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Abstract

The exposure of high voltage spacecraft systems to the charged particle environment of space can produce interactions that will influence system operation. An experimental investigation of these interactions has been undertaken for insulator and conductor test surfaces biased up to ±1 kV in a simulated low Earth orbit charged particle environment. It has been found that these interactions are controlled by the insulator surfaces surrounding the biased conductors. For positive applied voltages the electron current collection can be enhanced by the insulators. For negative applied voltages the insulator surface confines the voltage to the conductor region; this can cause arcing. Understanding these interactions and the technology to control their impact on system operation is essential to the design of solar cell arrays for ion drive propulsion applications that use direct drive power processing.

Introduction

Historically, the trend in operational power requirements for satellites has been towards ever-increasing levels. Studies are presently being conducted for future large, high power missions such as electric propulsion driven systems for scientific exploration and for movable satellite applications, space power generation, manufacturing and human habitation.[1-6] One means of improving electrical efficiency and reducing weight for these missions is by utilizing power systems operating at voltages higher than those presently considered.

For example, a study conducted for the solar electric propulsion driven Halley's Comet mission concluded that, while the mission can be flown with a conventional system, the net payload can be increased if a "direct drive" electric propulsion system is used.[7] In a direct drive system, the high voltages required for the thrusters (~3 kV) are generated directly on the solar array. Similar improvements in payload capability can also be realized by other electric propulsion missions through use of direct drive systems.

Space power systems have been proposed for missions ranging in location from low earth orbits to geosynchronous orbits. These systems would generate power in the range of hundreds of kilowatts to gigawatts for use by space systems or for beaming to Earth. These systems would incorporate multikilovolt operating voltages.

The exposure of such high voltage systems to a space environment requires careful consideration. To date, the highest operational power system voltage used was the 100 V system on Skylab. A simple extrapolation from this level to a multikilovolt system cannot be made. Space is not a pure vacuum; it has a tenuous, low energy charged particle environment that ranges from about a million particles per cubic centimeter at low Earth orbit to about 10 particles per cubic centimeter at geosynchronous orbit. This environment, called the thermal plasma environment, can interact with the exposed portions of high voltage systems and these interactions must be considered in the system design. The interactions identified as those that must be evaluated are the plasma coupling current between the high voltage system and the environment, the effects of charge stored in or on the insulator surface, and the plasma-initiated discharges. These interactions must be described as functions of operational voltages, time in orbit, plasma properties, and insulator properties and condition.

High voltage surface-plasma environment interactions have been studied at the Lewis Research Center for the past several years. The ground investigations have identified the basic interactions described above.[8-15] The SPHINX satellite (an acroynm standing for Space Plasma-High Voltage Interaction Experiment) to evaluate the interactions in the space environment was built and launched,[16] but was lost when the Titan-Centaur proof flight mission failed to orbit the payload in February 1974.

After the failure to place the SPHINX spacecraft in orbit, the interest in high voltage system technology diminished. However, recent studies for missions using high power and high voltage systems have revived the interest in this interaction technology. A program has been established to investigate all aspects of charged particle interactions with spacecraft systems. Ground simulation testing and analysis have been reemphasized. Studies of ion thruster efflux-high voltage solar array interactions[17,18] have been initiated. The first information on the interaction in the space environment will be obtained by the Plasma Interaction Experiment (PIX) to be carried on the Landsat C launch.[19]

In this report the results and implications of recent ground simulation testing will be discussed. Background information on the high voltage system - plasma environment interaction will be presented.

Spacecraft System- Plasma Environment Interactions

The basic interactions between spacecraft systems and the plasma environment are indicated in Fig. 1. A typical spacecraft employing a large, high power system is shown. The first type of interaction is that in which the higher energy (keV to MeV) particle environment acts on the spacecraft system. Radiation damage to electronic components or solar cells (resulting from ionization or atomic displacement, for instance) is typical of this type of interaction. At geosynchronous altitudes a special case of this type of interaction, known as spacecraft charging, occurs. The spacecraft charging phenomenon arises when kilovolt energy particles from a geomagnetic substorm electrostatically charge insulating surfaces to high negative potentials. If the voltage stress on an insulator exceeds its breakdown threshold, discharges that can cause anomalies in electronic systems occur. A considerable amount of information is available on both radiation damage[20] and spacecraft charging.[21,22] Further discussion of these interactions will not be pursued here.

A second type of interaction occurs when there are sources on-board the spacecraft like electric propulsion thrusters, that enhance the naturally-occuring charged particle environment. The principal concern is the efflux of charged particles from the thruster. There is a plasma environment, called the charge exchange plasma, that results from charge transfer reactions between thrust ions and neutral propellant atoms escaping from the thruster. Such a plasma can augment the naturally occurring charged particle environment and intensify the interactions with spacecraft systems especially if high voltage solar arrays are used. The question of whether or not such a charge exchange plasma will exist in space will be resolved by a space flight experiment to be flown in 1981.[24,25]

The principal interaction of concern in this report is the coupling between a high voltage system and the thermal plasma environment. This type of interaction is shown as the parasitic current loop in Fig. 1. A typical illustration of this type of interaction is a high voltage solar array (see Fig. 2). In typical solar array construction, the cover slides do not completely cover the metallic interconnects between the solar cells. These cell interconnects are at various voltages depending upon their location in the array circuits. Because the array is exposed to the space plasma, the interconnects act as biased plasma probes attracting or repelling charged particles. At some location on the array the generated voltage is equal to the space plasma potential. The cell interconnects that are at voltages above space potential will attract an electron current which depends upon electron number density in the environment and the voltage difference between the interconnect and the space plasma. Those interconnects that are at voltages below space plasma potential will repel electrons and attract an ion current again dependent on the density and voltage difference. This flow of electrons and ions can be considered a current loop in parallel with the satellite electrical load. This parallel current represents a power loss. A question to be resolved is how cover slides (or other insulating surfaces) influence this current collection. One would anticipate that this collection is pronounced at low Earth orbits since the thermal plasma density is highest there (see Fig. 3).

Experimental studies have been conducted in ground facilities to study the interaction of high voltage surfaces with plasma environments. A solar array segment of 1050 cm^2 area (476 2- by 2-cm cells) was tested in plasma environments ranging from 10^4 to 26 electrons per cubic centimeter.[12] In these tests the segment was not illuminated and bias voltages were applied from power supplies outside the vacuum chamber.

Results (see Fig. 4) indicated that at positive bias potentials the electron current collection was substantial at low Earth oribit plasma densities. At geosynchronous altitude densities, the collected currents were negligible. However, at negative bias potentials, the currents collected rose rapidly and terminated in an arc. The threshold for arcing depended upon the plasma density. Arcing did occur at all densities tested. Arcing is a serious detriment to the operation of systems (particularly high voltage systems) and must be understood so that it can be prevented or its effect minimized by system design.

A solution to the interaction problems would be the covering of all biased conductors. This will work only if there are no penetrations in the covering. The experimental results obtained when a small pinhole (0.038 cm diam) was placed in a Kapton insulation film over a biased conductor are shown in Fig. 5. It has been shown that such holes in insulators can result in disproportionately large electron current collection.[12,13,14,16] Furthermore, these tests have indicated that the collected currents may be proportional to the total insulator area.[12,14] This current collection phenomenon must be evaluated if high voltage systems are to be used in space.

It is recognized that there are serious limitations in ground test facilities. The uncertain simulation of the plasma environment, the distortion of the electric fields in the plasma by metallic vacuum tank walls, and the relatively high background pressure required to operate the plasma sources can influence the test results. However, flight experiments are expensive and not readily available. Experimental techniques and analysis have improved in recent years so that it is advantageous to initiate a new ground test program. The initial results of testing conducted at the Lewis Research Center will be given in the next section.

