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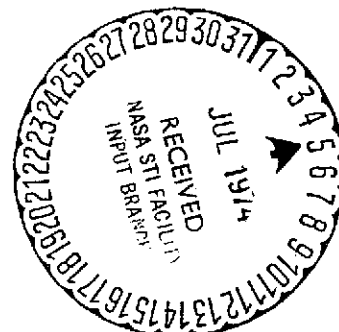
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**THE INTERACTION OF SPACECRAFT HIGH VOLTAGE POWER
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THE INTERACTION OF SPACECRAFT HIGH VOLTAGE POWER SYSTEMS WITH THE SPACE PLASMA ENVIRONMENT

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ABSTRACT

The interaction of high voltage systems immersed in a space plasma environment can cause power loss and damage to insulators and metal surfaces. Work in this area is reviewed and recent results presented.

INTRODUCTION

NASA is studying the development of spacecraft with electrical loads that require high voltage power. The high voltage solar array has been considered for supplying d.c. power directly to high voltage loads such as ion thrusters and communication tubes without intermediate power processing.(1),(2),(3) Space power stations for transferring solar power to Earth are being studied in the 40 kilovolt, multikilowatt regime.(4) Analytical and experimental studies have determined that with the advent of high voltage power, new problems will arise through the interaction of the high voltage surfaces with the charged particle environment of space.(5)-(14) The interactive environment has been identified and duplicated to some extent in simulation facilities at NASA-Lewis Research Center and at several contractor locations.

The phenomena of spacecraft charging, a related problem of spacecraft-charged particle interaction is now being actively investigated.(15-18) This paper presents a brief review and main results of work performed in the area of high voltage interaction with the space environment.

SPACECRAFT/PLASMA INTERACTIONS

The interaction of an orbiting spacecraft with the charged particle environment of space is due to the fact that electric fields from the spacecraft influence particle motion. The charged particle environment referred to is not that of the Van Allen radiation belts; for although the radiation belt environment is damaging, the particle energies are so high that their paths are not affected by spacecraft potentials. That is, all spacecraft are affected equally. Interaction re-

gions of concern are regions of high density low energy plasma shown in figure 1. Moving outward from the Earth the amount of ionization increases until a peak is reached in the ionosphere at about 300 kilometers at a density of about 10^6 electrons/cm³. The ionosphere, essentially an extension of our atmosphere, merges into another region called the plasmasphere. The plasmasphere, as shown in figure 1, follows the Earth's magnetic field lines and is composed of ionized hydrogen atoms at a density of 10^2 to 10^4 particles/cm³. Throughout most of the region the boundary of the plasmasphere is fairly sharp, and its outstanding characteristic is that it moves inward and outward from about 3 to about 7 Earth radii somewhat like an inflatable doughnut. The plasmasphere contracts during times of magnetic storm activity and expands during quiet times. For example, at synchronous orbit the number density may be fairly low, less than 1 electron/cm³, or as high as 100 electrons/cm³ depending on the location of the plasmasphere boundary.

Interaction Effects

The space-plasma current depends on whether parts of the spacecraft are maintained at different potentials. For a spacecraft that may be considered an equal potential surface the spacecraft floats at a potential that adjusts itself to balance the flow of positive and negative charges. In a steady state condition, therefore, the flow of negative charges balance the flow of positive charges to the spacecraft resulting in no net current flow.

When a voltage is applied between two segments of the spacecraft (fig. 2(c)), ions from the ambient plasma are attracted to the negative end and electrons flow to the positive segment thereby causing a current to circulate through the spacecraft. The current increases with the applied potential and represents real power loss to the system. The complete circuit must take into account photo electron emission, secondary electron emission and the effects related to operating electric thrusters, if applicable. Circulating currents also occur on normal low voltage spacecraft but are too small to affect the power system.

Another effect, shown on figure 2(a), is the electrical stress across insulators caused by the

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following sequence: 1) The electric field from the high voltage insulated surface at first extends out into the plasma attracting charges of opposite polarity. 2) The charges move to the surface of the insulator where they come to rest with the field lines terminating on the charges. 3) This process continues until the full voltage is across the insulator somewhat analogous to a charged capacitor. The insulator is thus subject to breakdown, causing undesirable transients and material erosion. If a hole appears in the insulation (fig. 2(b)), either from breakdown, micro-meteorite puncture or defect in manufacturing, current is collected by the exposed metal and power ($P = IV$) is expended locally. The important factor here is not the power loss but the fact that power can be dissipated in a small area causing local damage, erosion, and transient arcs in some cases.

