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Review of Biased Solar Array-Plasma Interaction Studies

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REVIEW OF BIASED SOLAR ARRAY - PLASMA INTERACTION STUDIES

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ABSTRACT

The Solar Electric Propulsion System (SEPS) is proposed for a variety of space missions. Thrust is provided by ejection of charged particles. Power for operating SEPS is obtained from large solar array wings capable of generating tens of kilowatts of power. To minimize resistive losses in the solar array bus lines, the array is designed to operate at voltages up to 400 volts. This use of high voltage can increase interactions between the biased solar cell interconnects and plasma environments. With the SEPS thrusters off, the system floating potential (relative to the space plasma potential) tends to be negative which will minimize interactions. With thrusters operating, the system ground is maintained at space plasma potential which exposes large areas of the arrays at the operating voltages. This can increase interactions with both the natural and enhanced charged-particle environments. This paper summarizes available data on interactions between biased solar array surfaces and plasma environments. The apparent relationship between collection phenomena and solar cell size and effects of array size on interactions are discussed. The impact of these interactions on SEPS performance is presented.

INTRODUCTION

Spacecraft must function in the space charged-particle environment. While it is normally assumed that any such interaction is inconsequential, experience with geosynchronous satellites has shown that charged-particle environments can induce disruptive interactions in spacecraft systems.[1] Satellites proposed for future missions will use larger strucures and require greater power generation capabilities.[2-6] It is anticipated that charged-particle interactions with these large satellites can be even more severe than those experienced by present geosynchronous satellites.[7]

One of the first generation of large spacecraft with a significantly increased power level is the Solar Electric Propulsion System (SEPS) which is proposed for a variety of geosynchronous and planetary missions[8-11]. The electrical power for SEPS is generated by large solar array wings which are sized for power levels of about 25 kW. To minimize resistive losses in the electrical bus, these arrays are proposed to operate at voltage levels up to 400 volts in conventional systems and up to 1200 volts in a "direct drive" configuration - one in which high voltages for thruster operation is generated directly on the array rather than by power processors.[12] With these configurations, then, large areas of solar arrays with exposed conductors at elevated voltages can interact with both the natural and possible thruster-enhanced charged-particle environments. In addition, ion thrusters with both ions and electrons which can control spacecraft potential relative

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to the space plasma potential. The conditions experienced by SEPS are unique in that it is a large system capable of controlling its own surface voltages. This, however, can give rise to high voltage surface interactions that must be understood and evaluated.

In this conference there are papers dealing with ion thruster performance and with predictions of interactions on SEPS.[13-15] In this report, a review of the possible high voltage surface interactions is undertaken. Ground test data collected at the Lewis Research Center (LeRC) over the past ten years is summarized and empirical relationships to explain the results are discussed. The implication of these interactions on SEPS performance is discussed.

BIASED SURFACE/CHARGED PARTICLE INTERACTIONS

The biased surface-charged particle interactions of concern are illustrated in the conceptual sketch of a spacecraft shown in figure 1. Power is generated in two large solar array wings at an operating voltage (V_{op}) relative to the central spacecraft body. The spacecraft body houses the payload, housekeeping systems and the ion thruster system. This SEPS moves through a natural charged-particle environment of which the low energy or thermal plasma is of the greatest concern.

The interactions with charged-particle environments are controlled by the biased, exposed interconnects on the solar array wings. With the ion thrusters off, the whole system floats electrically such that the net current is zero.[16] This means that the biased interconnects on the array act as plasma probes collecting either electrons or ions depending on voltage polarity relative to space. Because electrons are more mobile than ions, electrons are collected more readily than ions. Therefore, voltages relative to space are adjusted to inhibit electron collection and enhance that of ions. This usually results in a voltage distribution (relative to the space plasma potential) such that a segment of the array is approximately at 10 percent of V_{op} positive while the rest is approximately 90 percent of V_{op} negative. With electrons flowing to one area of the array and ions to others, a parasitic current loop is formed in the plasma reducing available power for the satellite. The insulating surfaces around the biased interconnects also conform to the current balance criteria imposing additional fields and contributing to arcing.[17]

With the ion thrusters operating, additional current flows must be considered. The high voltage ions are accelerated away under controlled conditions. The neutralizer, however, operates uncontrolled and has the capability of supplying copious amounts of electrons which can respond to external electric fields in the ion beam around the spacecraft and in space. The result of thruster operation is that spacecraft ground is locked at the space plasma potential with the arrays at V_{op} relative to spacecraft ground. Any imbalance in electron current caused by this operation is compensated for from the neutralizer. This behavior has been demonstrated on numerous satellite experiments.[18-19]

The thrusters also generates a charge exchange plasma which tends to drift radially away from the thrusters.[20] This plasma can enhance the low energy, natural charged-particle environment and increase interactions between the thrust system and biased solar array surfaces. This behavior is analogous to thermionic diodes where a tenuous plasma between the electrodes enhances current flow.[21] In this case the charge exchange plasma can enhance electron flow from the neutralizer into the power system effectively reducing operating power levels.