Experimental Results

Procedure

The high voltage surface-plasma interaction testing described in this report was conducted in the Lewis Research Center geomagnetic substorm simulation facility.[26] This facility is housed in a 1.8 m diam by 1.8 m long vacuum chamber. A nitrogen plasma generated by the facility plasma source was used. All tests were conducted with the samples at room temperature, no solar simulation and ambient pressures of about 5×10^{-5} torr.

The sample surfaces tested were a plain stainless steel disc (3.5 cm diam by 0.1 cm thick), a similar stainless steel disc on a 20 cm diam by 0.012 cm thick Kapton sheet and a solar array segment of 24 2- by 2-cm cells (area about 100 cm^2) arranged in four rows of six cells each. The solar array segment was on a Kapton sheet which was mounted on a fiberglass board (area about 180 cm^2). All three surfaces were mounted on a 91 cm diam aluminum plate which was maintained at tank ground potential (see Fig. 6). These experimental surfaces were chosen to determine the effect of Kapton insulation on current collection of the disc electrode (analogous to the pinhole current collection phenomenon) and to determine the effect of having voltage distributed among many small conductors (interconnects) surrounded by insulator surfaces. The solar array segment has a total interconnect area of 4.8 cm^2 or approximately half of the 9.9 cm^2 disc area.

A schematic diagram of the test arrangement is shown in Fig. 7. Tests were conducted by first generating a plasma in the facility. Plasma density was determined by spherical or cylindrical Langmuir probes. Probes were also used to obtain particle temperature (about 1 eV) and plasma potential (about +6 V). It is believed that the densities obtained by these measurements are accurate within a factor of two.

After a uniform plasma density was established, the bias voltages were applied to either the plain disc, the disc on Kapton or the solar cell circuit. Voltages were always applied increasing from 0 to the maximum positive or negative values. At each test voltage conditions were allowed to stabilize (about 1 to 2 minutes) before the current readings were taken. Surface voltage profiles of the disc-on-Kapton and solar array surfaces were obtained by sweeping the noncontacting/capacitance coupled electrostatic surface voltage probe[26] over the array about 2 mm above the test surface.

Plain Disc Experiment

The plasma coupling currents collected by the plain disc experiment as a function of positive and negative applied voltages are shown in Fig. 8 for plasma densities of about 2×10^4 and 2×10^3 electrons per cubic centimeter. Typically from 1 to 3 tests were conducted at each plasma density (within the accuracy of the Langmuir probes, i.e., within a factor of 2). Error bars represent the range of data that falls within the accuracy range of plasma density specified.

A theory for plain metallic discs as probes on spacecraft surfaces has been developed.[27] This theory indicates that current collection should be proportional to effective voltage; i.e., applied voltage minus space plasma potential. This has been found to be true for experimental data obtained in these tests. The empirical relationship found to fit the data is:

$$I = j_{eo}\frac{A_D}{4}\left[1 + \frac{V_A - V_P}{E_e}\right] \qquad V_A - V_P \geq 0 \qquad (1)$$

$$I = j_{io}\frac{A_D}{4}\left[1 + \frac{|V_A| + V_P}{E_i}\right] \qquad V_A - V_P < 0 \qquad (2)$$

where:

j_{eo} and j_{io}	the electron and ion thermal current densities
A_D	the surface area of the disc (9.9 cm^2)
V_A	the applied voltage
V_P	the plasma potential (~ +6 V)
E_e and E_i	the electron and ion temperatures (about 1 eV)

Comparison of this relationship with experimental data is shown in Fig. 8.

Plain Disc-On-Kapton Experiment

Plasma coupling currents collected by a biased disc resting on a Kapton insulation surface as a function of applied voltage and plasma density is shown in Fig. 9. The error bars again refer to the range of test values obtained at average plasma densities indicated.

Comparison of the average values from this experiment with the average values obtained with the plain disc experiment is shown in Fig. 10. This comparison illustrates the influence of Kapton insulation on disc plasma coupling current. For positive applied potentials, there is a tendency for the disc-on-Kapton current collection to be suppressed in the voltage range of +10 to +100 V (compared to the plain disc). Above +100 V, current collected by the disc-on-Kapton is greater than that of the plain disc. For all negative applied potentials, current collected appears to be the same for both experiments. Therefore, Kapton insulation seems to influence electron collection but not ion collection (at least for these test conditions).

Typical surface voltage profiles for the disc-on-Kapton experiment (see Fig. 11) can be used to understand the current collection phenomenon. At low positive potentials (≤100 V), the Kapton insulation will assume a potential such that electron current from the plasma to the insulation will be equal to ion current. This potential is referred to as the "floating" potential for that surface. In these experiments, the Kapton floating potential, according to the surface voltage probe, is about -6 V. Voltage applied to the disc will also generate fields in the plasma. Currents collected by the disc will depend on the net electric field in the plasma. This net field is determined by a superposition of disc electric field with that of the Kapton surface. Since the field generated by the negative surface voltage of the Kapton would repel electrons, one would anticipate that current collection of the disc-on-Kapton would be less than plain disc collection at low applied potentials. This appears to be verified by the experimental results.

When positive applied potential is greater than +100 V, the electric field from the disc expands into the Kapton. It is believed that this occurs because electrons from the plasma are accelerated by the electric field of the disc and strike the Kapton surface with sufficient energy to generate secondary electrons. Typically, for insulators, incident electrons with energies in the range of 50 to 1500 eV will generate at least one secondary electron per impact.[28] Since secondary electrons are emitted with only a few electron volts energy, they could be collected by the field generated by the voltage applied to the disc. Hence, the equilibrium condition for the Kapton surface (electron current equal to the ion current) is disturbed and the Kapton surface potential must change to reestablish equilibrium. The result is that the effective area of the disc as a current collector increases and the coupling current grows. When the disc electric field has expanded to encompass the Kapton surface completely, the rapid increase in the current stops and the experimental surface collects current proportional to the Kapton area and applied voltage. A comprehensive theory to account for these interactions requires treating material properties of the insulation as well as the expansion of fields in a plasma environment. No simple, empirical relationship has yet been found to fit the data.

For negative applied potentials, there is little difference between currents collected by the disc-on-Kapton and the plain disc. Surface voltage profiles show that the Kapton surface remains at its equilibrium potential (~-6 V) throughout the applied voltage range and that disc voltage remain confined to the disc region. Apparently, there are no secondary emission processes occurring that disturb the surface equilibrium. Therefore, ion current collection for the disc-on-Kapton should be proportional to only disc area for applied voltages to at least -1 kV.

It is believed that pinhole current collection phenomena can be explained by similar arguments. The difference between the disc-on-Kapton and a pinhole is that the insulation is between the biased conductor and the plasma for the pinhole experiment. This means that an electric field has to expand through the pinhole in the insulation. This may cause some variations in current collection, but the controlling factor in current collection should be the superposition of the field from the insulation surface voltage and the field generated through the pinhole from the biased conductor. These fields will depend on the material properties of the insulator. Additional experiments should be run to verify this behavior.

Scaling in this interaction still has to be addressed. Does the electron current collection through the same size pinhole become larger as the insulation area increases? Or are there limiting factors in this collection? Development of these scaling relationships will require addtional experimentation and analysis.

Solar Array Experiment

Plasma coupling currents obtained for the solar array experiment as a function of applied potentials and plasma densities are shown in Fig. 12. The data shows that electron current collection varies over orders of magnitude for positive applied potentials. When negative potentials are applied, discharges (arcing) occur. The threshold for arcing is at a lower potential for the higher plasma density.