Spacecraft Charging

Spacecraft charging is an effect, which does not require high voltage to be present in the spacecraft, but can occur under the following conditions: 1) The spacecraft must be operating outside the plasmasphere at very low ambient density. 2) All or part of the spacecraft is shadowed. 3) It must be bombarded by a stream of high energy electrons usually found outside the plasmasphere during magnetic storm conditions near local midnight. With the above conditions present, the spacecraft becomes charged by the high energy electron stream without being able to neutralize the charge, either by collecting ions from the ambient plasma or by emitting photo electrons. Thus the potential may climb to very high values. Potentials of -12 kV have been measured.⁽¹⁵⁾ Reference (16) describes the events that were believed to be responsible for failure of the Air Force DSCSII Satellite. The spacecraft skin became highly charged during an eclipse condition or partial shadowing, thereby placing a high potential across an input capacitor which failed. It is also believed that many cases of anomalous switching on other satellites were caused by transient arcs due to charging events.

EXPERIMENTAL RESULTS

Many ground tests have been performed at NASA and contractor facilities simulating the interaction of high voltage samples with the space plasma environment.^{(7),(10)-(14)} The environmental parameters simulated are as follows:

Electron number density: 1 to 10^5 electron/cm³
 Electron temperature: 0.3 to 3 electron volts
 Ion specie: O⁺, N⁺, and H⁺
 Neutral particle pressure: $<10^{-8}$ Torr

Figure 3 shows a vacuum facility at Lewis Research Center (LeRC) typical of the type used for interaction studies. Inside the tank plasma is generated by the ionization of nitrogen or helium by a magnetically confined, hot cathode discharge. The source provides ions of about 40 eV directed energy, electron temperature of a few electron volts, and number density from 10 to 10^5 elec-

trons/cm³. Faraday cups and Langmuir probes are used to measure plasma properties.⁽¹⁹⁾ Output measurements for interaction investigations are voltage current curves with number density as a parameter.

The simulation in such a facility should be valid for material tests, and most small scale interactions, becoming less valid at lower number densities and for larger scale models.

Insulator Tests

Insulating materials have been tested by covering a metal electrode with a film or coating and allowing free charges from the plasma attracted to the insulator to become the outer electrode. Table I shows voltage breakdown results for positive and negative polarities for several materials of interest used in spacecraft construction. Polyimide Kapton, FEP Teflon and glass 0.012 cm (5 mil) thick can withstand voltages up to 20 kV. The results for other materials such as RTV's and epoxies vary somewhat due to the presence of voids and differences in preparation. Kapton, Teflon, and glass also are superior in their resistance to erosion after breakdown occurs. Although the results show that breakdown voltage for an insulator tested in a plasma is about the same as the breakdown voltage for an insulator tested between metal plates, the presence of free charges involves new phenomena: 1) Because the arrival rate of charges is limited, the breakdown becomes current limited. 2) It is possible for free charges to find small holes and cracks that would not necessarily lead to breakdown in an insulator between metal plates.

Table II shows resistivity values of test specimens obtained with a beam deposition apparatus.⁽⁷⁾ The surface of the specimen is charged by directing a beam of ions or electrons of the desired energy onto the face of the test sample. It is found that resistivities measured in a plasma are approximately the same as resistivities measured by placing the insulator between metal plates.

Pin Hole Effects

Figure 4 shows the typical voltage current curves for holes in insulation covering a high voltage metal electrode. The sample is a 0.012 cm (5 mil) film of Kapton with a small hole, 0.05 cm, over a 5 cm diameter electrode. The experiment was performed in the facility shown in figure 3 at an electron number density of 10^3 /cm³. At low applied positive voltage the current is low following probe theory⁽²¹⁾ and the local power dissipated is nondestructive. Between 200 and 1000 volts a sharp rise in current occurs, usually of several orders of magnitude. After this rise the current increases linearly, but may saturate, depending on plasma conditions. The important result is that electron current to a pinhole at voltages above a few hundred volts is orders of magnitude greater than expected, and as a result of this, local power dissipation can be high enough to cause heating and erosion of metal and insulators.

