

INTERACTIONS BETWEEN LARGE SPACE POWER SYSTEMS AND LOW-EARTH-ORBIT PLASMAS

N. John Stevens
Hughes Aircraft Company
El Segundo, California

There is a growing tendency to plan space missions that will incorporate very large space power systems. These space power systems must function in the space plasma environment, which can impose operational limitations. As the power output increases, the operating voltage also must increase and this voltage, exposed at solar array interconnects, interacts with the local plasma. The implications of such interactions are considered herein. The available laboratory data for biased-array segment tests are reviewed to demonstrate the basic interactions considered. A data set for a floating high-voltage array test was used to generate approximate relationships for positive and negative current collection from plasmas. These relationships were applied to a hypothetical 100-kW power system operating in a 400-km, near-equatorial orbit. It was found that discharges from the negative regions of the array are the most probable limiting factor in array operation.

INTRODUCTION -

For the past several years NASA has been conducting mission-planning studies calling for extremely large satellites to be placed in low Earth orbits by the space shuttle.¹⁻⁴ Because the planners were freed from the constraints imposed by expendable launch vehicle shrouds, satellite dimensions grew to tens of meters and power generation requirements rose to hundreds of kilowatts.

Now that the Space Transportation System (i.e., shuttle) is operational, there is an effort under way to place such a large structure in orbit in the near future. The projected system could be a manned space platform capable of conducting Earth-oriented studies, space science investigations, or space manufacturing experiments. Although the mission is not finalized, it could involve an expandable platform - initially a simplified station that can be expanded in the future. The platform would probably be placed in an orbit similar to Skylab's (400 to 500 km) so that it could be serviced by the shuttle and yet be high enough to minimize reboost cost and have an adequate mission life. Array power requirements are postulated as being between 50 and 100 kW.

The generation of large power levels requires very large solar arrays since the nominal power density is of the order of 100 W/m^2 . Hence a 50-kW array would require an area of 500 m^2 . This area implies long cabling to bring power to the user. If the system were operated at a nominal voltage of 30 to 60 V, currents of the order of 1000 A would be required. Currents of this magnitude can produce either significant cable harness losses (I^2R) or unacceptable increases in weight if the cable loss is reduced by using thicker cross-sectional areas.⁵ In addition, large currents flowing in the array can generate magnetic fields that can interact with the Earth's. This increases

both the drag on the system and reboost cost. The alternative is to increase the operating voltages and thereby reduce currents. However, to date, the largest operating voltage used in space was the 100 V used for relatively short periods in Skylab.⁶ For this new space platform, operating voltages of 200 to 1000 V are being considered. The operation of power systems at high voltages can give rise to interactions with the space plasma environment that must be considered in designing these systems.

The interactions of concern are illustrated in the high-voltage space power system shown in Figure 1. This system consists of two large solar array wings surrounding a central body or spacecraft. The solar arrays are assumed to be assembled by standard construction techniques. This means that the cover slides do not completely shield the metallic interconnects from the environment. These cell interconnects are at various voltages depending on their location in the array circuits. Hence the interconnects can act as plasma probes and attract or repel charged particles. At some location on the array the generated voltages will be equal to the space plasma potential. Since the electrons are more mobile than the ions, the array will float at voltages that are mostly negative with respect to space plasma potential. Cell interconnects at voltages above this space plasma potential will collect electrons; those at voltages below this space plasma potential will collect ions. The voltage distribution in the interconnects relative to the space plasma potential must be such that these electron and ion currents are equal (i.e., the net current collected is zero).⁷

This flow of particles can be considered to be a current loop through space that is in parallel with the operational system and hence is a power loss. In addition, the cover glass used on the solar cells must also have a zero net current collection. This interaction with the space plasma forces the cover glass to a small negative potential and can produce large voltage gradients in the gap region between solar cells. This can give rise to arcing conditions or transient breakdowns to space.

The severity of these plasma interactions depends on the array operating voltages and the charged-particle environments. The operating voltage will be determined from power system studies but will probably be less than 1000 V. The charged-particle environment is determined by the orbital altitude (Fig. 2). At the projected operating voltages only the low-energy or thermal plasma environment should be of concern since the array voltage is too low to influence the higher energy environmental particles. This plasma environment has particles with temperatures of about 1 eV and densities that vary from a maximum of about $3 \times 10^6 \text{ cm}^{-3}$ at 300 km to between 1 and 10 cm^{-3} at geosynchronous altitudes. Hence plasma interactions should be more severe at the lower altitudes than at synchronous altitude.

These possible interactions between space power systems and plasma environments have been discussed elsewhere in general terms. In this paper the basic phenomena are reviewed and application to a space power system is discussed.