Comparison of the current collected by the solar array experiment with that collected by the plain disc is shown in Fig. 13. For positive applied potentials there is again current suppression at voltages less than +100 V and enhancement at higher voltages. At applied voltages greater than +200 V, rapid rise in current collection stops and current collection is dependent on applied voltage.

For negative applied voltage, the current collected seems to be similar in trends to that collected by the plain disc to the potentials at which arcing occurs. The magnitude of the current collected by the array is less than that collected by the plain disc by roughly the difference in total conductor area (factor of 2).

Typical surface voltage profiles for the fiberglass-Kapton-solar cell-interconnect region of the array are shown in Fig. 14. For low positive applied voltages (< 100 V), the voltage profile is dominated by the equilibrium potential of the cover slides. The potential in the plasma is limited to values less than 10 percent of applied voltage. This effect appears to be in agreement with the model proposed in Ref. 8. However, as applied potential is increased above 100 V, the surface potential profile changes. The surface potential of the cover slide approaches that of the interconnects. It is as if the voltage sheaths have "snapped-over" or expanded to encompass the cover slide. The effective surface voltage sensed by the probe after the snap-over occurs is 50 V less than the applied voltage. Current collection rise occurs at the snap-over condition.

If it is assumed that a similar functional relationship found for the plain disc applies to the solar array experiment and that effective voltages are those measured by the surface voltage probe, then currents collected by the array should follow the empirical equations:

$$I_e = j_{eo} \frac{A_I}{4}\left[1 + \frac{V_m}{E_e}\right] \quad V_A \le 100 \text{ V} \tag{3}$$

and

$$I_e = j_{eo} \frac{A_P}{4}\left[1 + \frac{V_A - 50}{E_e}\right]^{0.8} \quad V_A > 100 \text{ V} \tag{4}$$

where

A_I the total interconnect area (4.8 cm^2)

A_P the total fiberglass/array area (180 cm^2)

V_m the measured surface voltage ($V_m \sim 0.1\ V_A$)

V_A the applied potential

The comparison between these equations and the data is shown in Fig. 12. Agreement is reasonably good except for the transition region. To improve the relationship would require a more sophisticated model.

When low negative voltages are applied to the segment, small voltages are recorded by the surface voltage probe for the interconnect region. As the negative voltage is increased, the voltage at the interconnect region increases but remains confined to the interconnects. When a discharge occurs, the electric fields at the interconnects are very intense. These strong fields are probably the cause of the arcing. No simple, empirical relationship for the current collection under negative bias was found.

The occurrence of discharges at the edges of solar cells has been verified photographically (see Fig. 15). The array segment shown in this figure has wrap around solar cells mounted on a flexible insulator substrate. Test results for this segment are similar to those discussed above. At plasma densities of about 10^4 electrons per cubic centimeter and applied voltages of about -600 V, arcing occurred at a rate of about 3 per minute. The photograph is a time exposure of 3 minutes so that 9 arcing events are recorded. All occur as bright flashes of light at the cell edges. This test is described in Ref. 29.

As with the disc-on-Kapton experiment, current collection of a solar array segment as a function of array size must be understood in order to extrapolate from small samples to very large arrays proposed for space. In an attempt to determine scaling relationships a test was conducted with a solar array panel having an area of 1480 cm^2. Plasma coupling current collected by this panel as a function of applied voltage in Fig. 16. Average values for the small solar array experiment are also shown for comparison.

For positive applied voltages snap-over occurred at about +100 V as verified by the rise in current and surface voltage profiles. Current collection of the large panel for applied voltages up to 100 V is believed to be similar to that of the smaller panel. However, the empirical relationship developed for the smaller panel indicates a smaller predicted current than was observed when the higher applied voltages were used (see Fig. 16). This would indicate that electron current collection mechanisms for the solar array are size dependent. The theory that large biased surfaces should collect current as a flat plate with strong edge effects[29] predicts that the current should have been larger than observed. The data may have been influenced by chamber size, however, since current collection shows saturation above +200 V applied. The test must be repeated in a larger facility, but the preliminary indication is that current collection for solar array segments is size dependent.

For negative applied voltages, the current collected appears to be weakly dependent upon voltage. This also may be a result of chamber size which could be resolved by a test in a larger facility. Note that there is evidence that arcing appears at approximately the same voltage value as for the smaller panel. This would indicate that arcing is dependent on the solar cell-interconnect relationship and not on array size.

Concluding Remarks

An investigation of interactions between high voltage surfaces and charged particle environments is being conducted. The goal of these tests is to develop an understanding of the interactions so that design guidelines can be formulated for high voltage space systems. Interactions of concern are coupling current power losses through the environment and discharges initiated by the environment.

An experimental program has been established to study interactions at plasma densities simulating low Earth orbits where interactions will be the strongest.

It has been found that insulator surfaces surrounding biased conductors strongly influence interactions with the plasma environment. Electron current collection is suppressed at low positive potentials but enhanced at voltages above +100 V. This controls the current collection to solar arrays and through pinholes in insulators.

At negative potentials the strongest interaction occurred in the solar array experiments. Discharges occur at potentials larger than -600 V for the plasma densities used in these tests. These discharges occur at the cell interconnects and appear to be due to strong electric fields existing there.

The attempt to determine scaling relationships for extrapolation to large space systems was not successful. It appears that the current collection for solar arrays is size dependent and that the arcing phenomenon is not. Simple extrapolation from small samples is not justified. Development of scaling relationships must await tests of larger surfaces conducted in facilities larger than the 1.8 m diam facility used for these tests.

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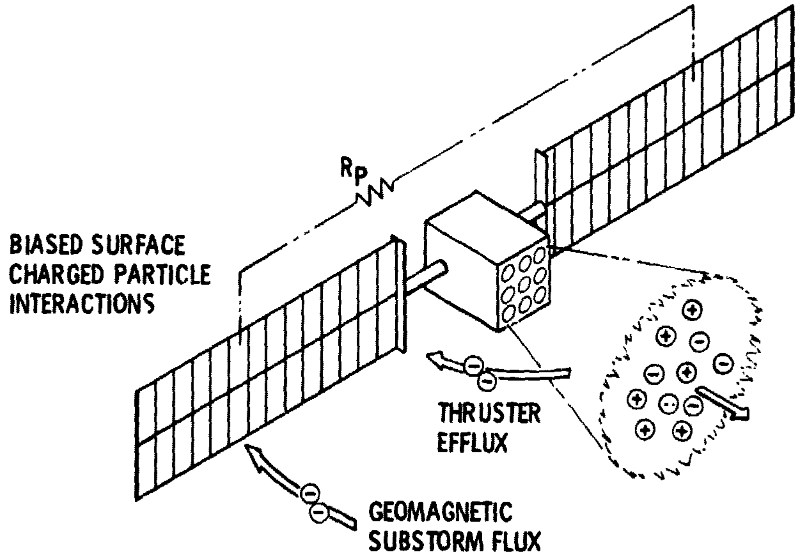

Figure 1. - Spacecraft-environment interactions.

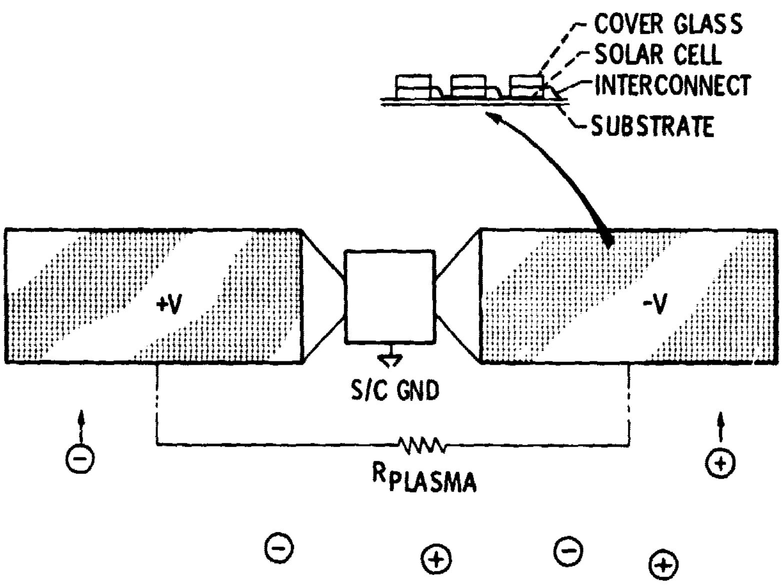

Figure 2. - Spacecraft higher voltage system-environment interactions.