The floating potentials of SEPS are illustrated in figure 2. In figure 2(a) the thruster-off behavior is illustrated for two different operating voltage configurations. The first configuration has each array at a constant positive voltage (V_{op}) relative to the spacecraft body. The spacecraft body floats essentially at $-V_{op}$ with small areas of the wing positive with respect to space. The second configuration assumes a distributed voltage along the array wing, positive and negative from the spacecraft body. This configuration floats with one end of the array at about 10 percent of V_{op} positive.

In figure 2(b) the thruster on behavior is illustrated. In both configurations the spacecraft body is at space plasma potential (0 volts absolute) and the imposed V_{op} conditions exist from this level.

GROUND TESTS

Tests have been conducted using samples biased by laboratory power supplies to determine interactions with plasma environments. Results have been reported by several investigators[22-25] and the data is in reasonable agreement. For this report, test results from the Lewis Research Center (LeRC) experiments on 100, 1400, and 13 600 cm^2 solar array panels are used to summarize the interaction characteristics.

Tests at the LeRC have been conducted in a 1.8 m diameter x 2.5 m long facility and a 4.6 m diameter x 18 m long facility. In both facilities a plasma environment (either nitrogen or argon) is generated in a bombardment source and allowed to drift into the chamber. Plasma particle temperatures in the range of 1.0 to 3.0 eV and densities between 10^5 and 10^2 particles/cm^3 are obtained by adjusting the source power supplies and gas flow. Plasma properties are measured before and after each run with Langmuir probes.. The ambient pressure in both facilities, with the sources operating, is about 10^{-6} torr.

The test sample is mounted in the chamber electrically isolated from tank ground. An external power supply provides the positive or negative bias to the test sample. A current sensor floats in the high voltage line to measure the coupling current through the plasma to tank ground. A noncontacting surface voltage probe (TREK) is used to measure voltage profiles 3 mm above the cover slides. The schematic diagram of the facility is shown in figure 3(a).

The 100 cm^2 solar array panel is shown in figure 3(b). This panel has twenty-four 2x2 cm solar cells connected in series mounted on a Kapton sheet attached to a fiberglass board. The 13 600 cm^2 solar array is a matrix of nine panels (see fig. 4) and is tested in the larger facility only.

Small Panel Test Results

Positive bias tests. - The plasma coupling current collected by the 100 cm^2 solar array panel as a function of applied positive voltages is shown in figure 5(a). Tests are usually conducted at several plasma densities and repeated to verify that the same characteristics occur. Results illustrated here correspond to tests conducted in a 10^4 particle/cm^3 plasma environment. The bias voltage has to be corrected since the plasma potential is not necessarily at tank ground during the test. This plasma potential can be obtained from the plasma diagnostic data.

At low voltages the collected currents are small and increases rather slowly with bias voltage. At about +100 volts, there is an abrupt transition in the current; it increases orders of magnitude in a few volts. Beyond this transition the current again increases slowly with voltage. The magnitude of this transition is directly proportional to the plasma density but the transition threshold (∿ +100 V) seems to be independent of plasma density.[25,26]

While this curve has a characteristic "S" shape, it is not a Langmuir probe characteristic since it occurs in the electron saturation region. The understanding of the behavior observed here can be found in the surface voltage probe data. This probe sweeps across the array about 3 mm above the glass cover slides. At low applied voltages, the cover slides assume a slightly negative surface voltage (to maintain a zero net current balance at each surface) and this negative voltage tends to mask the interconnect bias voltage (see fig. 5(b)). As bias voltages are increased, the capability of cover slides to mask interconnect voltage field expands and encompasses the covers - a phenomenon called "snap-over".[27] At this point, the whole panel, in effect, becomes a plasma collector. The process believed to cause this snap-over phenomenon is the collection of secondary electrons emitted from the glass covers. It has been shown that inclusion of secondary emission characteristics of dielectrics can explain this transition from local collection to large area collection for pinholes in Kapton.[28] Similar processes are believed to occur on arrays. Above this transition, the fields above the panel increases roughly linearly with applied voltage (see fig. 5(b)).

Empirical relationships can be developed which seem to fit the data and comply with an intuitive feeling about the collection mechanics. At the low voltages (less than 100 volts), it appears that cylindrical probe collection theory[16] is appropriate. Here the interconnects are assumed to be a series of small cylinders each collecting a current proportional to:

$$I_c \propto A_i \sqrt{1 + \frac{V}{\varepsilon_e}}$$

where I_c is the coupling current, A_i is the total interconnect area, V is the voltage relative to plasma potential and ε_e is the electron energy (eV).