As shown in figure 4 the collected current also depends on the insulator area surrounding the pinhole. This unexpected result is independent of the hole size, the electrode size, and the type of insulation. Teflon, Kapton, glass, and Lucite have been used as the insulator with similar results.

Figure 5 shows the area effect for positively biased electrodes covered with Kapton with a one centimeter hole in the Kapton. Electron current increases with insulator area but not linearly, and one would not expect current to continue to increase indefinitely. An explanation for the area effect is not yet at hand. Evidently the surrounding insulation is active in funneling charges into the pinhole. Experiments at LeRC have shown that the flow of charges is not necessarily a surface phenomena. If a small conductor, such as a sphere, is biased to high voltage and brought near an insulating surface, a sharp jump in current occurs (an area effect) when the sphere is still several centimeters from the surface. On the other hand, if the insulating surface is replaced by a floating metal surface, the above effect does not occur. The current, I , to a pinhole for applied positive voltage greater than 1000 V and an area of insulation surrounding the pinhole greater than 100 cm^2 , is of the form $I = KnV$, where n is the electron number density and K is a constant of the order of 10^{-11} .

For negatively biased electrodes the ion current collected to a pinhole is also larger than expected, but for higher voltages it is usually lower than the electron current by several orders of magnitude. The voltage-current curve is of the form $I \propto V^b$, where b varies from 1 to 2. Heating is not a great problem for ion current collection. Of greater concern is that transient arcs, or sparks, often occur. The dangerous feature of negative voltages is that the metal electrode is a cathode and, thus, has the capability of releasing a transient shower of electrons many orders of magnitude greater than the incoming ion current, so that the current limiting feature of the plasma is not operative. When the high voltage metal is the anode, electrons cannot be released very easily, since the field at the electrode is in the retarding direction. In laboratory experiments, when the biased electrode is negative either for a pinhole or a solar array, it is not uncommon for the transient arcs and sparks to be violent enough to cause damage to a power supply or an electrometer. Sparks have been seen with an applied voltage as low as -400 volts. This phenomena, therefore, requires some attention for future applications. Covering irregular electrodes with a thin layer of adhesive has been found to subdue sparking somewhat.

Solar Panel Tests

Small solar panels have been biased to high voltage in a dilute plasma to test solar panel materials. The current collected by a small panel tested in a plasma is not an indication of the total power dissipated by a large solar array. However, given a level of particle flux, the dam-

age inflicted on a small panel should be representative of large panel operation. A summary of the panel tests is as follows: 1) It is difficult and probably not practical in terms of weight and cost to completely insulate a solar panel from charged particle currents. If for no other reason micrometeorites will eventually cause pinholes. Once holes appear they collect current from a large area so that the advantage of insulation is lost. 2) However, insulation on interconnects does seem to protect the panel from transient arcs when the panel is biased negatively. 3) For positive bias, a panel with bare interconnects is ideal since the current is spread diffusely and sparks do not occur. Items 2) and 3) above are conflicting requirements so that the individual case must be analyzed in terms of geometry, operating regime and operating voltage. In one long term test (114 hr), a solar panel with bare interconnects and biased to +10 kV suffered a 7 percent loss in output power due to darkening of cover slides.⁽³⁾ It is not known whether the cover slide darkening was due to sputtering or some form of ion deposition. Obviously, more long term testing will be required for a particular solar panel construction.

Screening

Conductive screens have been found to be effective in preventing current flow to bare conductors biased to high voltage. As shown in figure 6 a small negative voltage is sufficient to reduce electron flow. Although screening has been routinely used on spacecraft, for example, to shield electric thrusters, and as a port enclosure to shield internal high voltage conductors, it does not appear that screening will be a practical solution for large scale structures such as a multi-kilowatt high voltage solar array.

Large Scale Tests

The overall power loss to large solar arrays due to plasma interaction has not been experimentally determined due to the limitations of facilities. As shown in figure 2, a variety of interactions take place. The electric field lines extend far out into space and reactions take place over hundreds of meters. Orientation of a spacecraft along magnetic field lines is a factor in determining current flow, as well as the geometry of the solar array and the arrangement of cells. Rigorous calculations of the charged particle flow to three dimensional objects under the influence of electric and magnetic fields has not been undertaken. Simplified analyses are performed by considering the two limiting cases: 1) The low energy random flux falling on a large flat plate, and 2) the space charge limited flow to a sphere. The low energy flux is $I_0 = nevA$ where I_0 is the random current to a plate of area, A , e is the electronic charge, v is the average particle velocity, and n is the electron number density. For large spherical collectors the space charge limited electron current is $I = 2.35 \times 10^{-3} I_0^{13/7} V^{6/7}$, where V is the sphere potential. Figure 7 shows power loss calculations made for a floating array with

$n = 100 \text{ ions/cm}^3$ using a spherical approximation. Power loss is roughly proportional to the square of the voltage and increases approximately as the square root of the area, so that the worst case is a small, very high voltage array, and the better case is a large low voltage array. Raising voltage is always a double penalty because it increases the collected current and at the same time increases particle energy and therefore lost power.