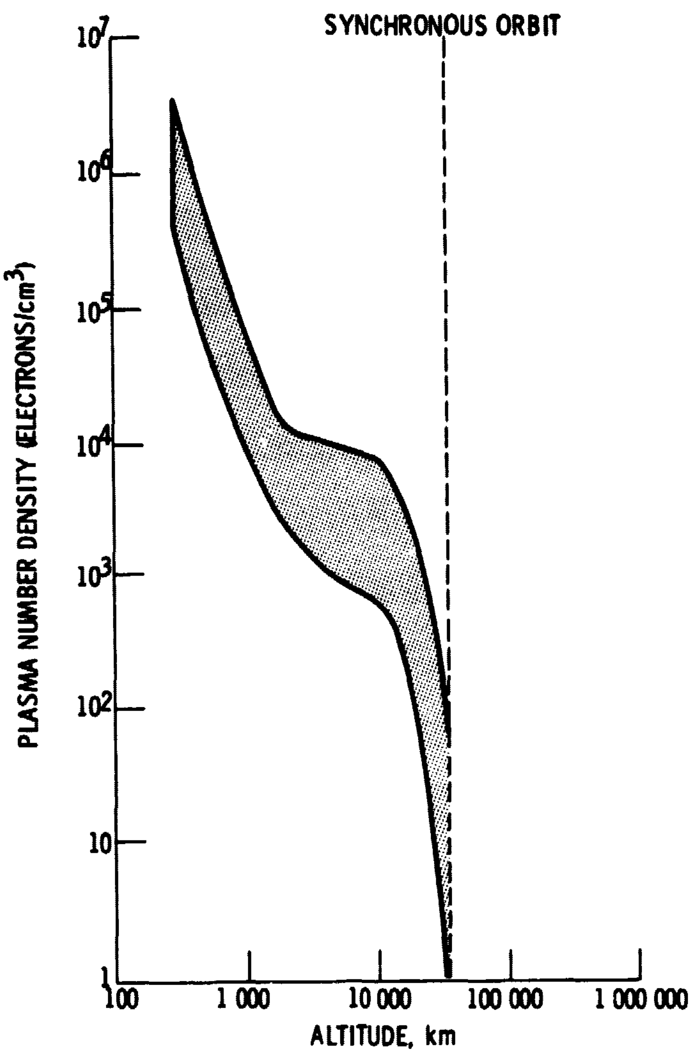

Figure 3. - Plasma number density vs altitude in equatorial orbit.

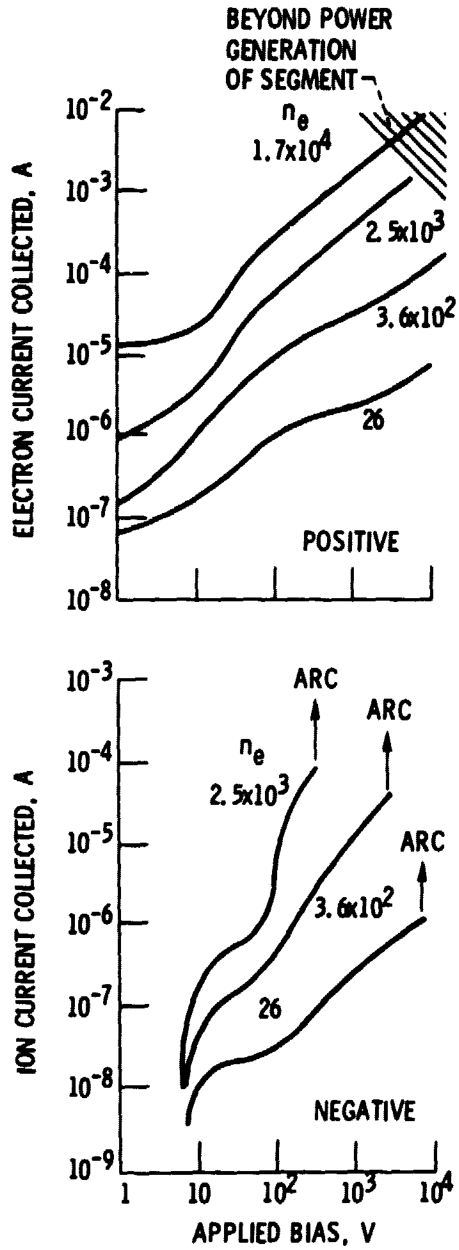

Figure 4. - Ground test results. Solar array segment; 1058 cm^2 area.

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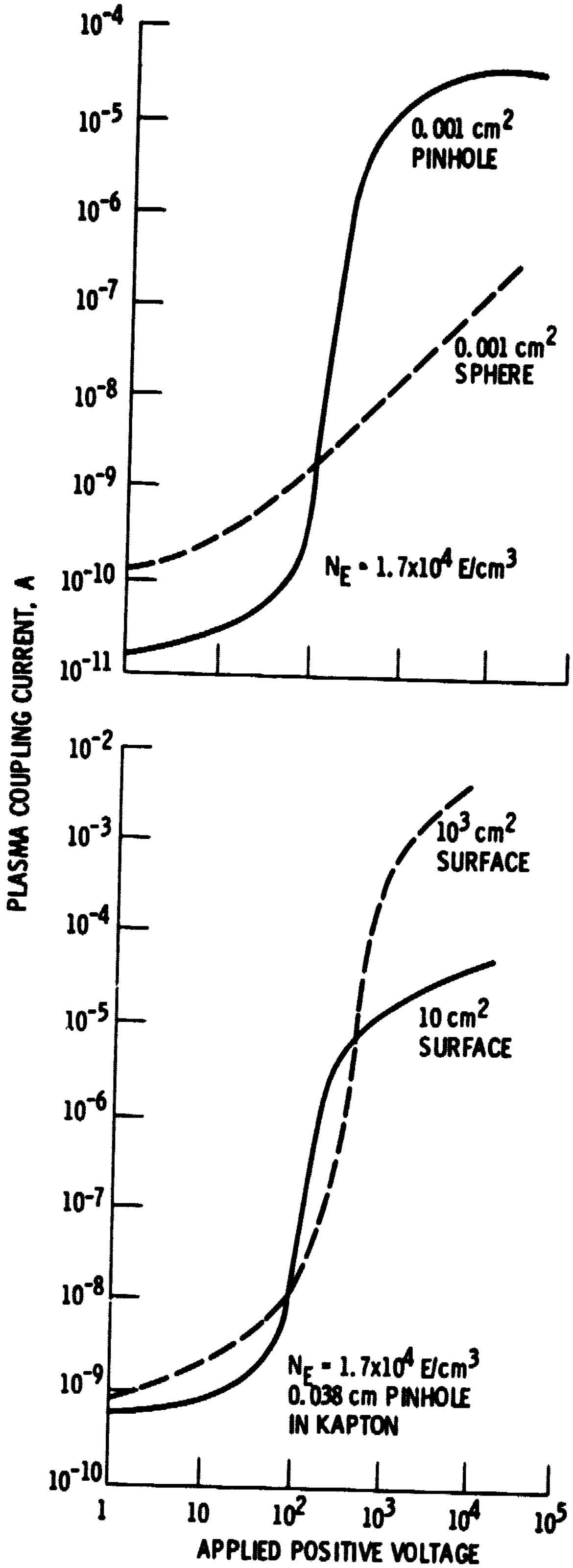

Figure 5. - Pinhole current collection phenomenon.