Above 100 volts, it appears that spherical probe collection[16] based on a reduced voltage and whole panel area is reasonable. Here the relationship is:

$$I_c \propto A_p \left[1 + \frac{V - 100}{\varepsilon_e}\right]$$

where A_p is the frontal panel area.

Negative bias tests. - Characteristic data for ion current collection by the 100 cm² solar array panel biased by negative voltages is shown in figure 6(a). Here, the experimental collection curve is simple, but it does terminate in arcing. The surface voltage probe data (see fig. 6(b)) shows that the interconnect electric fields remain constrained to the region between cells, becoming stronger until breakdown occurs. This behavior of negative voltage fields not expanding into dielectrics has been shown analytically for holes in

Kapton.[29] The voltage threshold for breakdown is plasma density dependent; voltage thresholds are higher for less dense plasma conditions[25,26,30,31].

The experimental data seems to indicate that spherical probe collection phenomena adequately models this ion current collection. A empirical fit can be obtained from:

$$I_c \propto A_i \left[1 + \frac{V}{\varepsilon_e}\right]$$

DISCUSSION

It is worthwhile to examine the data to determine if a plausible explanation can be found to explain the approximately +100 volt threshold for snap-over.

The small solar array panel data is especially adaptive to this evaluation. It has been tested numerous times and a body of data has been assembled. The panel itself has just 24 cells in series; this means that there are only 25 collection points at approximately the same voltage in the measurement circuit. If it is assumed that the collection current is 1/25 of the total current, then the field around a single interconnect could be examined. If it is further assumed that the voltage shealth is hemispherical and that, at the boundary of this hemisphere, all the collected current has to diffuse across from the undisturbed plasma environment, then:

$I_c = jeo\ A_{HS}$ where A_{HS} is the hemisphere surface area and
jeo is the electron thermal current density

or

$$r_s = \sqrt{\frac{I_c}{2\pi jeo}}$$

where r_s is the hemispherical spherical radius of the voltage sheath boundary.

Substituting numbers for the collected electron current and jeo from experimental data gives a sheath radius value of about 1 cm at about 100 volts. Indicating that voltage sheaths overlap at about 100 volts for 2 cm x 2 cm cells (see fig. 7). This is the intuitive assumption for the snapover. But, if cell size can be a controlling factor for snapover, then the transition might be driven to a higher voltage by increasing cell size. It is difficult to find data to support this premise, but there are indications. Tests conducted on a 20 cell panel of 2x4 cm cells mounted on Kapton seemed to show that snapover did not occur till between 160 and 190 volts (see fig. 8(a)). So, the possibility that snapover can be inhibited by using larger cells exists and is currently being evaluated at the LeRC.

It should be noted that this same panel arced when subjected to negative bias tests. Photographs of this arcing (see fig. 8(b)) indicated that arcing occurred at the cell edges. So, while snapover might be prevented by larger cell sizes, arcing continues to be a real concern.

Large Array Test Results

A matrix of 9 solar array panels having a total area of 13 000 cm^2 has been tested in the 4.6 m diameter facility along with a single panel of about 1400 cm^2 (see fig. 4).[32] The purpose of these larger panel tests is to attempt to determine scaling laws to extend concepts developed with small area tests to large space systems. The first thing that is found in any such test program is that chamber walls and plasma sources can influence plasma interactions with such large areas. It is felt that, for these matrix tests, collection data up to ∿ +250 volts and all negative voltages is valid.

The electron current collection test results for both the single panel and matrix is shown in figure 9. The single panel data appears to follow the empirical relationships developed previously. Snapover occurs at about 100 volts and at higher positive voltages the current data agrees with predictions.

The matrix panel test results indicate two items of importance:

- Snapover occurs at about 100 volts
- Electron current collection less than predicted at applied voltages above 100 volts.

This means that, for large solar arrays made up of 2x2 cm solar cells, there will be collection enhancement in those areas above +100 volts (with respect to space). However, the second item indicates that collection of voltages above 100 volts may not be as severe as one would expect from small area panel tests. Continuations of these studies are being pursued.

Under negative applied voltages arcing occurred in a fashion similar to the small panels. The threshold for arcing seems to be independent of panel area.

APPLICATION TO SEPS

As stated previously, SEPS will use ion thrusters to provide thrust. Operation of these thrusters will maintain the spacecraft potential at the space plasma potential. This will result in solar arrays being at operating voltages relative to space and this could enhance interactions with charged-particle environments.

The complete assessment of the impact of these interactions on SEPS must wait until interaction technology and thruster efflux technology are more advanced. However, the degree of interaction can be bounded by considering current collection as a function of plasma density. First, it is assumed that the solar arrays generate 25 kW and that the arrays are at constant positive voltages relative to spacecraft potentials. Second, currents collected are based on empirical relationships presented in this paper. Third, solar array area is assumed to be 250 m^2. Fourth and finally, plasma particle energy is assumed to be 0.22 eV, the electron temperature for space environment.

