INTERACTIONS BETWEEN SPACECRAFT AND THE CHARGED-PARTICLE ENVIRONMENT

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SUMMARY

Spacecraft-environment interactions are defined as the responses of a spacecraft surface to a charged-particle environment. This response can influence spacecraft system performance. Interactions can be divided into two broad categories: spacecraft passive, in which the environment acts on the spacecraft; and spacecraft active, in which the spacecraft causes the interaction. Passive interactions include the spacecraft-charging phenomenon. Active interactions include the relatively new interactions arising from the use of very large spacecraft and space power systems in future missions. In this category the concern is both for the effect the environment can have on spacecraft systems and for the effect the large spacecraft can have on the environment. To illustrate active interactions, a large power system operating at elevated voltages is considered. Possible interactions are described, available experimental data are reviewed, and the effect on power system performance is estimated.

INTRODUCTION

Spacecraft have traditionally been designed to fit within launch vehicle capabilities and shroud dimensions. At times, the ingenuity of designers has been severely taxed to include all systems within these constraints. As a result, spacecraft typically have been cylinders (or at least packaged as cylinders) 150 to 300 centimeters in diameter, with deployables as required. Now, with the advent of the shuttle space transportation system, these limits have changed. Very large spacecraft can be accommodated for future missions. Studies are being conducted on spacecraft to be used for such diverse activities as manufacturing, scientific exploration, power generation, and human habitation in locations ranging from low Earth orbits (250 to 400 km) to geosynchronous altitude and beyond (refs. 1 to 8). Structures proposed for these missions range in size from 200 meters for a large structure-assembly demonstration in the mid-1980's (ref. 9) to several kilometers for the Solar Power Satellite (SPS) (ref. 3). These large structures are being designed with relatively lightweight materials to achieve the required low densities.

These spacecraft must function in the space environment. Anomalous behavior of geosynchronous satellite systems has shown that the space environment is not completely benign. Interactions between the charged-particle environment and spacecraft exterior surfaces (i.e., spacecraft charging) can disrupt spacecraft systems (refs. 10 and 11). The size of the new generation of spacecraft will be approximately the plasma Debye length in the geosynchronous environment. This can result in increased interactions between the insulators and quasi-conductors and the charged-particle environment. The large size of these new spacecraft raises concern about charging effects on them in low Earth orbits. In this environment the spacecraft moving through the Earth's magnetic field can induce electromagnetic stresses that should be considered in the design. The spacecraft physical dimensions are also of real concern for their effect on the environment.

Proposed large, high-power systems ranging from tens of kilowatts to gigawatts have given rise to another aspect of environmental interactions. One means of improving electrical efficiency and reducing weight for these power systems is to operate at voltages higher than those currently being used. The SPS design calls for the generation of 15 gigawatts to 40 kilovolts. To date, the highest operating voltage used in space is the 100-volt system in Skylab. At this voltage, interactions with the environment are negligible (ref. 12). Operation at higher voltages in a plasma environment, however, can influence system performance.

For these reasons, spacecraft-environment interactions are associated with future space programs. These interactions must be understood, evaluated, and neutralized, if necessary, in the design phases of the programs. In this paper, categories of spacecraft-environment interactions are defined and briefly described. The primary emphasis is on interactions between the environment and large space power systems operating at elevated voltages. Available experimental data on high-voltage surface-plasma interactions are reviewed and, based on this information, the effect of these interactions on power system performance is estimated.

SPACECRAFT-ENVIRONMENT INTERACTION CATEGORIES

In this paper, spacecraft-environment interactions are defined as the responses of a spacecraft surface to the charged-particle environment of space. Spacecraft surfaces will respond to the environment at all altitudes. However, the interaction is of concern only where it influences system performance.

Interactions of concern between a spacecraft and the environment are illustrated in figure 1. A large spacecraft configuration with a large, high-power solar array is illustrated. There are two broad categories of interactions: category 1, spacecraft passive, where the charged-particle environment acts on the spacecraft surfaces; and category 2, spacecraft active, where the spacecraft causes the interaction. Each of these categories is described in the following paragraphs.

Category 1 - Spacecraft Passive Interactions

The principal spacecraft passive interaction of concern is spacecraft charging. This interaction occurs primarily at geosynchronous altitudes when kilovolt energy particles from geosynchronous substorms electrostatically charge shadowed insulating surfaces to high negative voltages. If the voltage stress on an insulator exceeds its breakdown threshold at an edge or an imperfection (ref. 13), discharges can occur. Energy from this discharge can couple into the spacecraft electrical harness, upset low-level logic circuits, and disrupt system performance. In addition, discharges can deteriorate thermal control surfaces and thus increase spacecraft temperatures. The differential charging of spacecraft surfaces can also ionize neutral gas molecules and enhance surface contamination by attracting charged particles back to the spacecraft surfaces (ref. 14). It can also disrupt scientific instrument measurements. Since there are many references available on this subject (e.g., see refs. 10 and 11), it is not discussed further in this paper.

Other aspects of this category of interactions, such as the possibility of charging by high-energy environmental particles and sputtered atoms, have not been fully investigated. It has been suggested that in a high-energy interaction such particles could charge the wires within a satellite by penetrating the exterior and depositing on wire insulation (ref. 15). Another possible interaction involving high-energy particles could occur if particles are deposited within the exterior surface of a satellite while the exterior surface is neutralized by the thermal plasma (low-energy components of the environment). This could build up an electrostatic bilayer, similar to that suggested in reference 16, which could discharge. This phenomenon would be more likely to occur where the charged-particle environment is more energetic, on spacecraft in the Earth's radiation belts or in the Jovian environment. In the sputtered-atom interaction, sputtered particles could become charged and, as such, they would be an additional current to be considered and an additional source of contamination particles. Specifically excluded from consideration in spacecraft passive interaction is radiation damage to solar cells and electronic components. This has been studied in detail by others.

Category 2 - Spacecraft Active Interactions

In spacecraft active interactions the spacecraft itself or a system on the spacecraft causes the interaction with the environment. These interactions are of concern at all altitudes in space. Spacecraft active interactions include those involving the motion of very large spacecraft proposed for future missions. The orbital velocity of spacecraft through the Earth's magnetic field can induce electric fi 's within the structure. The differential voltages induced by a large spacecraft can be significant and can give rise to electromagnetically induced forces that can cause distortions within the structure (ref. 17). These induced forces and any subsequent interaction with the environment must be accommodated in the design of large space structures. These interactions are discussed in more detail in references 18 and 19. Very large structures in space can also modify the environment by sweeping out charged particles (ref. 17). Such structures can drastically change the charged-particle environment and cause further interactions with themselves. These problems must be resolved before large space structures are launched.