REVIEW OF BIASED-ARRAY TESTS

Tests of small segments of solar arrays biased by laboratory power supplies while exposed to simulated plasmas in vacuum facilities have been conducted over the past 10 years.⁸⁻¹⁶ A test of a similar nature has been conducted in space.¹⁷ Regardless of the size of the array segment (from 100-cm² to 13 600-cm² areas have been tested) the results are quite similar. In this section the test procedure and the pertinent results are summarized.

Such plasma interaction tests are typically conducted in an experimental arrangement shown schematically in Figure 3(a). The vacuum chamber is capable of pumping to background pressures of 10⁻⁶ torr or less. The plasma environment is created by ionizing a gas (e.g., nitrogen, argon, or helium). The plasma parameters (plasma number density and particle temperature) are usually determined with either cylindrical or spherical Langmuir probes. The solar array segment (Fig. 3(b)) is mounted in the chamber and is electrically isolated from the tank ground. A high-voltage power supply is connected to one or both ends of the array through an isolated feedthrough in the tank wall. A current-sensing instrument is placed between the power supply and the test sample to measure any coupling current between the segment and the tank ground through the plasma environment. This lead is shielded to minimize extraneous currents. A surface voltage probe (such as that manufactured by TREK) is used to sense the voltage on the array during the test. Hence a surface voltage profile and a leakage current measurement are obtained as functions of applied positive or negative voltage for a given plasma environment. It should be pointed out that the tank ground is not the plasma potential. This plasma potential is determined from the probe readings and must be added to, or subtracted from, the applied bias voltage in order to interpret the test data. It is very important to make this correction at low bias voltages since the plasma potential can be in the range ± 20 V.

Typical results for a 100-cm² solar array segment biased positively and negatively are shown in Figures 4(a) and (b).¹⁴ In the positive bias voltage case (Fig. 4(a)) the current collection starts at relatively low current values and increases slowly until a bias of about 100 V is reached. At this point there is a marked increase in current collection (by orders of magnitude). Above about 250 V the current tends to increase linearly with voltage. The surface voltage probe traces give an indication as to why this behavior occurs: At the low applied biases the voltage is confined to the gap region between the cells. The cover glass maintains its required zero current balance with the plasma by a slightly negative surface voltage. The superposition of the fields resulting from these voltages shields the bias voltage from the plasma. At biases greater than 100 V, the shielding appears to break down. The bias field now is stronger and starts to encompass the cover glass. This accelerates electrons from the plasma into the cover glass and creates secondary-emitted electrons. The surface voltage must now change to maintain a zero current balance at the glass surface. This surface voltage assumes a value that is about 50 V less than the bias voltage. Hence at this transition, called "snapover,"¹⁸ the collecting area is increased to the full segment area, and this increase changes the coupling currents. The data can be modeled empirically as cylindrical probe collection at positive bias voltages up to 100 V and as spherical probe collection (with the bias reduced by 100 V) at positive voltages greater than 100 V.¹⁶

For negative bias voltages (Fig. 4(b)) the data indicate that the coupling current increases slowly and then transits into an arc or breakdown, which is signified by a rapid rise in current that trips off the laboratory power supply. Since the supply is also used to bias metallic probes without breakdowns, it must be assumed that the arcing results from the interaction between the negatively biased conductor (cell interconnects), the dielectrics (cover slides), and the plasma environment. The surface voltage probe traces indicate that the gap region between cells is the probable cause for the breakdown. As the bias voltage is made more and more negative, the fields resulting from the cover glass voltage confine the bias field to this limited area. It is known that a negative conductor confined by a less negative dielectric is prone to breakdown and this appears to be happening here.

Both the positive and negative bias voltage effects described above are plasma-density-dependent phenomena. For the positive bias voltage cases both the low- and high-voltage collection changes in direct proportion to the density.^{11,14} However, the transition remains at about 100 V. The only condition that seems to influence the transition appears to be the relative areas of the segment and its dielectric and conductive boundaries. The data obtained in support of the PIX flight seemed to indicate a higher transition voltage¹⁷ probably because of the use of a small segment mounted on a large plate. The negative bias breakdown thresholds as a function of plasma density are shown in Figure 5. At the peak space plasma density environment (about 300-km altitude), this breakdown value is uncomfortably low (about 300 V negative relative to the space plasma potential).

The phenomena described above seem to occur independently of the interconnect configuration and array size. Both the standard interconnect configuration and wraparound configurations have been tested. Array sizes of 100 to 13 600 cm² gave similar results. The higher positive bias voltage results for the larger panels can be questioned, however, since the tank walls can interact with bias voltage sheaths and distort the results.