Flight Test

Figure 5 shows the experimental surface of the SPHINX spacecraft which is designed to test insulators, pinhole experiments, and small solar array panels operated at high voltage in the space environment. Such flight data will be necessary not only to obtain quantitative data but also to calibrate ground facilities so that further ground testing can proceed with some confidence. Eventually larger scale flight experiments must be conducted to measure power loss and solar array interactions over long periods.

CONCLUSIONS

Potentially harmful interactions can result from the interaction of a spacecraft and its high voltage components with the space plasma. High voltage power processing equipment can be affected by power loss, and by transients due to plasma interactions. Kapton, Teflon, and glass appear to be satisfactory insulating materials for use where high voltage is exposed to a plasma environment. Pinhole currents can be very large and the phenomena must be taken into account in solar array design. Large, very high voltage, solar arrays such as those proposed for space power stations will present a challenging problem. None of the problems seem insurmountable but may require close attention to spacecraft and power systems designs.

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TABLE I. - BREAKDOWN VOLTAGE OF INSULATORS
TESTED IN A PLASMA

Insulator	Thickness, cm	Voltage positive, kV	Voltage negative, kV
Kapton	0.008	>16	19
Kapton	.013	>18	>24
FEP Teflon	.005	14	10
FEP Teflon	.013	>20	>20
Fused silica	.012	>20	>20
Microsheet	.008	14	>16
Microsheet	.015	16	17
R63-489	.015	>16	>16
RTV 560	.002	2	6
Parylene C	.004	<1	4
Parylene C	.048	>20	--
RTV 41	.005	<1	5
RTV 602	.005	<1	<1
Sylgard 182	.048	17	--
Sylgard 182	.066	>20	--

TABLE II. - BULK RESISTIVITY OF SELECTED MATERIALS WITH CHARGE DEPOSITION APPARATUS

Material	Thickness, in.	Resistivity in ohm, cm							
		Ion deposition				Electron deposition			
		4 kV	8 kV	12 kV	16 kV	4 kV	8 kV	12 kV	16 kV
Kapton	0.005	8.0×10^{15}	3.3×10^{15}	1.2×10^{15}	5.5×10^{14}	8.0×10^{15}	4.9×10^{14}	9.8×10^{14}	8.5×10^{14}
	.003	1.4×10^{15}	1.2×10^{15}	3.7×10^{14}	1.0×10^{14}	6.8×10^{15}	1.4×10^{15}	1.4×10^{14}	1.5×10^{13}
FEP-Teflon	.005	6.0×10^{16}	3.1×10^{16}	1.3×10^{16}	3.1×10^{15}	2.0×10^{16}	1.3×10^{16}	6.1×10^{15}	7.0×10^{15}
	.002	3.1×10^{16}	8.1×10^{15}	2.7×10^{15}		1.5×10^{15}	6.4×10^{15}	1.8×10^{15}	S
Fused silica	.005	4.8×10^{15}	3.2×10^{15}	1.9×10^{15}	* 1.1×10^{15}	7.0×10^{14}	4.1×10^{14}	1.6×10^{13}	S
Microsheet	.006	3.2×10^{15}	4.7×10^{14}	1.3×10^{14}	1.3×10^{13}	2.4×10^{14}	7.9×10^{13}	2.9×10^{13}	1.1×10^{13}
	.003	1.2×10^{15}	1.3×10^{14}			2.4×10^{14}	1.7×10^{13}	1.1×10^{13}	S
Parylene-C	.0015	4.0×10^{14}	S	S	S	8.5×10^{14}	S	S	S
RTV-41	.001	1.7×10^{15}		S	S	4.1×10^{15}	2.4×10^{14}	S	S
RTV-560	.001	3.7×10^{13}	S	S	S	1.0×10^{14}	S	S	S
RTV-602	.002			S	S	6.0×10^{15}	1.5×10^{15}		
XR-63-489	.005	4.9×10^{13}		S	S	1.3×10^{14}	1.5×10^{14}	9.4×10^{13}	8.0×10^{12}
	.002	6.0×10^{13}		S	S	S	S		

S Saturation beam current.