The principal interaction of concern in this paper is the coupling between the thermal or low-energy plasma environment and a space power system operating at elevated voltages. This interaction, illustrated as the parasitic current loop in figure 1, is discussed in more detail later in this paper. The thermal plasma environment in equatorial orbit (fig. 2) ranges from about a million particles per cubic centimeter in low Earth orbits to about 10 particles per cubic centimeter at geosynchronous altitude. The thermal energy of these particles is less than 5 eV. This environment can interact with exposed portions of high-voltage systems, and these interactions must be considered in system designs. Interactions that must be evaluated are plasma coupling currents between the high-voltage system and the environment, effects of charge stored in or on the insulator surface, and plasma-initiated discharges (refs. 20 and 21). These interactions are described as functions of operating voltages, time in orbit, plasma properties, and insulator properties. The effect of these interactions on power system performance is illustrated in the next section.

INTERACTIONS WITH LARGE SPACE POWER SYSTEMS

The concept of a large space power system is used to illustrate the rationale for operating at elevated voltages and to estimate the influence of environmental interactions on system performance. Since some effects are configuration dependent and plasma interactions are complex, simplifying assumptions are made in this illustrative example. More sophisticated computer programs are being developed to investigate these interactions in more detail (refs. 22 to 25).

Power System Characteristics

The concept of a large space power system assumed to illustrate interactions with the environment is shown in figure 3. This system is composed of 5-kilowatt solar-array modules connected to give the desired total power output. These modules are each 5 meters by 10 meters and have operating line voltage and current, V_L and I_1 as shown in figure 4. The modules are arranged in pairs on two wings. Power is generated with all modules at the same specified voltage and is brought into a central load region on a pair of transmission lines on each wing. Power is converted to the required voltages within the central body. With this arrangement the modules on each wing form parallel electrical circuits: All are on the same voltage V_L with the load current increasing in equal amounts in the transmission line as modules are added. Power systems capable of generating 20 to 500 kilowatts (in increments of 20 kW) can be conveniently studied.

The first consideration is to determine the operating voltage for the system. As shown in figure 4, voltages for a 5-kilowatt module could vary over a wide range from the commonly used 30 volts to 5000 volts. The advantage of higher voltages is usually a reduction in power loss and weight. This advantage can be demonstrated by simple computations of the power loss and weight of the transmission lines alone as the power level increases.

In these computations the transmission line is assumed to be aluminum, based on the results given in reference 26. The cross-sectional area of each line is assumed to be constant at 1 square centimeter. The power lost in the four main transmission lines, expressed as a fraction of the total power generated, can be calculated from

$$\frac{P_L}{P_T} = \frac{4}{P_T}\left(I_1^2R_1 + I_2^2R_2 + I_3^2R_3 + \ldots + I_n^2R_n\right) = \frac{4\rho}{P_TA}\sum_{i=1}^{n} I_i l_i \qquad (1)$$

where

P_L power lost in transmission lines, W

P_T total power generated, W

I_i load current in line at each module, A

R_i resistance in line at each module, ohms

ρ electrical resistivity of aluminum, 2.8×10^{-6} ohm-cm

A cross-sectional area of transmission line, 1 cm^2

l_i characteristic line length for each module, cm

n number of 10-kW module sets on one wing

Since the modules are considered to be added in pairs on each wing in parallel electrical circuits, the load current is computed on the basis of 10-kilowatt module sets at a specified operating voltage. As module sets are added to increase power output conditions, the load current increases by equal amounts. The characteristic line lengths have been assumed to be the distance to the center of each module set. For the first module set this is the distance from the central load section (assumed to be 10 m). Line lengths for subsequent module sets are assumed to be 5.5 meters.

Results of computations based on equation (1) are shown in figure 5. It is apparent from this figure that any power system, with the assumptions used here, would dissipate nearly all its power in the lines if 500 kilowatts were generated at 100 volts. For large space power systems, operational voltage levels must be increased to reduce line losses.

The assumption of constant cross-sectional area for the transmission line is poor because of thermal considerations. A 1-square-centimeter cross-sectional line would probably vaporize at the currents indicated for 100-volt operation. A trade-off must be made between power loss and the weight gained by increasing the line cross-sectional area. Such a trade-off can be approximated for the power system considered here. The line weight in grams is

$$W_L = 4\gamma A \sum_{i=1}^{n} l_i \tag{2}$$

where γ is the density of aluminum (2.7 g/cm^3). Thus, the line weight required to maintain a 5-percent power loss in the transmission line is computed. This weight is compared with a total system weight based on a design goal of 10 kg/kW. Combining equations (1) and (2) to eliminate the cross-sectional area and expressing the result as the desired weight fraction results in

$$\frac{W_L}{W_T} = \frac{16\gamma\rho}{W_T P_L}\left(\sum_{i=1}^{n} I_i^2 l_i\right)\left(\sum_{i=1}^{n} l_i\right)$$

where W_T is the total system weight in kilograms. Since it is assumed that $P_L = 0.05\ P_T$ and $W_T = 10\ P_T$, then

$$\frac{W_L}{W_T} = \frac{32\gamma\rho}{W_T P_L}\left(\sum_{i=1}^{n} I_i^2 l_i\right)\left(\sum_{i=1}^{n} l_i\right) \tag{3}$$

The results of equation (3) are shown in figure 6. Here again a 500-kilowatt system operating at 100 volts with a 5-percent power loss in the transmission lines would have a line weight approximately equal to the desired total system weight. Hence, operating voltages must be increased to make large power systems feasible. The method of computation used here totally neglects any effects within the 5-kilowatt modules. If these effects are considered, there could be additional line losses that would be minimized by higher voltage operation.

Other power system design concepts - such as a single, very large solar array and modular designs with multiple transmission lines (a pair for each module) - have been subjected to similar reviews. The results are similar: Power losses and weight can be significantly reduced by operating at higher voltage levels.

In the example described here, operating voltage levels are allowed to vary from 100 to 5000 volts. In an actual system, high-voltage components would be needed for switching and other operations. Although these high-voltage components do not now exist, the technology for developing them is being pursued (ref. 26). Although large power systems should use high operating voltages to minimize power losses and weight, a high-voltage system exposed to space could interact with the charged-particle environment. This interaction could influence system performance. These possible interactions and their effect on system performance are discussed in the following paragraphs.

Background. - The spacecraft-system - charged-particle-environment interaction considered here was briefly described in the definition of category 2 interactions. In this section, the description of this interaction is expanded.

Consider a solar-array power system as shown in figure 7. In the standard construction of this array, cover slides do not completely cover the metallic interconnections between solar cells. These cell interconnections are at various voltages, depending on their location in the array circuits. Because the array is exposed to space plasma, the interconnections act as biased probes, attracting or repelling charged particles. At some location on the array, the generated voltage is equal to the space plasma potential. Cell interconnections that are at voltages V_+ above the space potential will attract an electron current that depends on the number density and energy of the electrons in the environment and on the voltage difference between the interconnections and space. Those interconnections that are at voltages V_- below the space plasma potential will repel electrons and attract an ion current. The voltage distribution in the interconnections relative to space must be such that electron and ion currents are equal. This flow of electrons and ions can be considered as plasma coupling currents that form a current loop in parallel with the spacecraft electrical load. The loop is parasitic and represents a power loss. This interaction should be more pronounced in low Earth orbits because of the high number density of the low-energy thermal plasma (fig. 2).