REVIEW OF FLOATING-ARRAY TESTS

Although the phenomena of plasma interactions with high-voltage solar arrays can be studied on small segments with bias voltages provided by external power supplies, tests must be run with self-generated voltages in order to validate the concepts developed. Unfortunately there have been relatively few such tests primarily because of the large array required to generate the high voltages needed and the subsequent large facility (with large solar simulators) required to obtain interaction data without wall effects. Even the small amount of data available is incomplete.

A nine-panel array is shown in Figure 6. This array was made up of surplus flight solar array panels with no attempt to match panel characteristics. Seven panels (1400 cm² each) were originally assembled in the late 1960's for the Space Electric Rocket Test (SERT-2) project, and two panels (1950 cm² each) were assembled in the early 1970's for the Space Plasma High-Voltage Interaction Experiment (SPHINX) project. This nine-panel array was used in a series of tests conducted at both the Johnson Space Center and the Lewis Research Center to evaluate the influence of facilities on plasma interactions.¹⁹ Johnson also did a series of floating tests using the solar simulator.

For this paper the results obtained with the nine-solar-panel array in the Johnson Space Center facility¹⁹ are used to provide a basis for predicting performance of large space power systems in a space environment. Since the panels were not matched and the solar simulator did not uniformly illuminate all nine panels, the results must be viewed as an approximation to the desired test data. Furthermore not all of the plasma properties were reported, so the particle energies and the plasma potential in the chamber had to be approximated.

The test was run with the array in an open-circuit condition but with the capability of measuring each panel voltage and the current between panels. The plasma density was $2 \times 10^4 \text{ cm}^{-3}$. The distribution of open-circuit voltages per panel after correcting for the assumed value of the plasma potential (10 V) is shown in Figure 7. The slope of the voltage is not the same for each panel because of the nonuniformity of the panels. In this configuration the array open-circuit voltage was about 248 V or slightly less than the 260 V obtained without the plasma. This is either due to a fluctuation in the solar simulator or, more probably, a slight loading of the array by leakage through the plasma. As shown in Figure 7 the array floats slightly positive and predominantly negative. This distribution was expected because the electrons are more mobile than the ions. It is interesting to note that the average value of the positive voltage panel is about 10 percent of the overall voltage. This is the assumption usually made in computing power system interactions with plasma environments.

The following empirical approximations for current collection¹⁶ were used to compute the coupling currents:

$$I_- \propto j_{e0} A_{int} \sqrt{1 + \frac{V_+}{E_e}}$$

$$I_+ \propto j_{i0} A_{int} \left(1 + \frac{V_-}{E_i} \right)$$

where

j_{e0}, j_{i0}	thermal electron and ion current densities, A/cm ²
A_{int}	interconnect area, cm ²
V_+, V_-	positive and negative average panel voltage (relative to plasma potential), V
E_e, E_i	electron and ion energies (normalized to electronic charge), eV

The relationships were iterated until the electron coupling current was approximately equal to the ion current. The results are shown in Figure 8 along with the measured values. The agreement is reasonable.

The agreement obtained here may be fortuitous in view of the many approximations made. If the behavior of high-voltage solar array systems is to be understood, it is mandatory that a well-conceived, complete set of experiments be conducted. These experiments must include bias voltage tests and self-generated voltage tests with the capability of achieving positive voltages above the snapover condition. This would answer questions on the negative voltage breakdown phenomena as well.

APPLICATION TO SPACE-POWER SYSTEMS

To illustrate the effect of plasma interactions on a large, high-voltage space power system, consider a 100-kW generator, made up of 10 modules of 10 kW each, operating in a 400-km, near-equatorial Earth orbit (Fig. 9). It is assumed that the modules are connected electrically in parallel to avoid a single-point failure that could occur with a series connection. Each of the modules is assumed to operate at a load voltage V_L and a load current I_L . The 100-kW power output of the system would then be available to the loads at a voltage V_L and current $10 I_L$.

Furthermore each of the modules is assumed to be built up from ten 1-kW solar array blocks connected in series. Each block would then generate a current I_L at an average voltage of $0.1 V_L$. Approximately one block would be at a positive potential relative to the space plasma potential; the other nine would be negative (Fig. 9).

The plasma environmental parameters for the 400-km orbit are given in Table I.18. The implications that could arise from the environmental measurements made on the third shuttle flight are discussed later in this section.