* 15 kV value, breakdown at 16 kV.

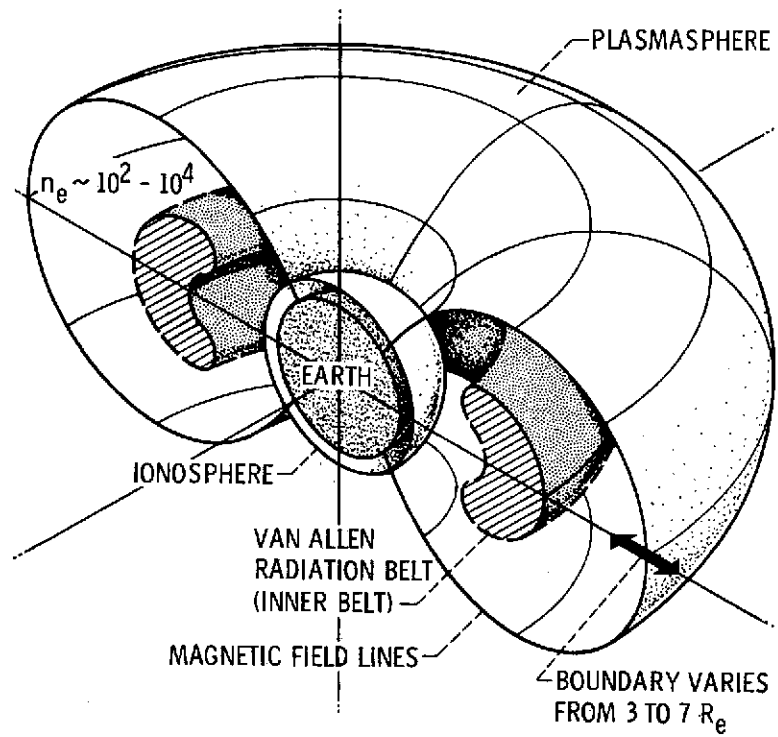


Figure 1. - Interaction regions.