Experimental results. - To assess the impact of space plasma on solar-array performance, it is necessary to estimate the current collection (i.e., the plasma coupling current) of an array that has small, biased conductor areas surrounded by large areas of insulation. This estimate is based on results of experiments conducted on biased solar-array segments in plasma environments. Such experiments (refs. 27 to 30) have been conducted ever since an interesting enhancement effect was first reported 10 years ago (ref. 31). The results presented here are based primarily on tests made at the Lewis Research Center (ref. 12). All other results are in substantial agreement with these.

A small solar-array segment of twenty-four 2-centimeter-by-2-centimeter cells mounted in series on a Kapton sheet and a fiberglass board was tested in Lewis' geomagnetic substorm simulation facility. This segment had standard mesh interconnections between the cells. Bias voltages V_A were applied to the segment by laboratory power supplies to determine both positive and negative voltage interactions. The test facility was housed in a 1.8-meter-diameter by 1.8-meter-long vacuum chamber capable of operating in the 10^{-6}-torr range. A plasma environment was generated by ionizing nitrogen gas. Both plasma coupling currents and surface voltages on the array segment were measured during the tests, which were conducted at plasma densities of about 10^4 and 10^3 per cubic centimeter (ref. 32).

Surface voltage profiles for part of the segment are shown in figure 8. For low, positive applied potentials ($\leq$100 V), the quartz cover slide assumes a small negative voltage in order to maintain electron and ion currents to that surface (fig. 8(a)). This voltage is measured about 3 millimeters above the quartz surface by a noncontacting, capacitively coupled surface voltage probe.

Negative voltage on the quartz cover slides appears to suppress the voltage in the plasma above the interconnections to less than 10 percent of the applied voltage. As positive potentials are increased above 100 volts, a transition occurs in surface voltage profiles (fig. 8(b)): The surface voltage of the quartz cover slides approaches that of the interconnections. It is as if the voltage sheaths have "snapped over" or expanded to encompass the cover slides. A voltage sheath is the distance required for the voltage to decay to plasma potential through the rearrangement of plasma particles. Snap-over seems to occur when the sheath approaches solar-cell dimensions. Effective surface voltage after snap-over is 50 volts less than the applied voltage.

Results for negative applied voltages are shown in figures 8(c) and (d). The quartz cover slides again assume slightly negative voltages. Electric fields in the plasma due to the biased interconnections are suppressed and confined by the quartz surface voltage. Instead of a snap-over phenomenon, this confinement remains until the field builds up to a point where discharge occurs. The voltage at which breakdown (discharge) occurs depends on the plasma density. For these tests, breakdown occurred at about -600 volts at densities of about 10^4 per cubic centimeter and about -750 volts at densities of about 10^3 per cubic centimeter. Other tests have indicated that breakdown can occur at densities corresponding to geosynchronous altitudes when the negative bias voltage magnitudes are greater than 5000 volts (ref. 28).

Plasma coupling currents for the small segment are shown in figure 9. The current collection phenomenon agrees with the trends indicated by the surface voltage data. For low, positive applied potentials (<100 V), plasma currents in amperes can be approximated by an empirical relationship that depends on the measured or suppressed voltage in the plasma and the interconnections:

$$I_e = j_{eo} \frac{A_i}{4} \left(1 + \frac{V_m}{E_e}\right) \qquad \text{for} \quad V_A < 100 \text{ V} \tag{4}$$

where

j_{eo} electron thermal current density, A/cm^2

A_i total interconnection area, 4.8 cm^2

V_m measured voltage in plasma at interconnection, V

E_e electron temperature in plasma, eV

V_A applied bias voltage, V

The measured voltage V_m has been found to be about 10 percent of the applied voltage V_A.

For positive applied potentials greater than 100 volts, the current collection in amperes can be approximated by what appears to be space-charge-limited current collection based on a reduced voltage and the panel area:

$$I_e \approx j_{eo} \frac{A_P}{4} \left(1 + \frac{V_A - 50}{E_e}\right)^{0.8} \qquad \text{for} \quad V_A > 100\ \text{V} \tag{5}$$

where A_P is the total fiberglass panel area (180 cm^2). In the transition region (≈100 V), no expression has been found to fit the current data.

Plasma coupling current collection at negative voltages seems to fit a relationship similar to equation (4), where ion thermal current density and temperature j_{io} and E_i are substituted for j_{eo} and E_e to the point where there is a transition to discharge. No relationship has been developed to predict the onset of discharge at various plasma densities.

Modern solar-array technology seems to favor a wraparound interconnection over the conventional mesh interconnection (fig. 10). Wraparound interconnection construction eliminates the expansion bend of the conventional interconnection, and this conceivably might influence plasma interactions. A sample of 2-centimeter-by-4-centimeter solar cells, with wraparound interconnections, mounted on a Kapton sheet was tested to evaluate the interaction (ref. 12). Surface voltage profiles for tests in plasma densities of 10^5 per cubic centimeter at positive applied voltage are shown in figure 11. Here snap-over occurred at a slightly higher voltage (190 V), possibly because of the large solar-cell size. When negative voltages were applied, the discharge phenomenon was again observed. Onset of breakdown for this sample was about -700 volts. In this test, the discharges were photographed (fig. 12) and are seen to occur at the cell edges, as would be expected from surface voltage profiles.

High-voltage operation may cause long-term degradation of solar-array performance even if plasma coupling currents can be neglected. The only test conducted to date to evaluate this condition is a 114-hour test of a 100-square-centimeter solar-array segment. The segment was biased to 4 kilovolts and the plasma environment was controlled so that the coupling current was kept at 10 microamperes (ref. 28). (From short-term tests this coupling current was considered to be too low to cause detrimental effects.) After the test, however, the interconnections had obviously darkened and the cover slides appeared to be coated. Voltage-current curves of the array segment made before and after the test indicated a 7-percent decrease in short-circuit current (fig. 13). This contamination may have been due to facility effects, and additional testing is required to evaluate possible enhanced contamination effects.

A solution to interaction problems would be to cover all biased conductors. This would work only if there are no penetrations in the covering. Experimental results obtained when a small pinhole (0.038 cm diam) was made in a Kapton insulating film over a biased conductor are shown in figure 14. Such holes in insulators can result in disproportionally large electron currents. Furthermore, tests have indicated that collection currents can be proportional to the total insulator area (ref. 28). The mechanism for this pinhole current collection phenomenon appears to be an interaction between electric fields from the pinhole expanding into the plasma and along the insulator surface. This effect can be seen from results of tests with a biased metal disk placed on a Kapton insulator (ref. 32). At low, positive applied potentials the Kapton surface assumed a slightly negative voltage (fig. 15). As the applied voltage exceeded 100 volts, the surface voltage on the Kapton changed: It became more and more positive until the whole surface was strongly positive. It is believed that plasma electrons are accelerated into the Kapton and generate secondaries that are collected by the disk and increase the measured currents. For negative applied potentials, the electric fields remained in the region of the disk and no increased currents were found.