The plasma coupling or drainage current can be computed for the 10-kW module operating at an average V_L of 500 V and producing an I_L of 20 A. Each block would generate 1 kW of power at an average voltage of 50 V. The relationships derived in the previous section are used to compute the positive and negative coupling currents for this module, which is assumed to be typical for the system. The results are summarized in Table II. These results indicate that the currents do not balance and that another iteration should be made. But the average loss, of the order of 15 mA, represents a possible power loss of about 0.1 percent. This is such a negligible loss that refining the computations is considered to be unwarranted. This is true only when the positive voltage stays below snapover conditions (i.e., <100 V).

What is a concern is whether the blocks that are at negative voltages relative to the space plasma potential approach the breakdown threshold. This can have more serious consequences than the coupling current losses -- a block discharging to space can disrupt the whole power system output.

From discharge photographs obtained in ground tests on small biased solar array segments,^{16,18} it appears that the whole segment area is not involved in a given discharge. Hence only a finite area of a large solar array may be involved in any single discharge. The location of this finite area within the power system 1-kW block then becomes critical to evaluating the effect of discharges on system performance. If discharges occur at parallel paths within the block, thus allowing the module to continue to be a power generator, one would expect a ripple impressed on the dc voltage (Fig. 10). Since the breakdown threshold is not an absolute value and since there are 10 modules in this power system, there should be considerable randomness in the breakdowns and the resulting overall ripple.

The worst case would be when the discharge occurs in the series portion of the block and thus interrupts the block power output. If the output of a whole block is involved, the module output will also have a transient behavior since all blocks are in series. If a module power output is involved, then

the whole array output could temporarily collapse (Fig. 10). Random oscillations in the power output could be caused by the breakdowns in each module and by the, as yet unknown, lifetime influence on breakdown thresholds.

Environmental measurements on the third shuttle flight^{20,21} compound the difficulties imposed by possible plasma interactions. It has been found that because of photoemission from the surface the plasma environment around the shuttle in sunlight is approximately 10 times denser than previous measurements would indicate. Furthermore this dense environment seemed to stay with the shuttle for the 8 days of the mission. If this phenomenon holds true for all altitudes and for extended periods of time, the plasma surrounding a large power system could also be denser than previously considered. A factor of 10 increase in plasma density would increase the coupling current losses to about 1 percent, which may still be unimportant. However, the discharge threshold would be reduced significantly by such an increase and more blocks would be involved in discharge transients. This is a much more serious interaction problem.

These considerations apply to cases where the environment is assumed to be isotropic. Such conditions do not always exist in low Earth orbits and there can be significant changes during the orbit (Fig. 11). At certain times the active area of the array faces the orbital velocity direction ("ram"). Under such conditions the ion currents are increased (ram velocity is greater than ion thermal velocities), and this causes the array to float more positively relative to the space plasma potential. The result is higher coupling currents and lower discharge tendency. When the active area faces away from the orbital velocity direction ("wake"), the resulting deficiency of ions causes the system to float more negatively and thus the discharge probability to be greater. Finally the system will enter eclipse each orbit. This eclipse period is long enough to allow the array to cool significantly. Upon reentry to sunlight the cold solar array system could generate up to twice its normal voltage until the temperature returns to normal. Unfortunately the system would be entering the ram condition upon leaving eclipse, and so for a short time both power losses and discharges could be a concern.

The conditions described apply to a large space power system operating in a 400-km, near-equatorial Earth orbit. If the system were placed at a lower altitude (~300 km), the higher plasma density would increase the coupling losses and the discharge probability. At a higher altitude high-energy particle damage to solar arrays must be considered. Operating in a polar orbital environment brings in a variable plasma environment along with possible auroral flux interactions. Yet a plasma environment is not prohibitive to operations of space power systems provided that the possible interactions are considered and accounted for in system designs. The alternative of lower voltage operations is not necessarily safe nor conducive to power system growth.

CONCLUDING REMARKS

Plans for future NASA missions call for large space platforms operating in low Earth orbits. These platforms require large space power systems capable of generating a few hundred kilowatts of power. At these levels the operating voltage must be greater than voltages commonly used in present power systems. However, the higher voltage can result in interactions with the space plasma environment that can influence the operating characteristics of the power system.

Tests in ground simulation facilities in which small solar array segments were biased to positive and negative voltages in a plasma environment have shown that interactions can be detrimental. When positive voltages are applied, electron currents can be collected that become proportional to the panel area at voltages greater than 100 V. Under negative bias voltages arcing or breakdown can occur. This arcing threshold depends on the plasma density and can be as low as -300 V in simulated 300-km-orbit plasma environments.