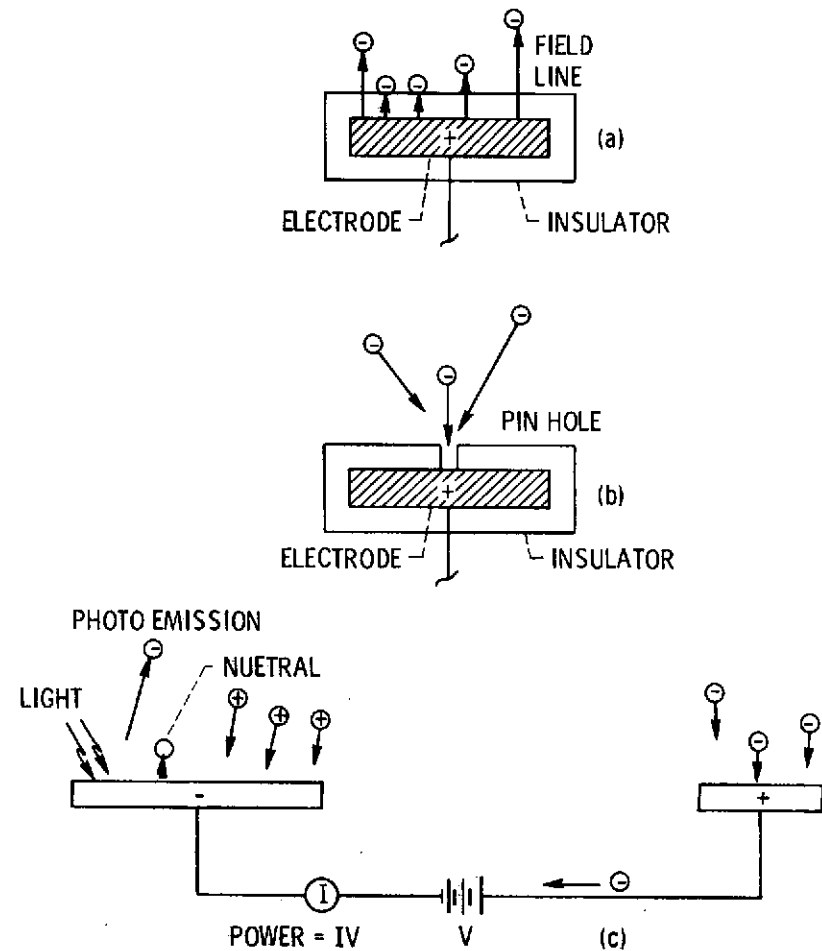


Figure 2. - High voltage - plasma interactions

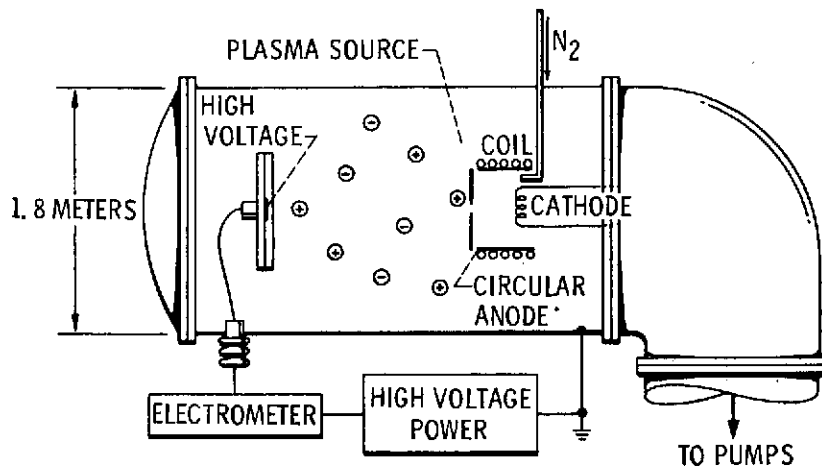


Figure 3. - Space simulation chamber.

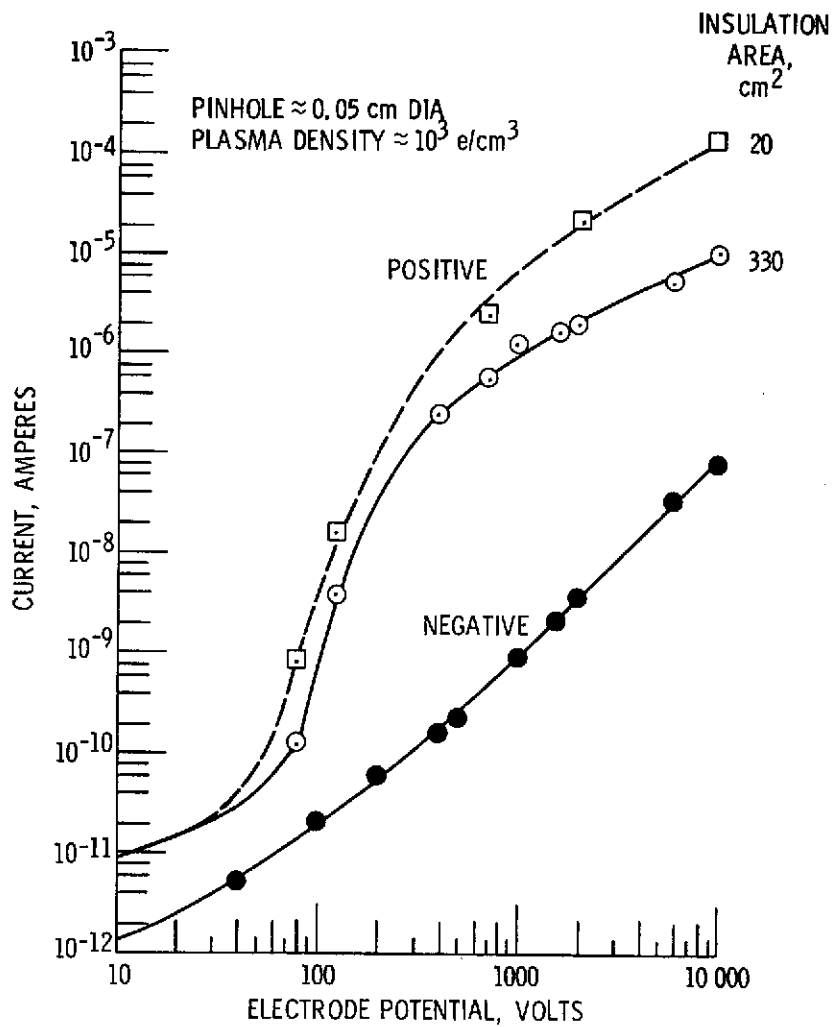


Figure 4. - Pinhole voltage - current curve.