The experimental results reported here were obtained on relatively small solar-array and insulator-pinhole samples. The effects obtained with these small samples have been verified in space by the Plasma Interaction Experiment (PIX) flight results (ref. 33). Tests with larger samples (10 m by 1 m) to evaluate increased area effects have recently been started (ref. 34). The small-sample tests indicate that there can be significant interaction effects that could influence space power system performance. The initial indications from the large-sample tests seem to verify the results of the small sample tests. These results are summarized in figure 16. For those areas of the array that are positive with respect to the space plasma potential, there will be electron collection interactions. At low, positive voltages these interactions will depend on biased interconnection areas and a suppressed voltage. As voltages increase, there will be a transition to whole-panel current collection that probably will depend on space-charge-limited current collection. At negative voltages, ions will collect at the interconnections at suppressed voltages. As the array voltage becomes more strongly negative, discharges or arcing will disrupt the power generation.

The influence of these experimentally determined interaction effects on the performance of large, high-voltage space power systems is considered in the next section.

Interaction Effects on Large Power Systems

By using information gained from experimental results, we can estimate the influence of environmental interactions on a large space power system like that shown in figure 3. Such a power system will float electrically at some voltage relative to the space plasma potential so that equal electron and ion currents will be collected. Since electrons are more mobile than ions, the array will be predominantly negative with respect to space potential. Absolute ground reference is the space plasma potential and not the spacecraft. Those areas of the array that are positive V_+ with respect to the space plasma potential will collect electrons as in the positive applied potential experiments. Those areas of the array that are negative V_- with respect to the space plasma potential will collect ions as in negative applied potential experiments. System operating line voltage V_L will be the sum of the absolute values of the positive and negative voltages (i.e., $V_L = |V_+| + |V_-|$).

To determine the floating potential of this power system, electron and ion currents have to be computed as a function of environmental parameters, system geometry, and voltage differences between the array and space. The method of current collection of large panels is not completely understood at this time.

Several papers on this phenomenon have been given at this conference (refs. 22 to 25). However, to illustrate the environmental interaction effects, experimental results given in the previous section are extrapolated here to large systems.

Based on experimental results, the following charged-particle interactions should occur in a large space power system:

(1) Those portions of the array that are at positive voltages less than 100 volts will collect electron current proportional to the interconnection area and to a voltage that is about 10 percent of the actual voltage at the interconnections (eq. (4)).

(2) Those portions of the array that are at positive voltages greater than 100 volts will collect electron currents proportional to the panel area and to a voltage that is 50 volts less than the actual voltage at the interconnections (eq. (5)).

(3) Those portions of the array that are at negative voltages will collect ion currents proportional to the interconnection area and to a voltage that is about 10 percent of the actual voltage at the interconnections (ion current version of eq. (4)).

(4) Discharges will occur in low Earth orbits in those portions of the array that are between -500 and -1000 volts, and at geosynchronous altitudes in those portions of the array that are greater than -5000 volts.

The second interaction states, in other words, that higher-positive-voltage portions of the array will collect electron current proportional to the 0.8 power of the voltage. Another model for current collection at these voltages has been proposed (ref. 12). This model assumes that current collection can be computed as the electron flux to an expanded sheath. The sheath is curved at the panel edges, with the radius of curvature determined from the Child-Langmuir relationship, and flat across the central portion of the array. In this model the radius is proportional to the 0.75 power of the voltage. So the functional dependence of both models is similar.

Since environmental interactions between a space power system at various voltages and the space charged-particle environment should be more pronounced in low Earth orbits, this environment is used in this illustrative example. Pertinent environmental parameters for 400-kilometer orbital conditions are given in table I (ref. 35). The magnitude of plasma coupling current interactions at geosynchronous altitudes can be assumed to be orders of magnitude less than those in low Earth orbits since the thermal plasma density is less.

Under equilibrium conditions, the voltage distribution on the interconnections will assume values such that the total electron current I_e collected from the plasma (electron plasma coupling current) will equal the ion current I_i collected. Since electrons are more mobile than ions, areas A_+ of the array that are at positive voltages will be smaller than areas A_- that are at negative voltages. Furthermore, it can be expected that the positive voltage

V_+ of the electron collection areas (relative to the space plasma potential) will be less than the negative voltage V_-. These conditions can be written as

$$I_e = I_i$$

or

$$j_{eo} \frac{A_+}{4} \left(1 + \frac{0.1\ V_+}{E_e}\right) = j_{io} \frac{A_-}{4} \left(1 + \frac{0.1\ V_-}{E_e}\right) \qquad \text{for } V_+ \leq 100\ \text{V}$$

and

$$j_{eo} \frac{A_+'}{4} \left(1 + \frac{V_+ - 50}{E_e}\right)^{0.8} = j_{io} \frac{A_-}{4} \left(1 + \frac{0.1\ V_-}{E_e}\right) \qquad \text{for } V_+ > 100\ \text{V}$$

where

$$|V_+| + |V_-| = V_L$$

and

A_+' panel area at positive voltage

j_{eo}, j_{io}, E_e, and E_i plasma properties (table I)

The total interconnection area is assumed to be 5 percent of the total array area.

To solve these equations, a relationship between collection areas and voltages above and below space plasma potentials is needed. Since all array modules have been assumed to be at the same operating line voltage V_L and voltage distributions within the module have been neglected, many combinations of voltage and area are possible. For this example, it is assumed that positive portions of the array are at 10 percent of operating voltage (i.e., $V_+ = 0.1\ V_L$ and $V_- = 0.9\ V_L$). The array will probably not be significantly more positive than this, so the example is valid for illustrative purposes.

Plasma coupling currents can now be computed for large power systems at various operating voltages. These parasitic currents can then be compared with the operating current to evaluate the influence of the loss through the environment. Since a fixed percentage was used for the positive and negative voltages relative to the space plasma potential and since the array size is proportional to the power generated, the ratio of coupling current to operating current has turned out to be independent of power level. Results, as a function of operating voltage, are shown in figure 17. These results are in reasonable agreement with those given in reference 12.

The results of this exercise indicate that plasma coupling current losses at operating voltages less than 500 volts are not serious in low Earth orbits and, therefore, are definitely not a problem at geosynchronous altitudes. The limitation in going to higher operating voltages appears to be the arcing in the negative portions of the array. This arcing also will be a problem at geosynchronous altitudes but at negative voltages greater than 5000 volts. If this arcing is truly an electric-field-confinement effect, a technological investigation should lead to practical methods of overcoming this limitation. Once arcing is eliminated, operation of power systems, in the kilovolt range, without detrimental plasma interactions should be possible at all altitudes.

There is a possibility that ion thrusters will be used with large space power systems (ref. 3). If ion thrusters are used, additional current flows must be considered. Since the thruster neutralizer produces electrons in response to electric fields surrounding it, it can maintain the structure at space plasma potential. The array, then, will be at a positive voltage (relative to the space plasma potential) that approaches the operating voltage. Under these conditions, a large electron current can be collected that can influence array performance. In addition, electron collection may be enhanced through a charge-exchange plasma from the thrusters. This interaction has been reported in references 36 and 37 and is described further in a paper for this conference (ref. 38).