Relatively few tests have been conducted in which an array capable of generating high voltages under solar simulation conditions was operated in a plasma environment. One such test of a nine-block, 13 600-cm² array has shown that the array would float electrically such that one block would have an average positive voltage that would be 10 percent of the overall voltage, with the other eight blocks progressively more negative. This test indicated that array behavior could be approximated by considering the interaction with separate blocks at an average voltage.

This approach was applied to a 10-kW array that was considered to be part of a 100-kW space power system operating at 500 V. Ten 10-kW arrays, each in parallel, made up this system. It was found that, under normal quiescent conditions, the power drain due to the electron coupling current would be negligible. However, the arcing in the negative-voltage regions could seriously disrupt system operations either by introducing a ripple on the output or by terminating operations depending on the severity and location of the breakdowns. The orbital oscillations ranging through ram, wake, and eclipse conditions generally tend to make the situation worse. Finally the evidence from the shuttle experiments that indicate that large space structures could create their own plasma environment tends to make plasma interactions even more critical.

For the past 12 years the advantages and disadvantages of large space power system operations at high bus voltages have been argued and discussed. There are obvious advantages to using high voltages in space. Possible hazards to such operations with standard array technology have been addressed herein. These interactions are not insurmountable but can be overcome given adequate understanding of the phenomena. What is needed is a systematic investigation to determine why discharges occur and how to prevent them. This would require test programs involving large arrays with self-generated voltages and finally a flight experiment to prove that all of the interactions can be minimized.

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TABLE I. - ENVIRONMENT AT 400-km ORBIT

Plasma characteristics:	
Electrons:	
n_e, m^{-3}	2×10^{11}
E_e, eV	0.22
Ions (O_{16}^+):	
n_i, m^{-3}	2×10^{11}
E_i, eV	0.09
Spacecraft orbital velocity, km/sec	
77	
Plasma current densities, A/m ² :	
Isotropic:	
Electron, j_{eo}	2.4×10^{-3}
Ion, j_{io}	9.4×10^{-6}
Ram-(ion): j_{io}	2.6×10^{-4}

TABLE II. - SUMMARY OF PLASMA COUPLING CURRENTS

[Assumed operating conditions for module: $V_{op} = 500$ V and $I_{op} = 20$ A; for block: $V_{op} = 50$ V and $I_{op} = 20$ A.]

Block	Average potential (relative to space), V	Plasma coupling current, mA
1	50	-10
2	0	-4
3	-50	-6
4	-100	1.1
5	-150	1.7
6	-200	2.3
7	-250	2.8
8	-300	3.4
9	-350	4.0
10	-400	4.5

C-4

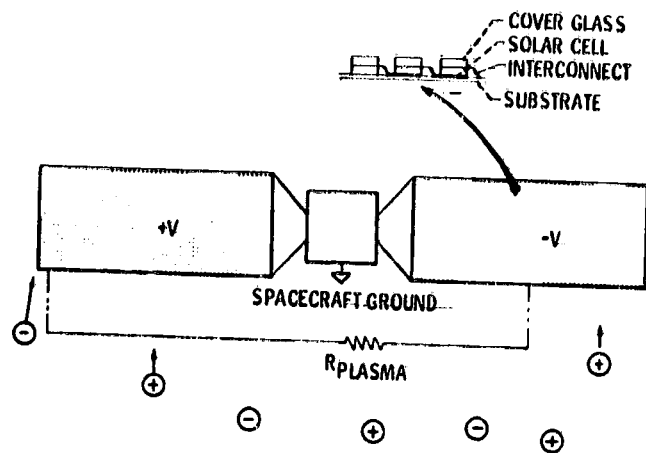


Figure 1. - Spacecraft high-voltage system - environment interactions.