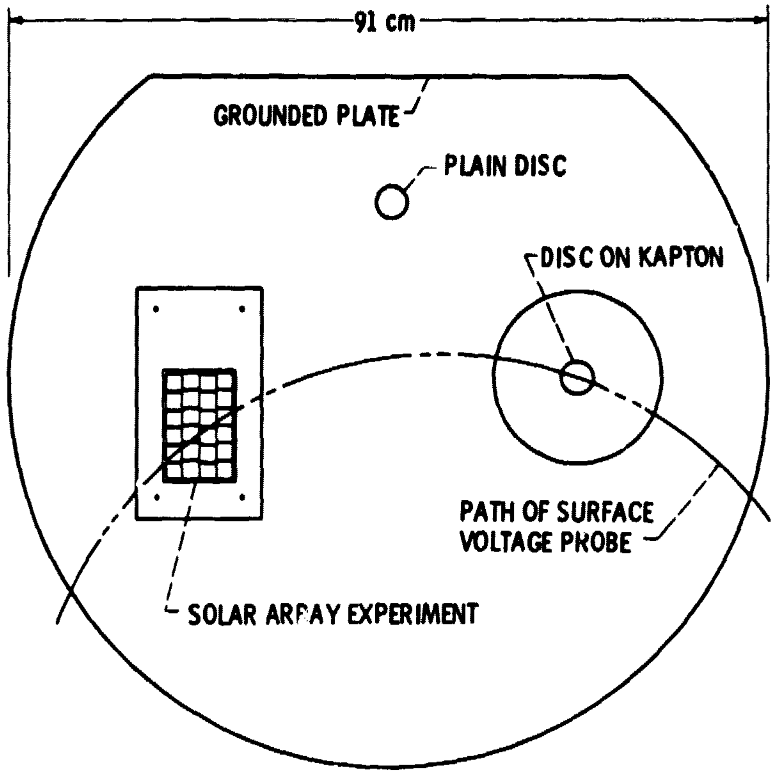

Figure 6. - Experiment surfaces.

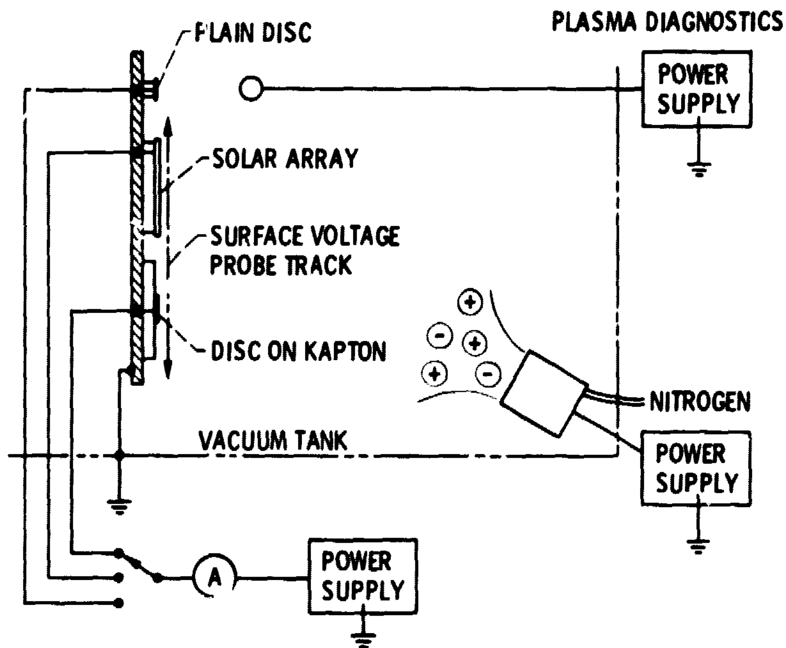

Figure 7. - Schematic diagram - test facility.

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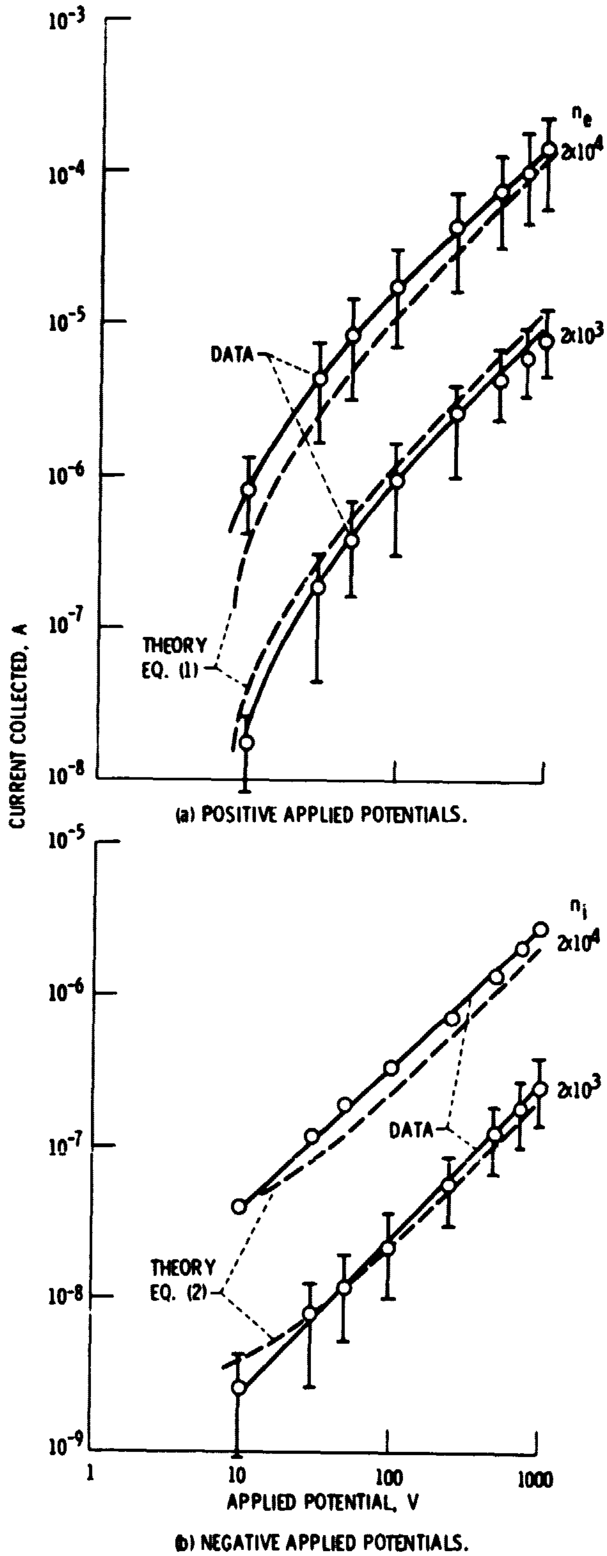


Figure 8. - Plasma coupling current. Plain disc experiment.