It is recognized that the computations presented here are simplistic. A considerable number of factors have been neglected: for example, the motion of the system through space producing ram and wake effects, material secondary and photoemission characteristics, effects due to voltage distributions within the array, and magnetic field effects. Even so, it is believed that the general conclusions indicated by this example are valid.

A considerable amount of work still has to be done in a technological investigation to improve the accuracy of analytical models, to verify ground test results in space, and to analyze complex geometries used in large space power systems. The questions of long-term interaction and enhanced contamination effects still have to be addressed. However, significant benefits to power systems can be achieved if high-voltage operation can be shown to be feasible.

CONCLUDING REMARKS

Very large spacecraft with dimensions ranging to kilometers have been proposed for future space missions. These spacecraft will incorporate relatively lightweight materials (composites and insulators) to achieve the required low densities. The spacecraft charging investigation has shown that such materials can be charged by environmental fluxes and that these interactions cannot be ignored. Similar spacecraft - charged-particle-environment interactions can be expected for these new, large spacecraft. Large space power systems are also being considered for future missions. Powers to multikilowatt levels are proposed. At these power levels, it is advantageous to use operating voltages higher than those presently being used in order to reduce transmission-line weights and losses. This elevated-voltage operation could cause interactions with the space charged-particle environment. Therefore, there is a need to expand technological investigations of such interactions.

Two broad categories of spacecraft environmental interactions have been defined: spacecraft passive, where the environment acts on the spacecraft; and spacecraft active, where a system on the spacecraft causes the interaction. The principal interaction in the first category is spacecraft-charging phenomena. Considerable progress has been made in understanding this interaction, but the study is not yet complete.

Spacecraft active interactions present relatively new interaction concepts. As an example of these interactions, a large space power system in low Earth orbit operating over a wide range of voltages is considered. Based on the available experimental data, it appears that the environmental interactions are negligible for operating voltages to 500 volts in Earth orbits above 400 kilometers. The limiting factor in going to even higher voltages is the tendency to discharge in the portions of the array that are strongly negative relative to space (-500 to -1000 V in low Earth orbits and -500 to -10 000 V at geosynchronous altitudes). This tendency to discharge appears to be due to the confinement of electric fields at the interconnections between solar cells. A comprehensive technological investigation should lead to a means for controlling this discharge characteristic.

Large systems will interact with the environment to produce effects within the spacecraft, and the converse can also occur: Large spacecraft can affect the environment by sweeping up the charged particles to cause as yet unknown repercussions. This emphasizes the need to understand and evaluate all possible interactions with the environment before proposed large spacecraft are launched, to safeguard both the spacecraft systems and the environment.

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TABLE I. - ENVIRONMENTAL PARAMETERS

[Orbit, 400 km; O_{16}^{+} ions.]

Electron number density, n_e, cm^{-3}	2×10^5
Electron temperature, E_e, eV.	0.22
Electron current density, j_{eo}, A/cm^2. . .	2.4×10^{-7}
Ion number density, n_i, cm^{-3}.	2×10^5
Ion temperature, E_i, eV	0.09
Ion current density, j_{io}, A/cm^2	9.4×10^{-10}

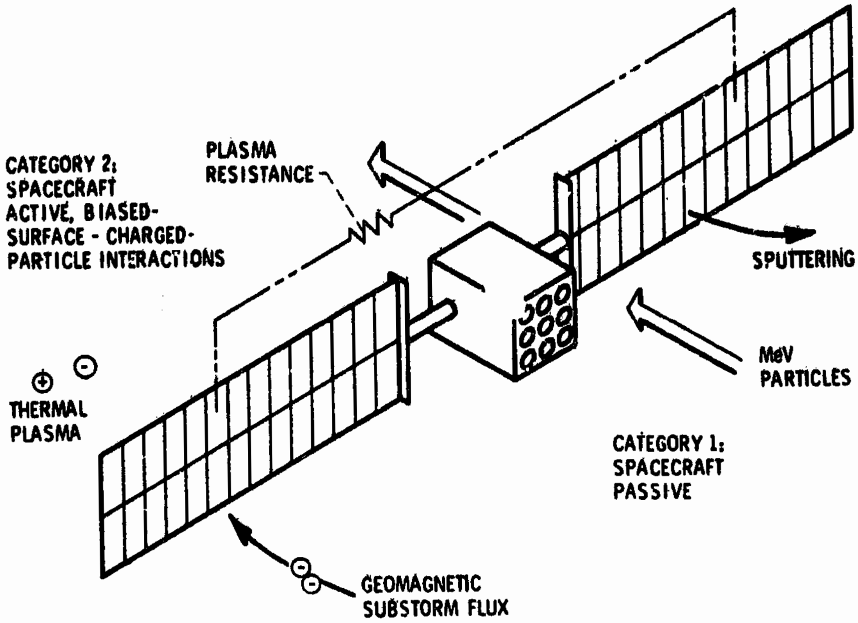

Figure 1. - Spacecraft-environment interactions.

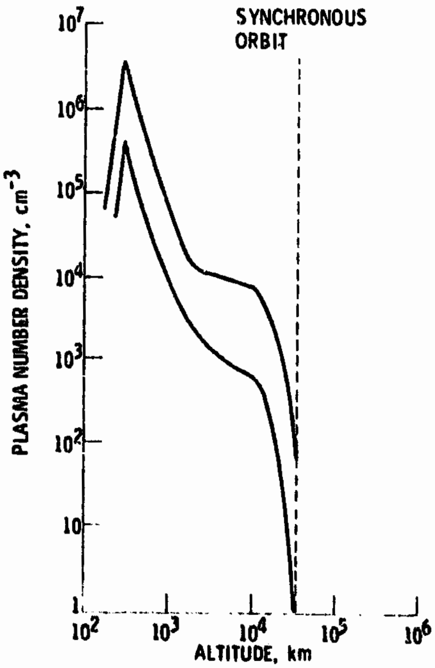

Figure 2. - Plasma number density as function of altitude in equatorial orbit. (From ref. 32.)

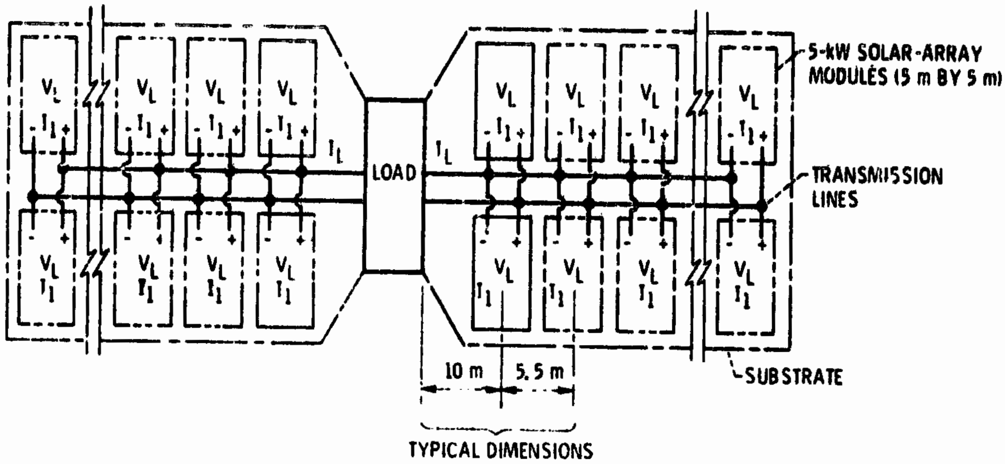

Figure 3. - Conceptual model of large space power system.