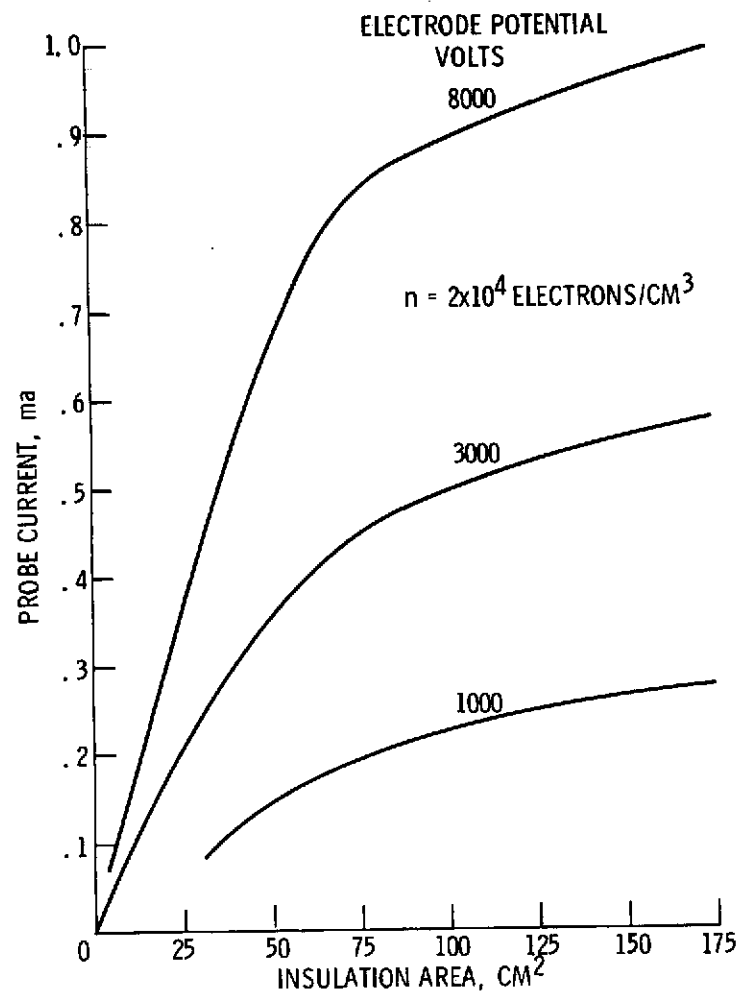


Figure 5. - Pinhole current as function of kapton insulation area.

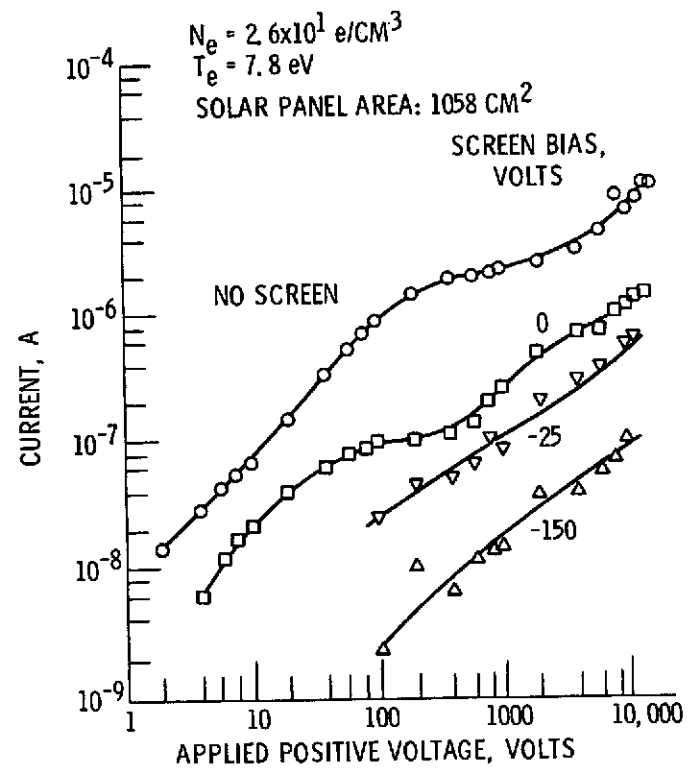


Figure 6. - Effect of screening.