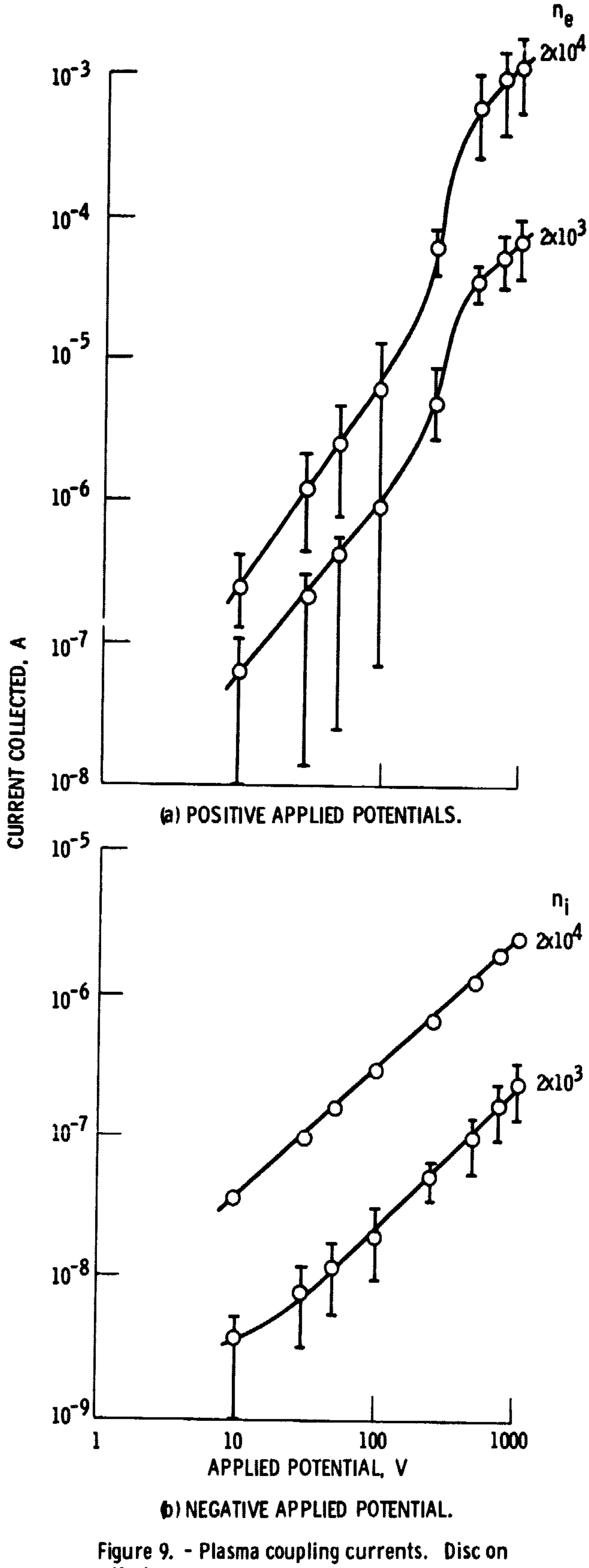


Figure 9. - Plasma coupling currents. Disc on Kapton.

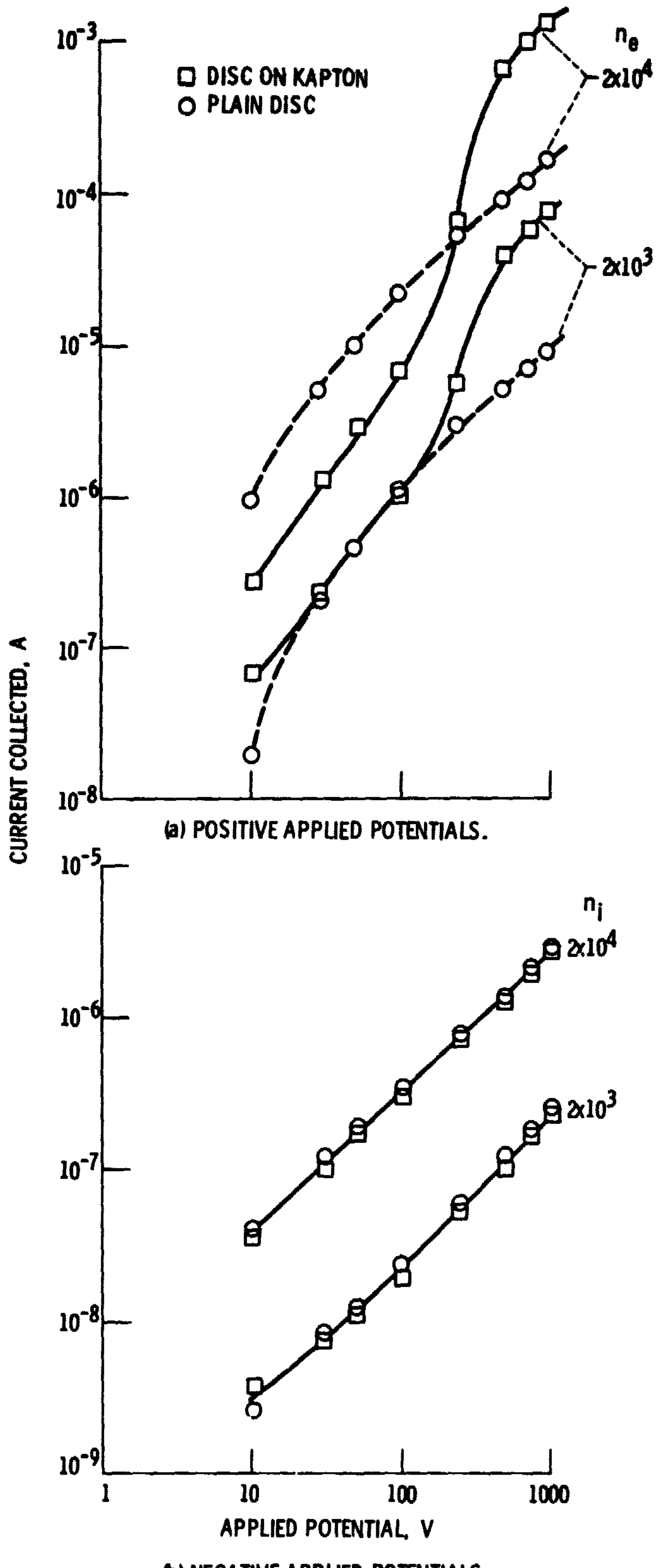


Figure 10. - Comparison of collected currents. Plain disc with disc on Kapton.

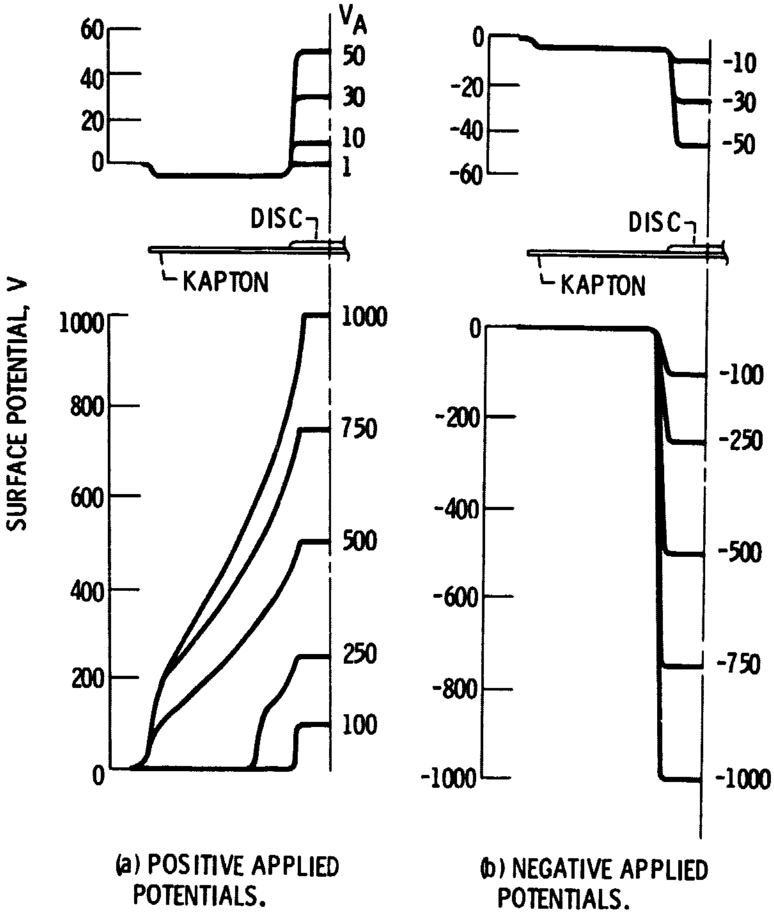


Figure 11. - Typical surface voltage profiles. Disc on Kapton.