The computed plasma current collection per unit area of solar array for various plasma densities is shown in figure 10. Load current lines for operation at 100 and 200 volts are indicated. The curve identified by $V = 10$ volts would represent current collection that could be expected for the 100 volt array without thruster operations. Under these conditions the power loss is negligible.

With ion thrusters operating, the degree of interaction depends upon the operating voltages and local plasma density. If the array were operating at 100 volt bus voltage, then the difference between interconnect collection and whole panel collection is about a factor of 10. If the local plasma density is no more than the 300 km natural environment value (∿ 10^6 electrons/cm^2), then losses would be on the order of 1 percent. If the electron temperature in a thruster-enhanced environment were higher than the nature plasma electron temperatures, then the losses would be further reduced.

However, if the array operating voltage were at 200 volts, then fully developed snapover collection could be expected (for 2x2 cm cells). Under these conditions, at low Earth orbit, the power loss would be severe and probably would influence ion thruster operations. At higher altitudes, the degree of interaction would depend primarily upon thruster-efflux-enhanced plasma densities.

There are possible approaches that can be used to minimize thruster/solar array interactions at low altitudes. One is to use larger solar cells. As previously shown, larger solar cells appear to have a snapover at higher voltages. A second approach is to use a center tapped array with distributed voltages. Then positive array voltage is halved and areas at high voltage are reduced. Another approach is to make the array operate at negative voltages with respect to the spacecraft potential. While this option could be viable, it has not yet been completely evaluated. Possible drawbacks to the last two approaches could be arcing at negative voltages or enhanced ion contamination.

This section is not meant to be a catalog of possible catastrophes: There are far too many unknowns and too much uncertainty for definitive claims on ion thruster interactions. Rather, the intent is to point out areas where interaction technology should explore to provide input to system design.

CONCLUDING REMARKS

There are trends towards larger satellites in studies for future missions which require far larger power generating levels than presently being used in space. With these larger power levels comes the need for operation at higher voltages; voltages larger than the present 50-60 volt systems common on European satellites and 30 volt systems on present U.S. satellites. With increased operating voltages comes the need to consider interactions between biased conductors on the array and the space charged-particle environment. These interactions involved current collection through the space plasma, which reduces the output power level, and arcing to space, which interrupts the power output.

SEP is being designed with power systems operating at voltages in the range of 200-400 volts. Since SEP has ion thrusters which can maintain spacecraft ground of the space plasma potential. This will drive large areas of the array to elevated voltages (with respect to space) which then can react with either the natural or thruster-enhanced plasma environment. These interactions can influence systems operations and must be understood.

The available laboratory data, generated at the LeRC has been reviewed to determine trends in these interactions. From small area tests, it appears that electron current collection can be treated as a cylindrical plasma probe, constrained to the area of biased interconnects, for voltages up to about 100 volts. This means that current collection grows relatively slowly with increasing voltage ($I \propto V^{1/2}$). At about 100 volts, a phenomenon called "snap-over" occurs - the current collection becomes proportional to the whole panel area. At higher voltages, the current increases with voltage approximately as if it were a spherical plasma probe. For negative bias voltages, data seems to show that current collection increases with voltage until arcing occurs. Thresholds for arcing are plasma density dependent ranging from a few hundred volts at low Earth orbit densities to several leilovolts at geosynchronous orbit conditions.

From these small area tests it appears that solar cell size has an influence on the snapover phenomenon. Two by two centimeter cells have voltage sheaths that are computed to overlap at the snapover thresholds. If the cell size dependence can be substantiated, then snapover could be controlled by larger cell sizes.

Tests of a large solar array matrix indicates that snapover and arcing both occur at approximately the same thresholds as the small panel. In both cases, the cell size was the same. Electron collection for the large matrix, however, seems to be less than the empirical model predictions indicating that electron current collection at higher voltages could be less for larger arrays than that predicted from small panel extrapolations.

Finally, SEPS operations are reviewed from the point-of-view of array operating voltages interactions at various plasma densities. It has been found that an array biased at a constant positive voltage with respect to spacecraft potential probably would have serious coupling losses if operated at 200 volts in low Earth orbit. Larger cell sizes or center-tapped, distributed voltage arrays could alleviate the interaction losses. Interactions at higher altitudes would depend primarily on thruster-efflux-generated environments.

This review of possible interactions between SEPS and charged-particle environments (both natural and thruster-efflux generated) indicates that there are many unknowns. Interactions between large biased solar arrays and plasma as well as thruster efflux environments are not that well characterized. Additional studies are required and are underway.