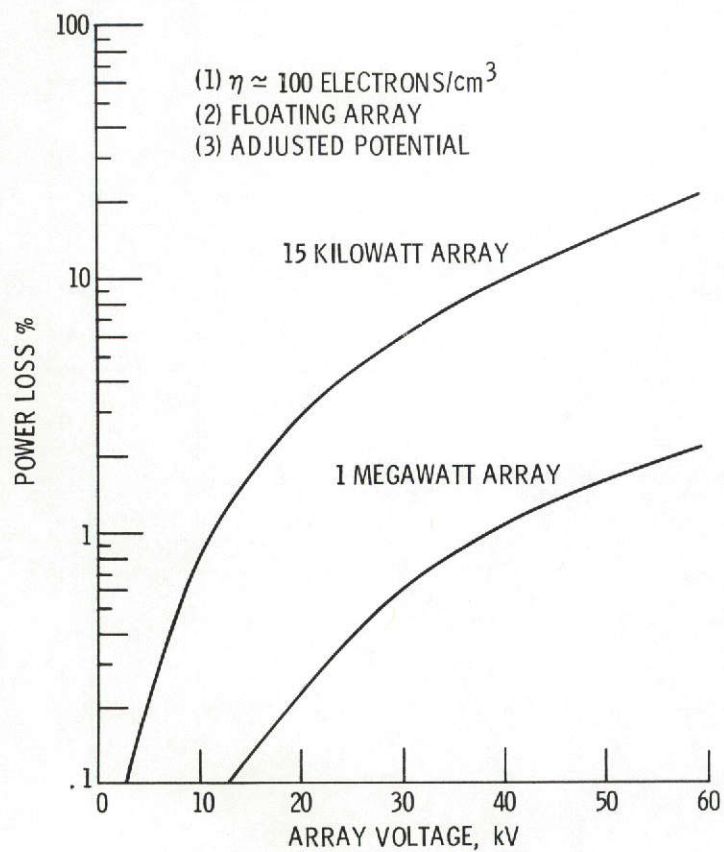


Figure 7. - Power loss

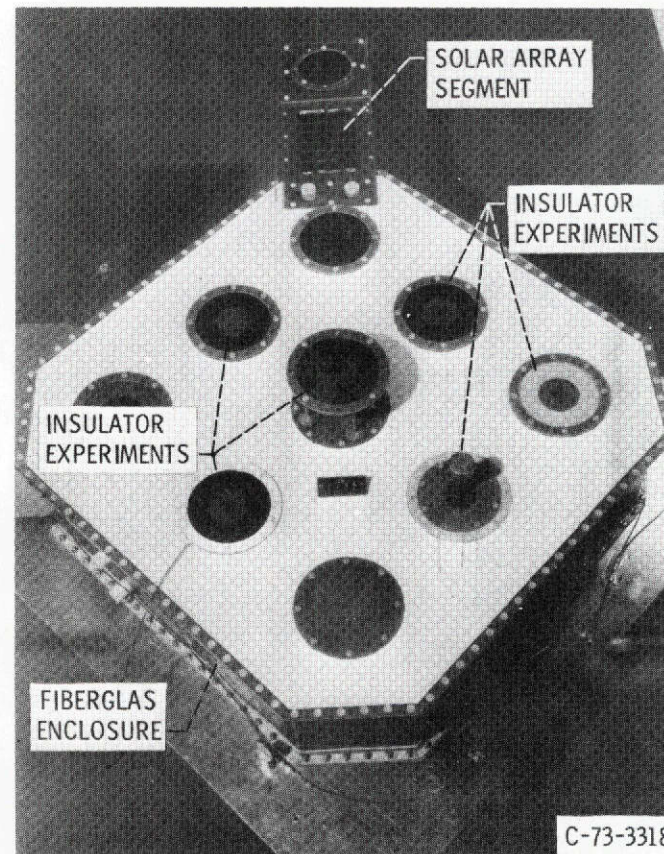


Figure 8. - Sphinx satellite experiments.