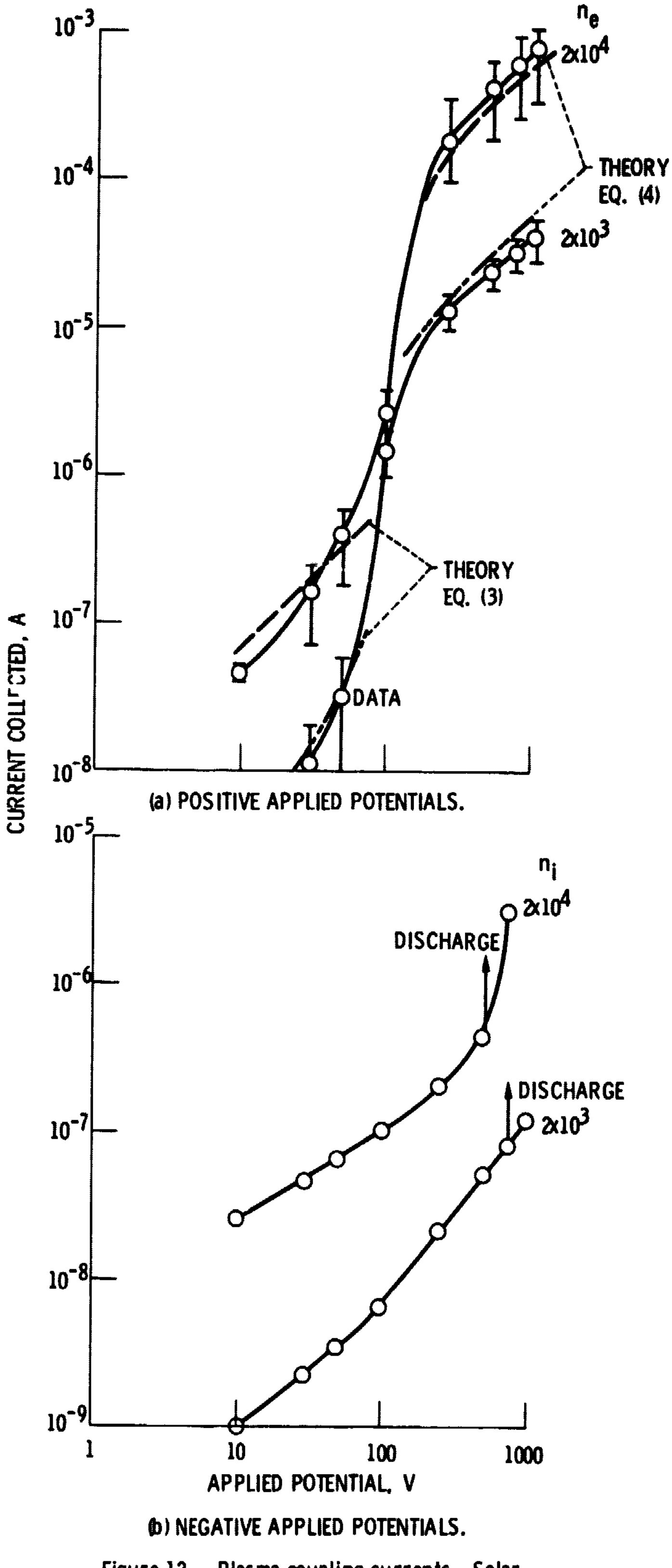


Figure 12. - Plasma coupling currents. Solar array experiment.

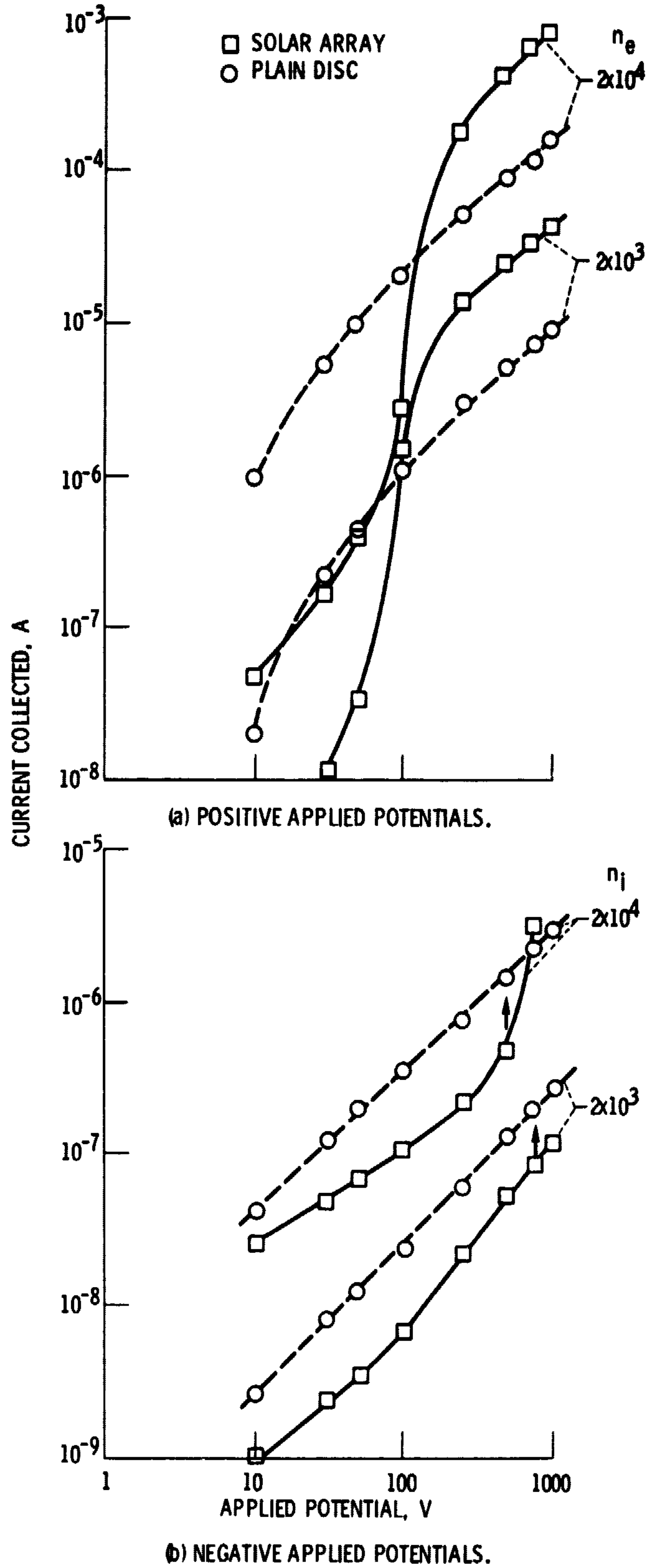


Figure 13. - Comparison of collected currents.
Solar array experiment.