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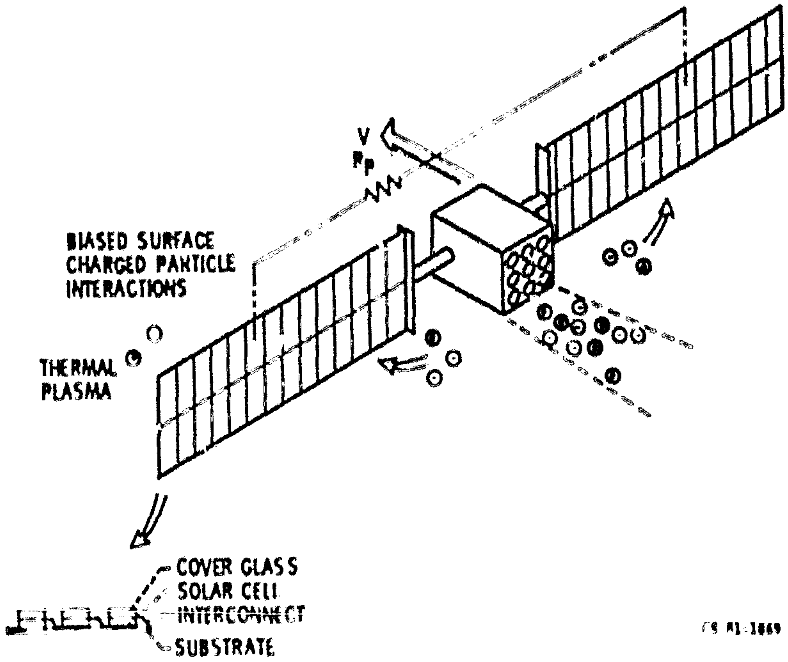
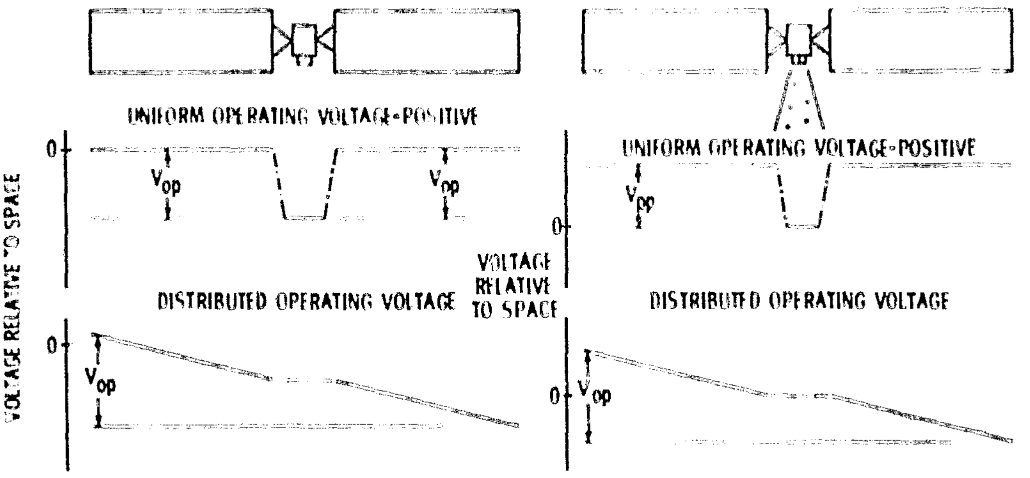


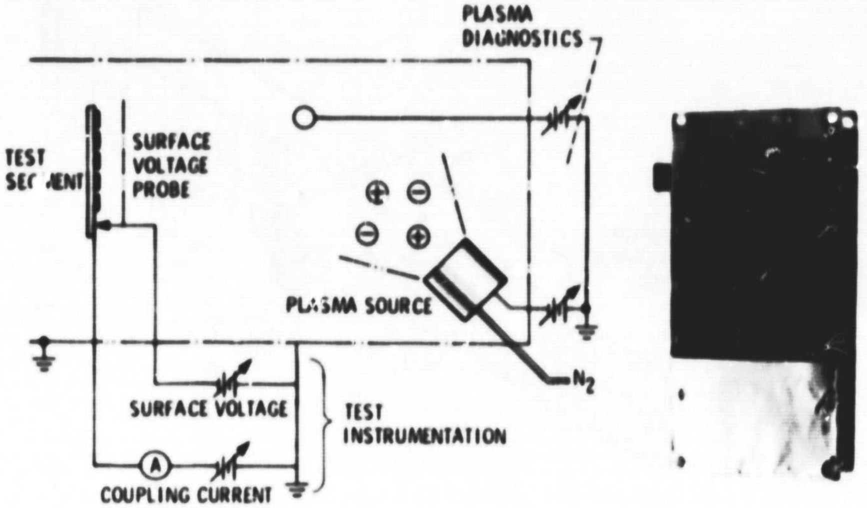
Figure 1. - SEP - charged particle interactions.