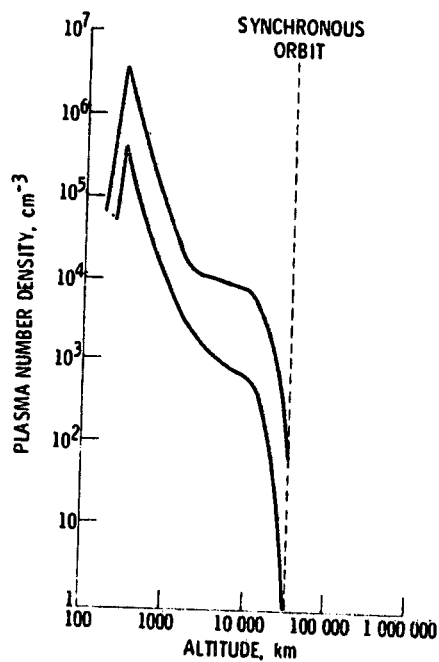
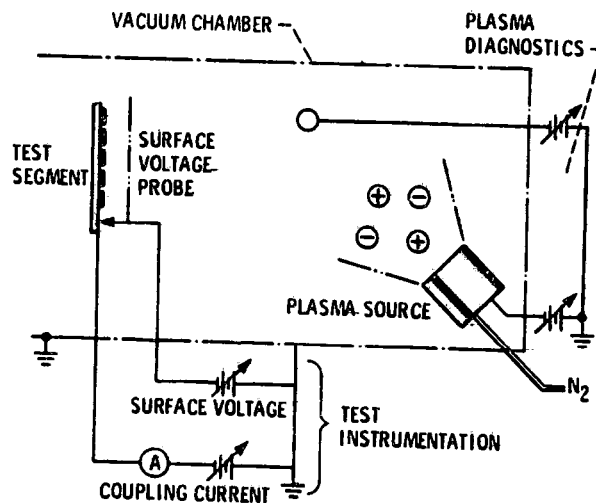
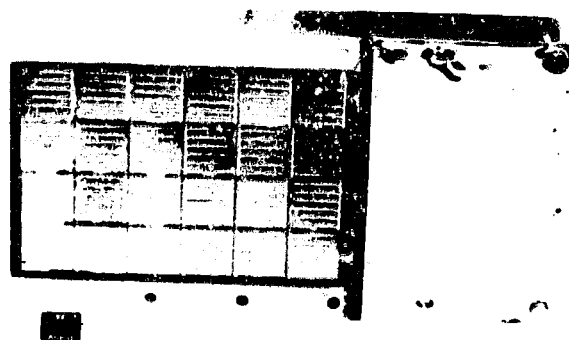


Figure 2. - Plasma number density versus altitude in equatorial orbit.

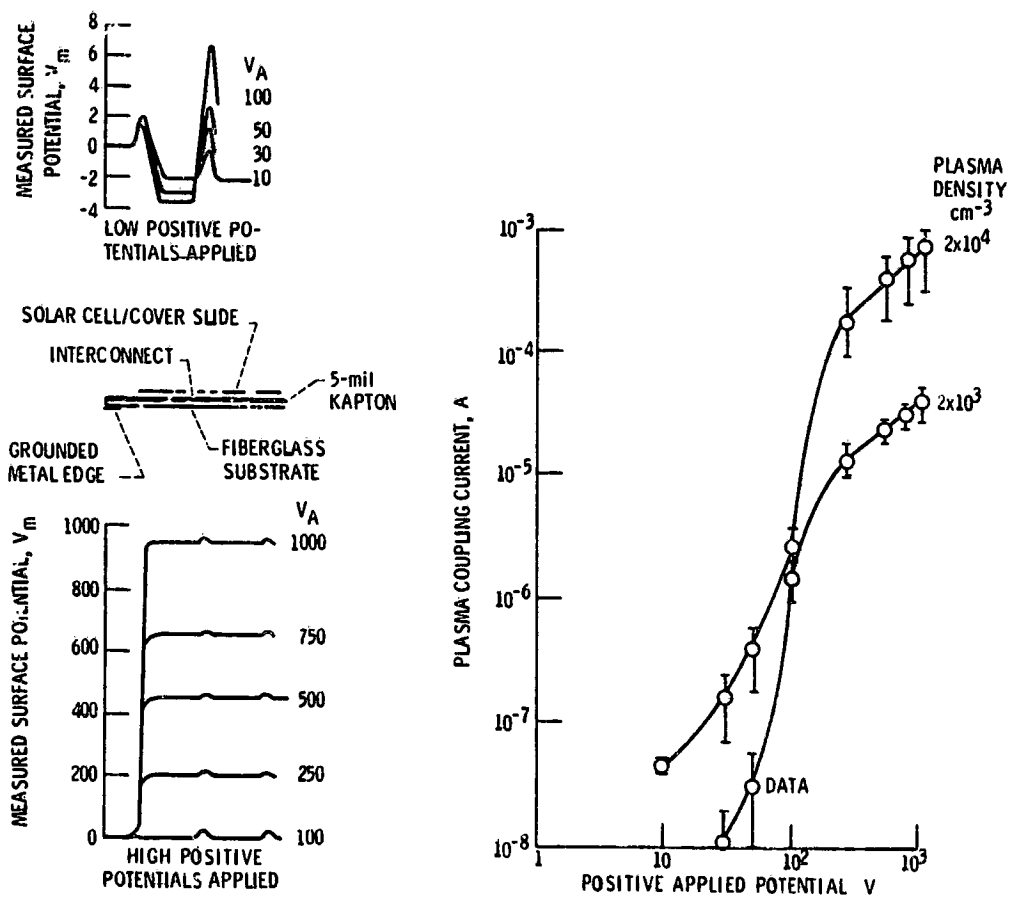


(a) Schematic diagram of test arrangement.