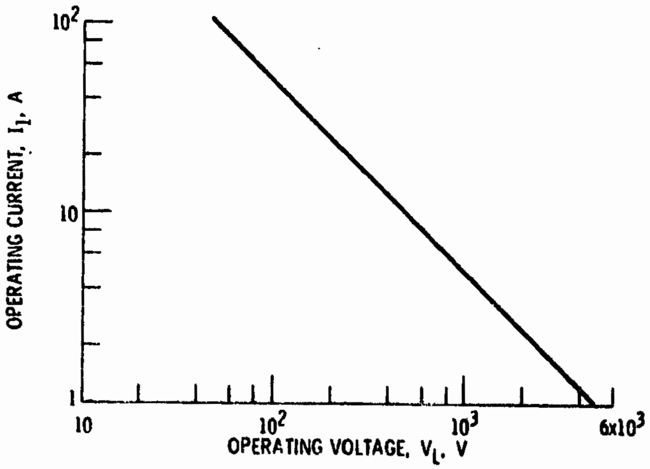

Figure 4. - Load characteristics for 5-kilowatt module.

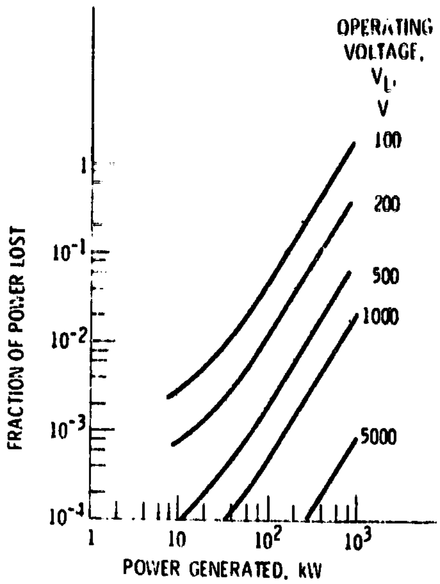

Figure 5. - Fraction of power lost in aluminum distribution lines with 1-square-centimeter cross-sectional area.

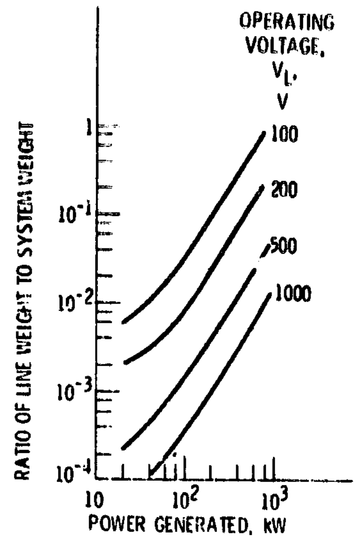

Figure 6. - Ratio of transmission line weight to design goal system weight for 5-percent power loss. Design goal, 10 kg/kW.

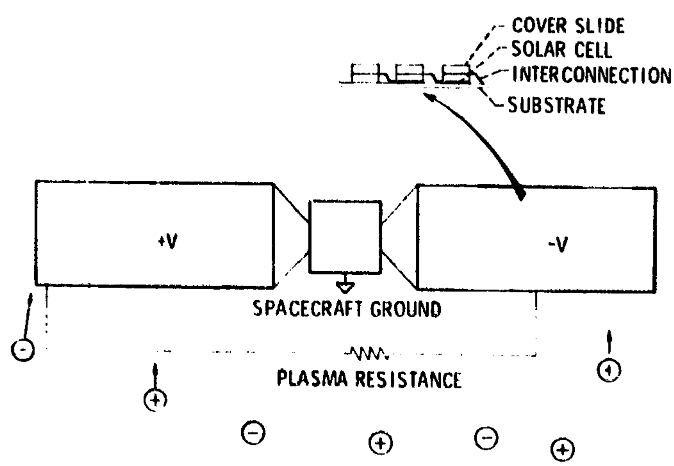

Figure 7. - Spacecraft higher-voltage-system - environment interactions.

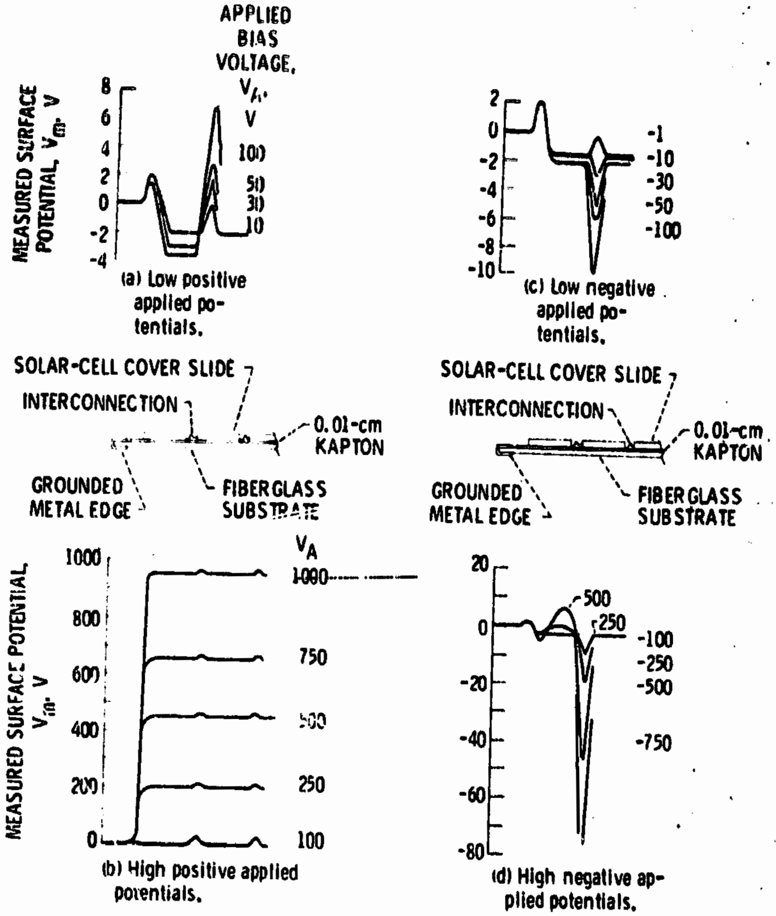

Figure 8. - Typical surface voltage profiles for a solar-array segment. (From ref. 32.)