(a) THRUSTERS OFF.

(b) THRUSTERS ON.

Figure 2. Typical SEP operating voltage relationships.



(a) TEST FACILITY.

(b) TEST PANEL.

Figure 3. - Ground test simulation.

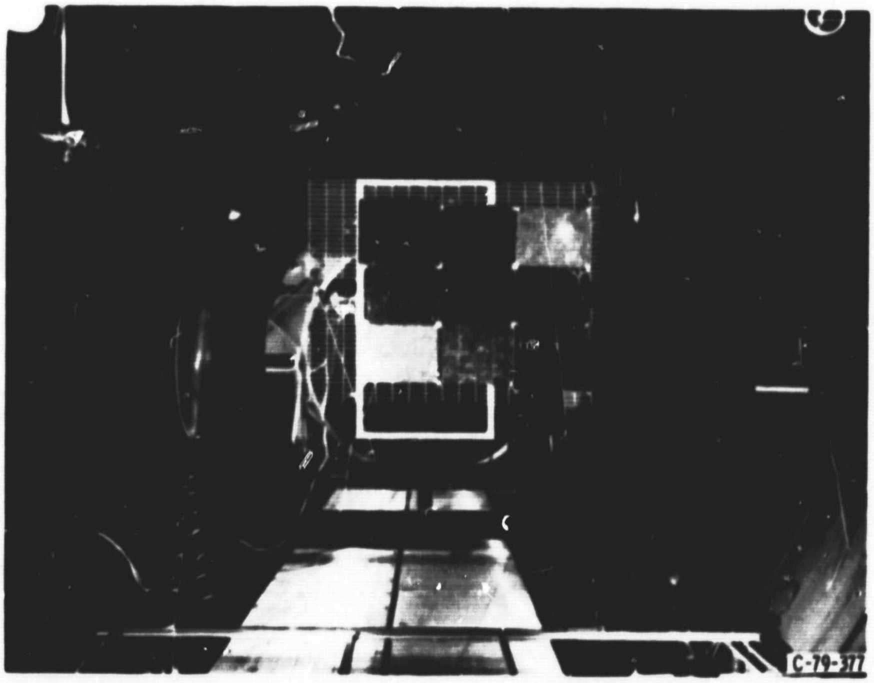
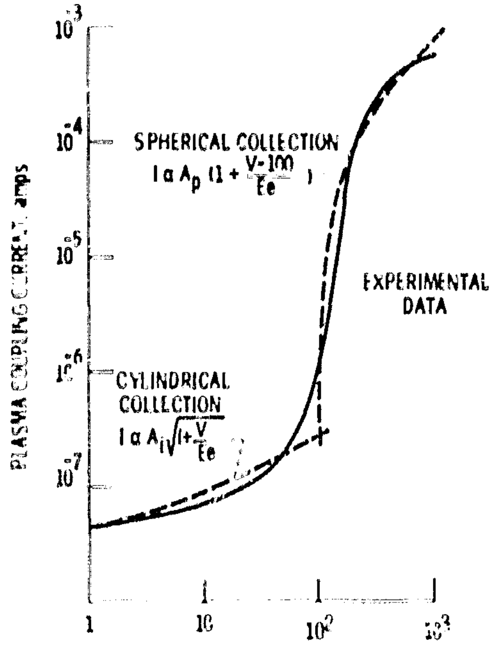
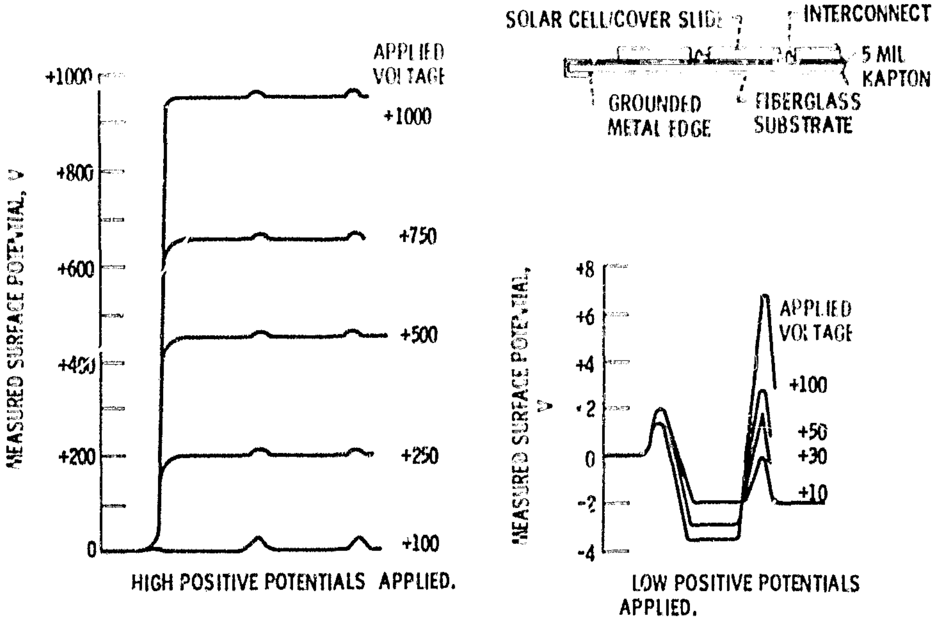


Figure 4. - Large array test.