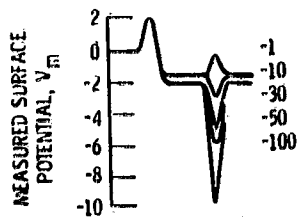
(b) Solar array segment.

Figure 3. - Ground simulation tests.

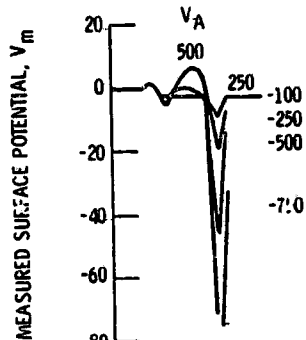
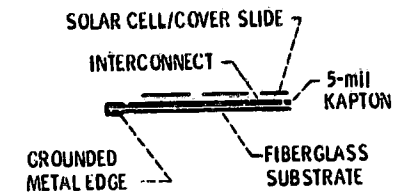


(a) Positive applied potentials.

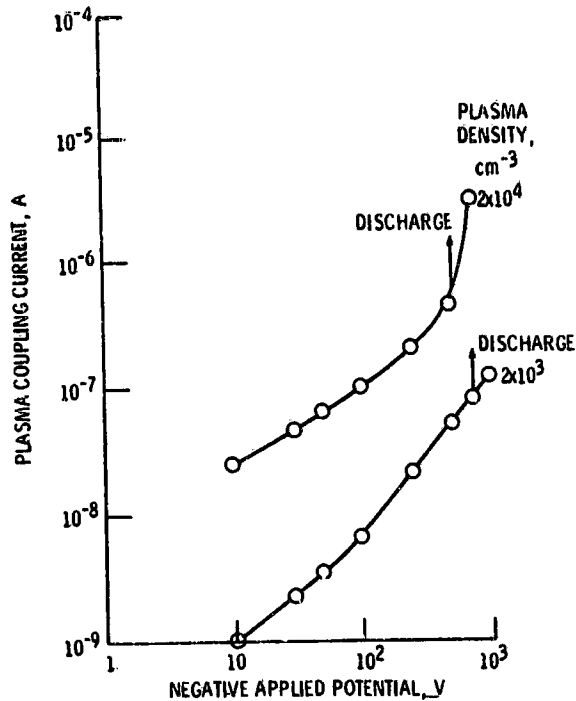
Figure 4. - Solar array surface voltage profiles and coupling currents.



LOW NEGATIVE POTENTIALS APPLIED



HIGH NEGATIVE POTENTIALS APPLIED



(b) Negative applied potentials.

Figure 4 - Concluded.

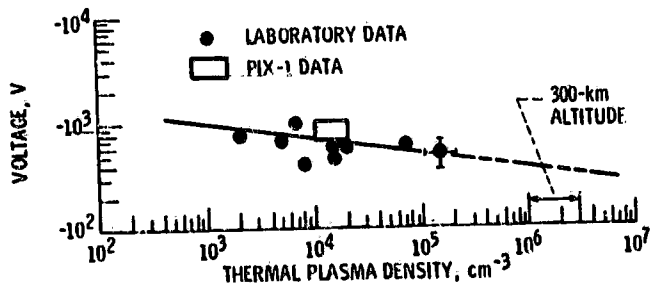


Figure 5. - Voltage threshold for breakdown.

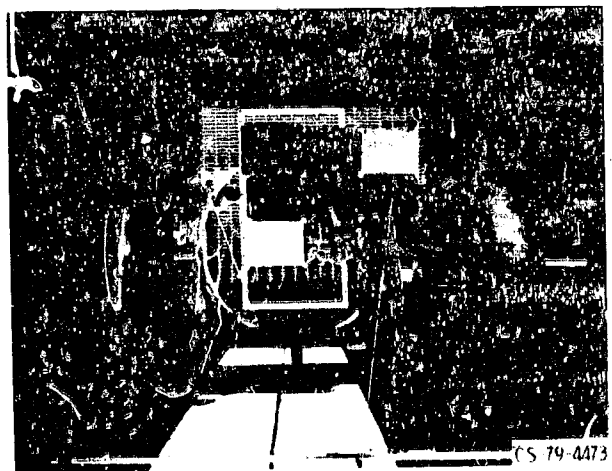


Figure 6. - Large solar array panel test.