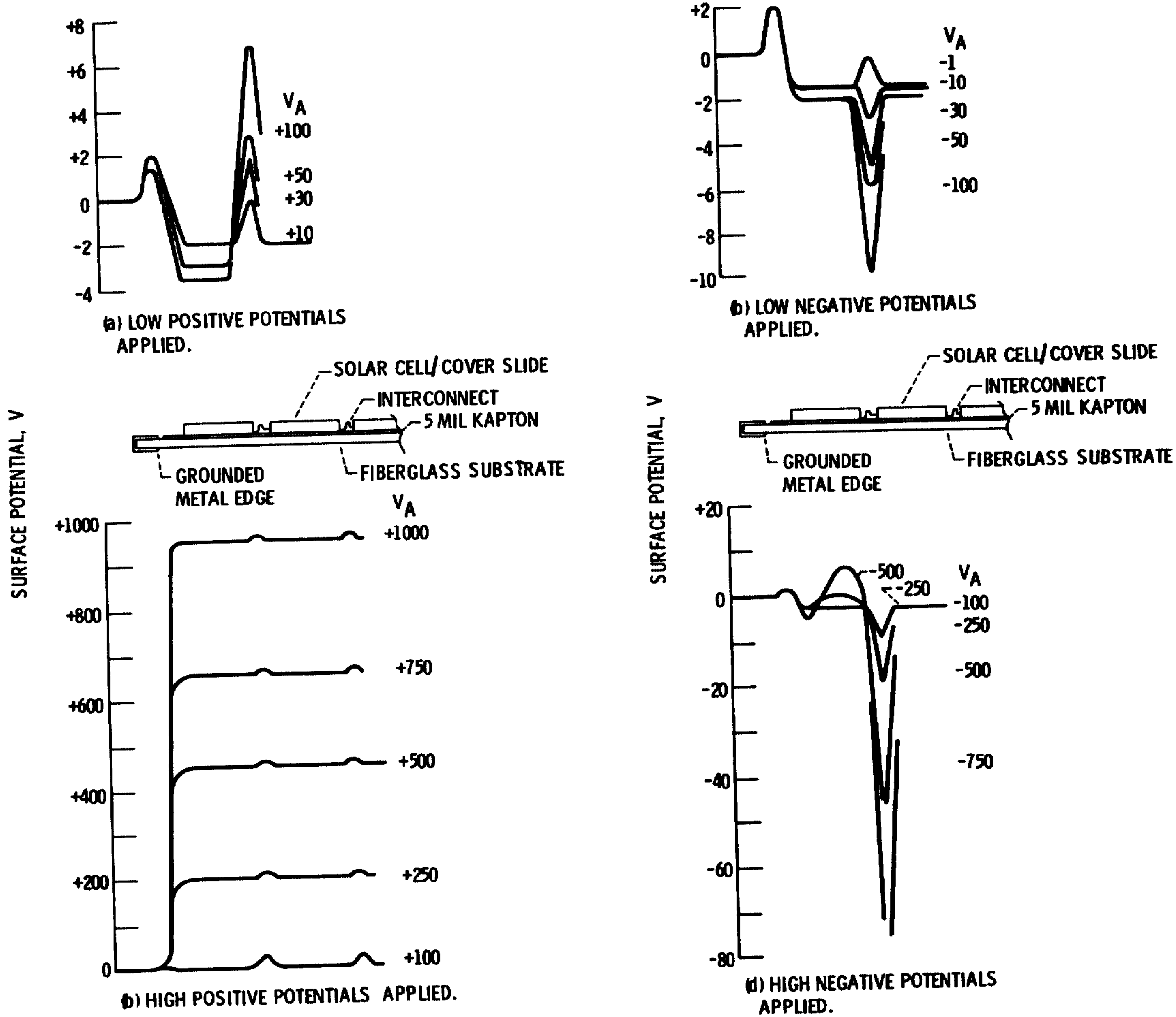
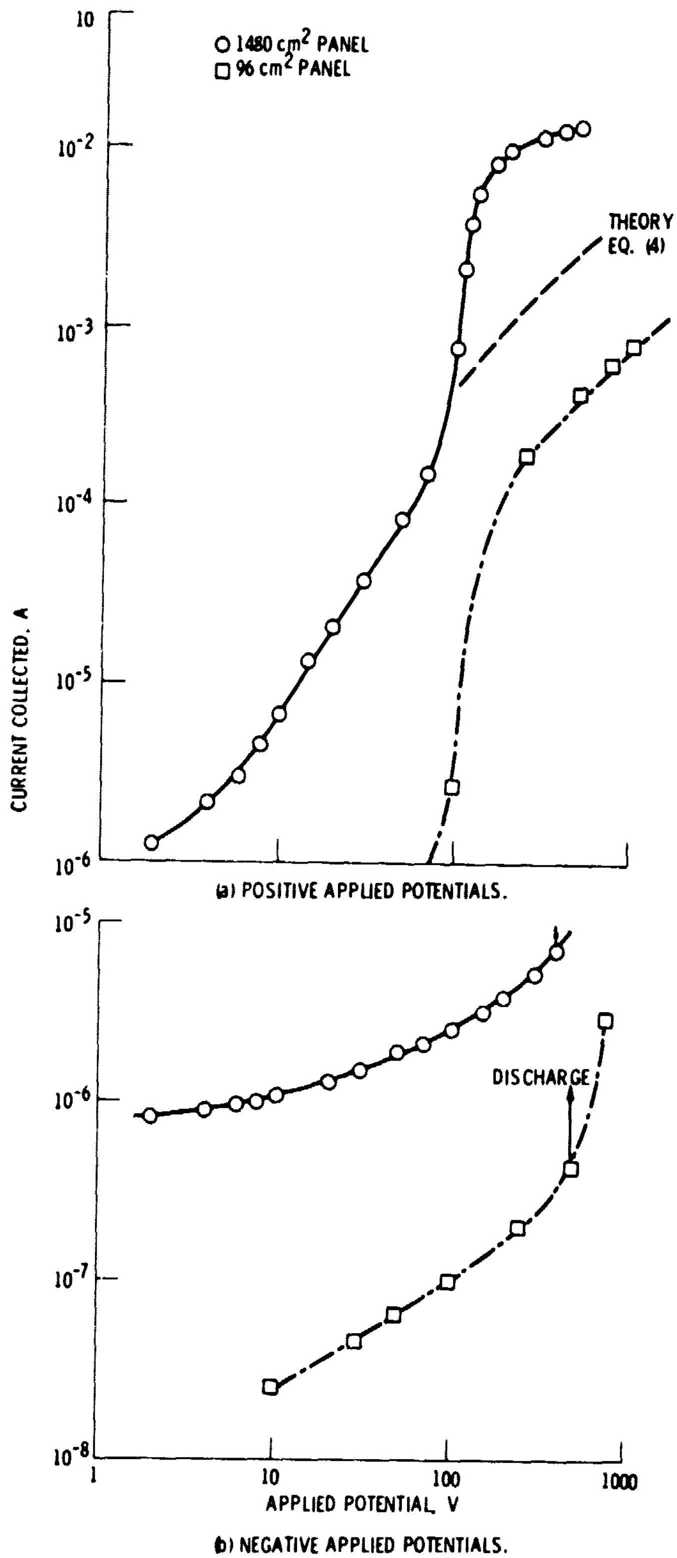


Figure 14. - Typical surface voltage profiles solar array segment.

Figure 15. - Arcing on solar cells array sample (cell side) 2x4 cm wraparound cells on Kapton.



(b) NEGATIVE APPLIED POTENTIALS.

Figure 16. - Effect of surface size on interaction. Solar array panels. $n_e \sim 10^4$ E/cm^3.