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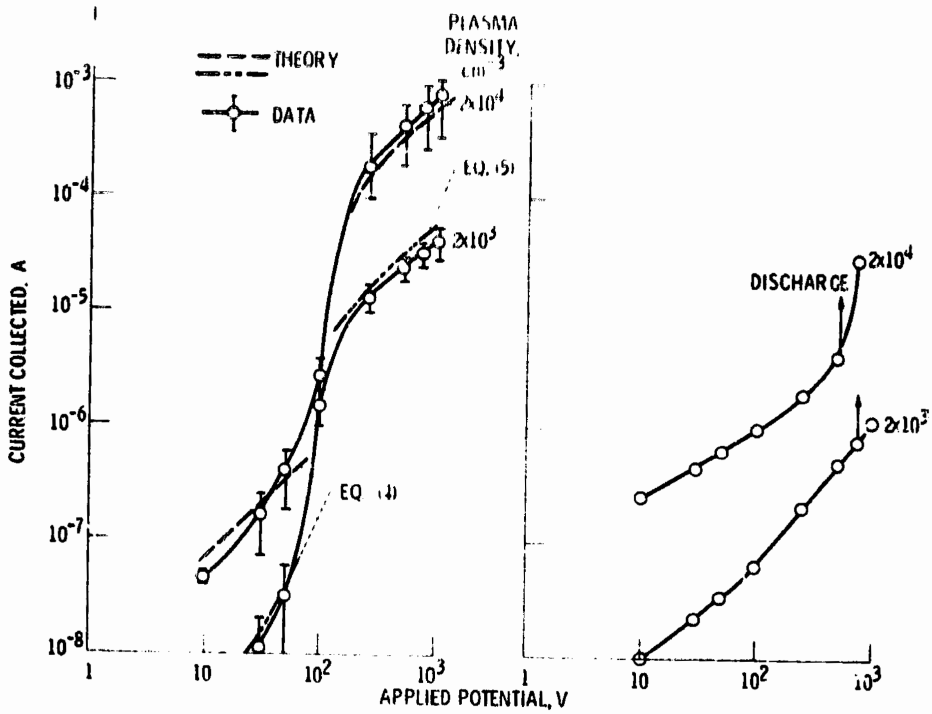
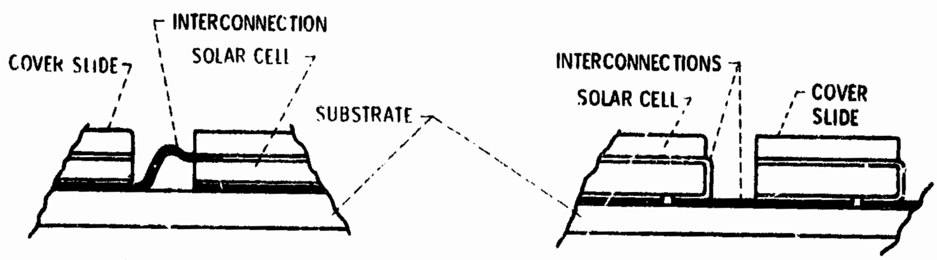


(a) Positive applied potentials. (b) Negative applied potentials.

Figure 9. - Plasma coupling currents for solar-array experiment. (From ref. 32.)



(a) Conventional design. (b) Wraparound design.

Figure 10. - Solar-array interconnection configurations.

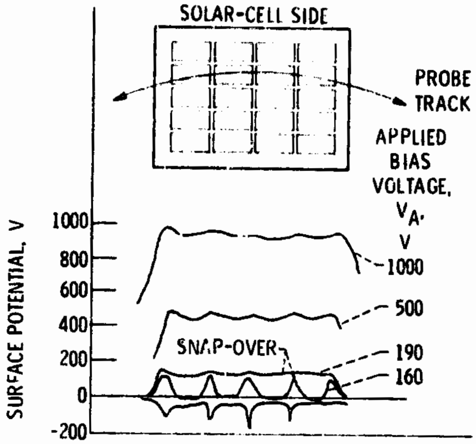


Figure 11. - Surface voltage profiles with wraparound interconnects. (From ref. 12.)

Figure 12. - Arcing on solar-cell array sample (cell side). Two-centimeter-by-4-centimeter wraparound cells on Kapton. (From ref. 32.)

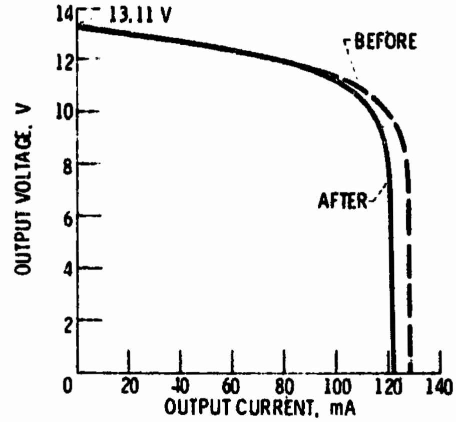


Figure 13. - Degradation in solar-array segment performance after 114-hour test at 4 kilovolts. Solar-array segment area, 100 cm^2; cell temperature, 49° C; light intensity, 135.3 mW/cm^2. (From ref. 28.)

