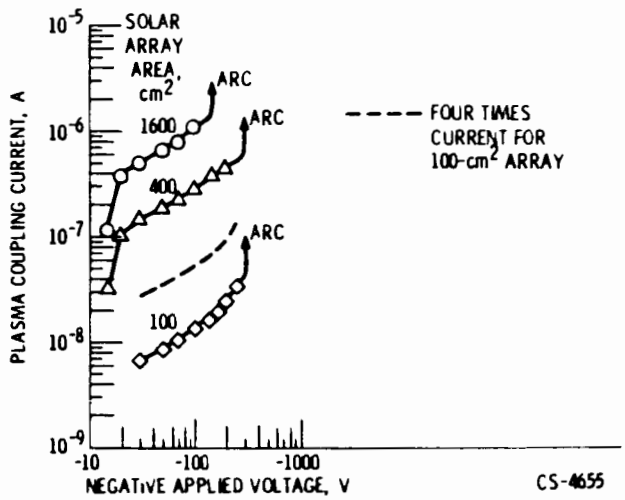

Figure 9. - Plasma coupling current as a function of negative applied voltage for 100-, 400-, and 1600-cm^2 arrats. Plasma density, n, 9.3x10^3 electrons/cm^3.