(a) ELECTRON CURRENT COLLECTION.

Figure 5. - Ground test data - positive applied voltage.



HIGH POSITIVE POTENTIALS APPLIED.

LOW POSITIVE POTENTIALS APPLIED.

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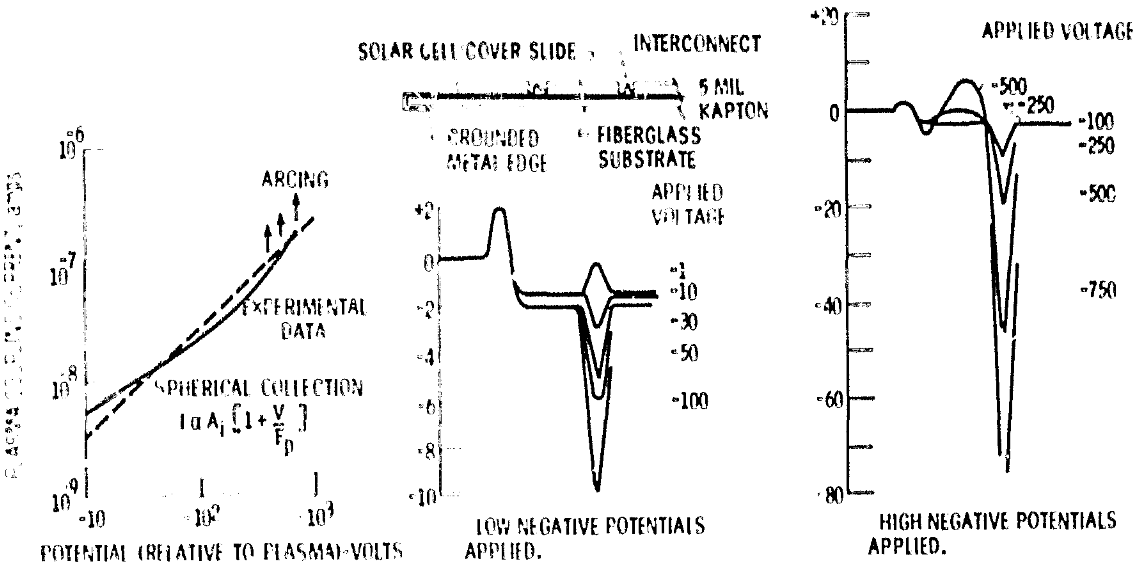
(b) SURFACE VOLTAGE PROFILE.

Figure 5. - Concluded.



(a) ION CURRENT COLLECTION.

(b) SURFACE VOLTAGE PROFILE.

Figure 6. - Ground test data - negative applied voltages.