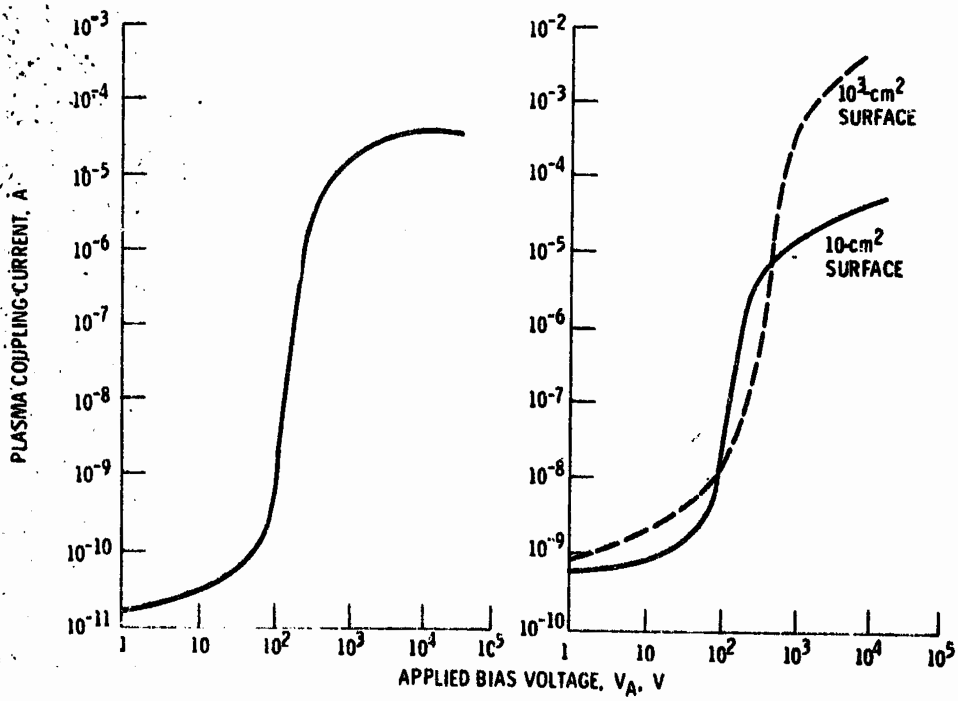
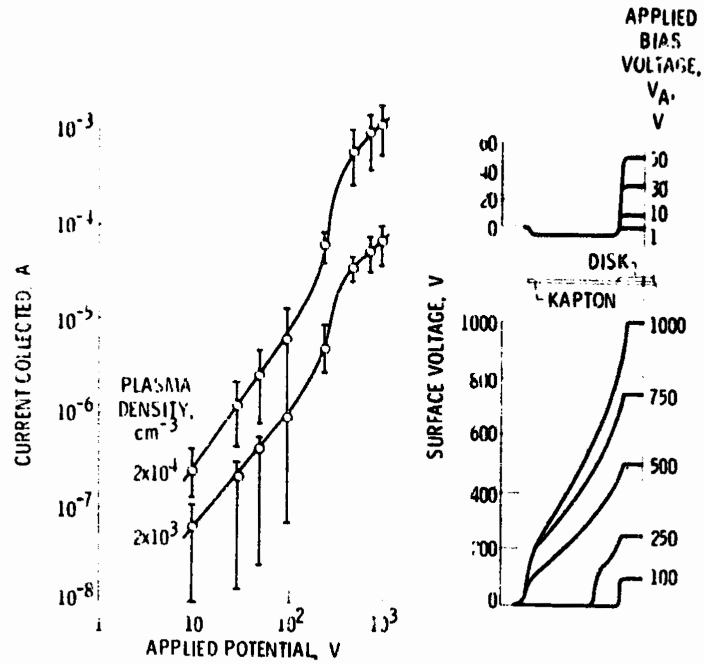


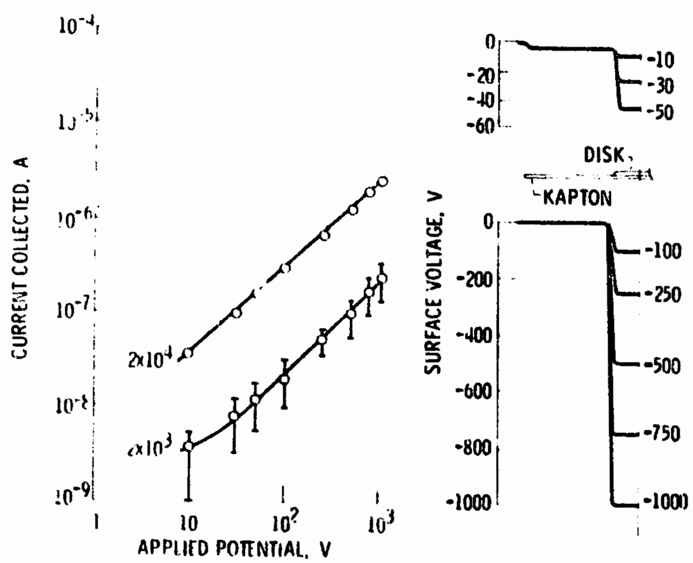
Figure 14. - Current collection phenomenon with pinhole in Kapton film. Plasma density, 1.7×10^4 cm^{-3}. Pinhole diameter, 0.038 cm.



(a-1) Plasma coupling currents.

(a-2) Typical surface voltage profile.

(a) Positive applied potentials.



(b-1) Plasma coupling currents.

(b-2) Typical surface voltage profiles.

(b) Negative applied potential.

Figure 15. - Plasma interactions with metal disk on Kapton surface. (From ref. 32.)

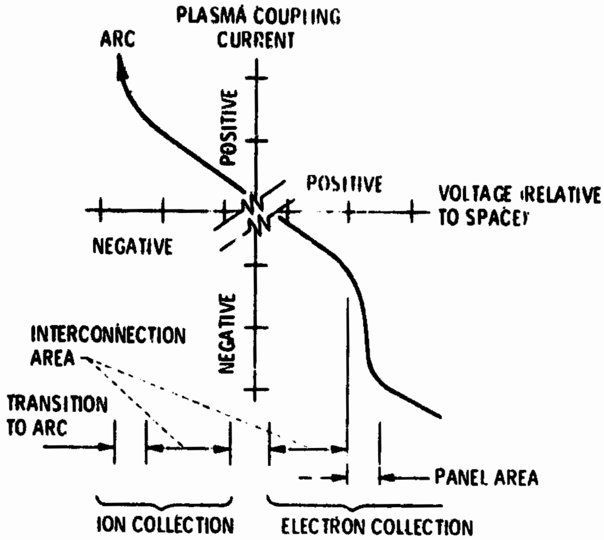


Figure 16. - Solar-array - charged-particle-environment interactions summary.

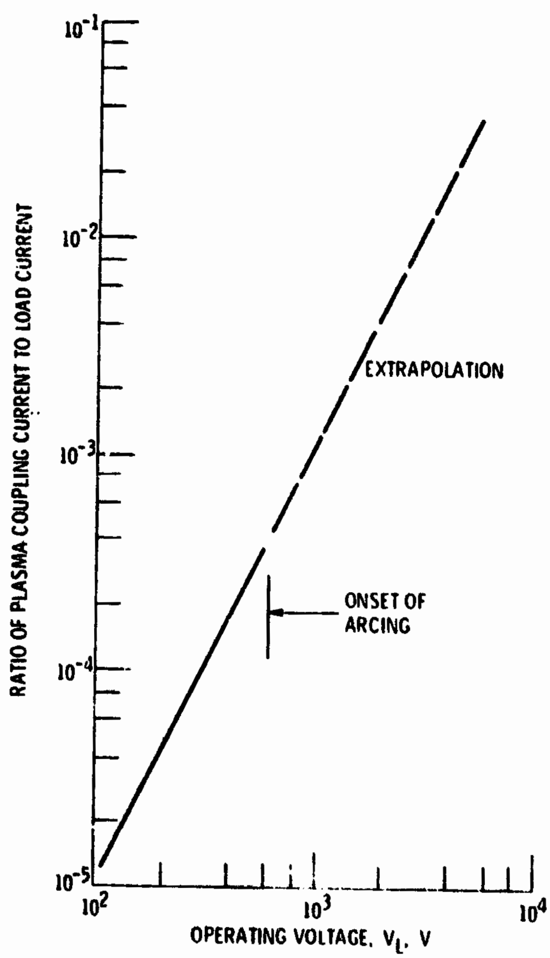


Figure 17. - Plasma coupling losses. All power levels; 400-km orbit. ($V_+ = 0.1\ V_L$; $V_- = 0.9\ V_L$.)