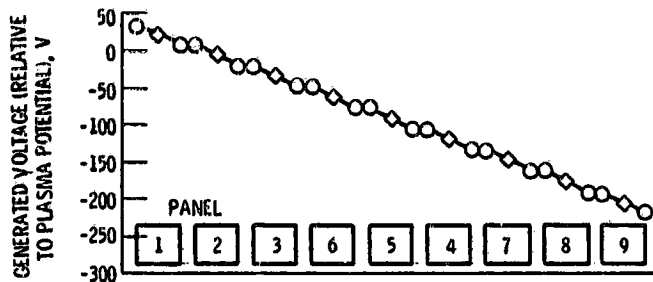


Figure 7. - Generated voltage distribution for nine-panel array.

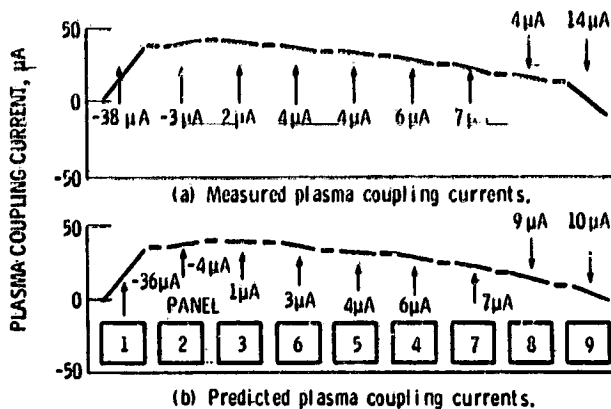


Figure 8. - Comparison of measured and predicted plasma coupling currents for nine-panel array.

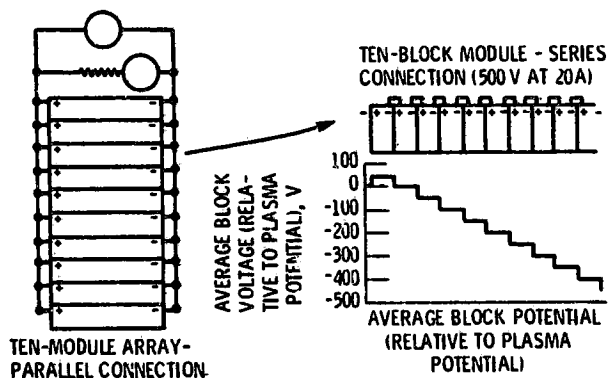


Figure 9. - Space power system concept (100 kW generated at 500 V).

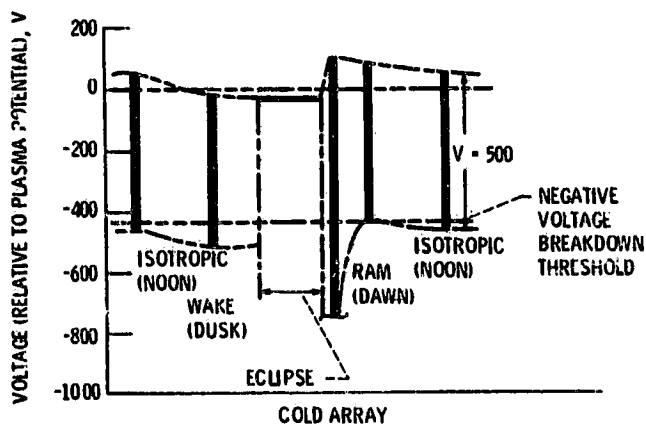


Figure 11. - Orbital variations in operating conditions - 400-km orbit.

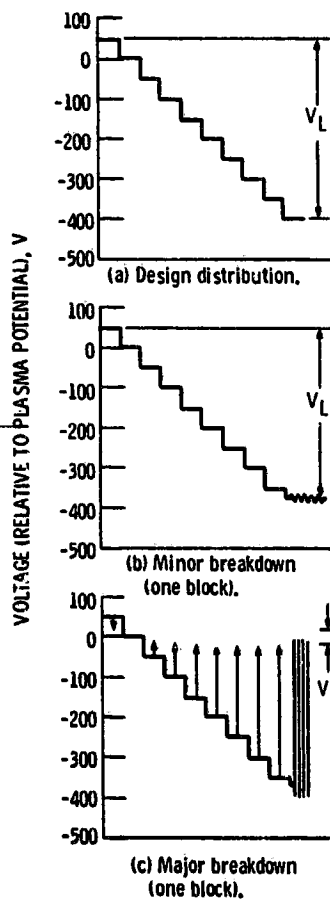


Figure 10. - Influence of breakdowns on solar array behavior.