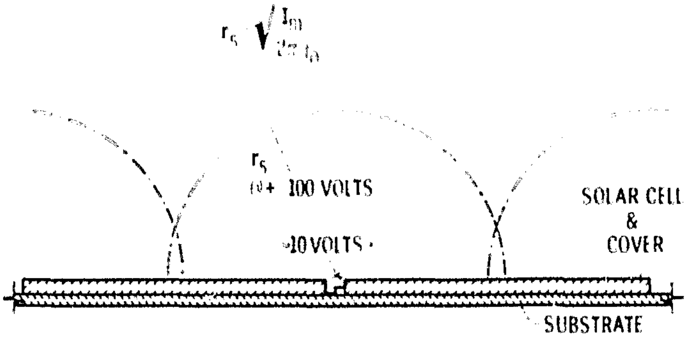
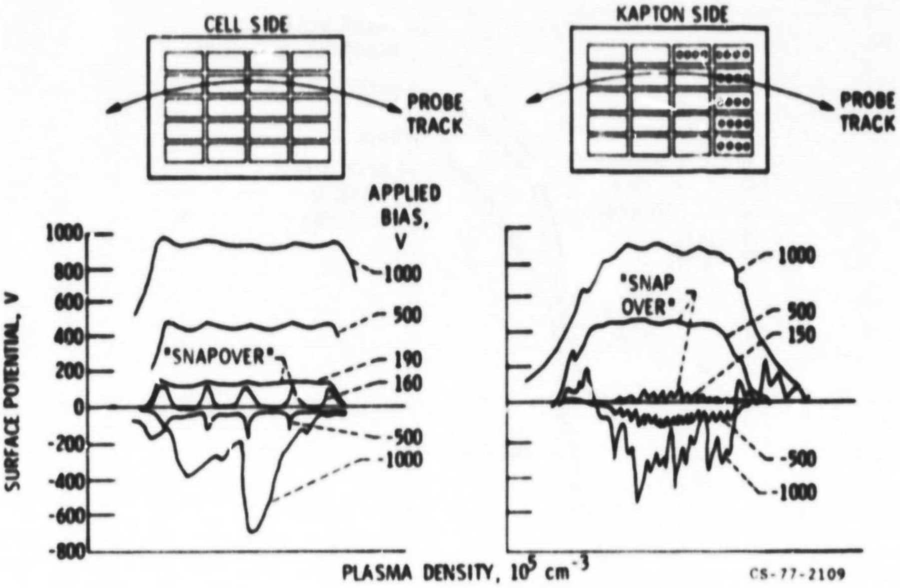
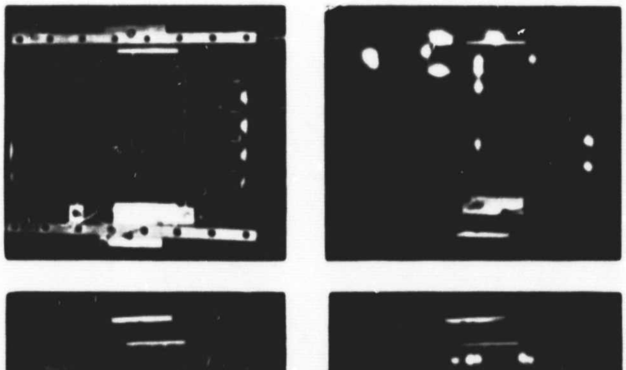


Figure 7. - Computed voltage sheaths (hemispherical sheath collection).



(a) EXPERIMENTAL RESULTS.

Figure 8. - SEP array segment tests.



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(b) ARCING ON SOLAR CELL ARRAY SAMPLES.

Figure 8. - Concluded.

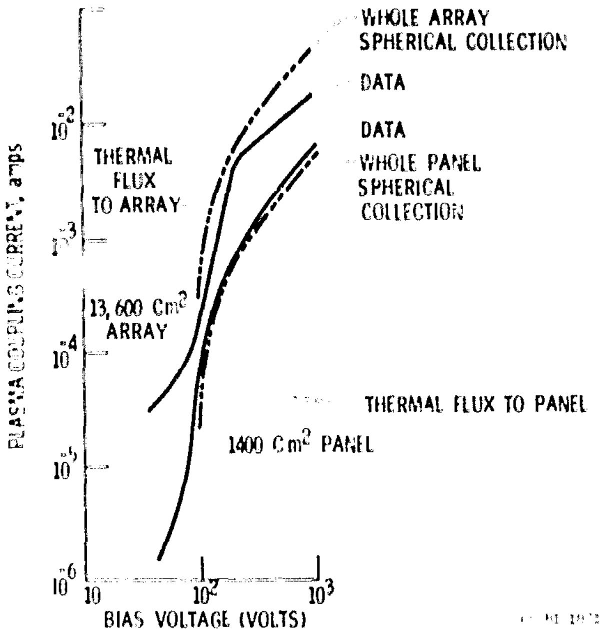

Figure 9. - Electron collection for larger solar arrays.

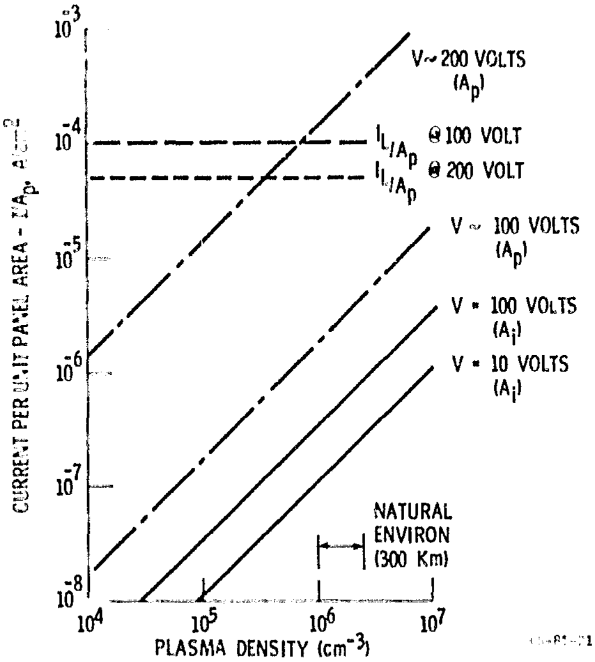

Figure 10. - Panel plasma current collection at various plasma densities -25 kw array.