D22

N79-24023

SHEATH EFFECTS OBSERVED ON A 10 METER HIGH VOLTAGE PANEL IN SIMULATED LOW EARTH ORBIT PLASMA

James E. McCoy and Andrei Konradi
NASA Johnson Space Center

SUMMARY

A large (1m x 10m) flat surface of conductive material was biased to high voltage (±3000 V) to simulate the behavior of a large solar array in low earth orbit. The model "array" was operated in a plasma environment of 10^3-10^6/cm^3, with sufficient free space around it for the resulting plasma sheaths to develop unimpeded for 5-10 meters into the surrounding plasma. Measurements of the resulting sheath thickness as a function of plasma density and applied voltage were obtained. The observed thickness varied approximately as $V^{3/4}$ and $N^{1/2}$ as would be expected for space charge limited flow between large plane surfaces with a constant source current density. This effect appears to limit total current leakage from the test "array" until sheath dimensions exceed about 1 meter.

Total leakage current was also measured with the "array" biased 0-4 kV from end to end, floating in equilibrium with the ambient plasma. The positive end of the array was observed to float at +93 V, with a total current leakage through the plasma slightly under 2 mA/m^2, or 0.7 watt/ft^2.

INTRODUCTION

Hardware and techniques have recently been developed to adapt the large thermal vacuum test chamber at NASA Johnson Space Center to simulate the ionospheric plasma environment characteristic of low earth orbit (LEO). Plasma density, flow direction and magnetic field strength were controllable for test purposes within the 20 meter diameter chamber. Plasma simulation and testing on this large scale is expected to become of increasing value as requirements to operate large systems at high voltage increase. We report here the initial results obtained in tests of a 1 meter by 10 meters simulated high voltage solar array, typical of development tests which will require this type of facility.

The test model used consists of roughly one square meter of actual solar cells at the top of the panel, with the remaining 9 meters simulated by a panel of conductive plastic material of sufficient internal resistance to be biased at several kilovolts end-to-end. The resulting panel surface potential varies in an approximately linear manner, the same as would be obtained from a string of very many solar cells connected in the simplest series configuration to give the same high voltage output end-to-end. Copper strips are placed across the panel every five feet to provide good electrical contact for the bias voltage power supplies, or for monitoring of intermediate surface voltage and current values. Three moveable probes are located in front of the panel as it hangs in the test chamber, used to locate the outer boundary of the high voltage "sheaths" expected to form around the panel and control its equilibrium interaction with the surrounding plasma.

LEO PLASMA CURRENT LEAKAGE

Although space is a very good vacuum, it is not absolute and the very thin residual "gases" present are capable of causing significant electrical interactions under certain conditions. This has been noticed particularly by various satellites in geosynchronous orbit (GEO), which are observed to charge up to surface potentials of several kilovolts under solar eclipse/geomagnetic "storm" conditions. The ambient plasma is too thin to effectively bleed off the charge acquired from "storm" radiation absorbed by the satellites (refs. 1 and 2).

In LEO, the denser plasma easily overcomes any radiation charge build-up. This should eliminate the problems with unwanted charge build-ups observed in GEO but results in a new problem for large high power solar arrays due to the exact inverse of the GEO problem. In LEO, even necessary high voltages may be bled off by the dense ambient plasma.

Feasibility studies of the SPS concept have identified this as a potential problem in attempting to operate the large solar arrays at high voltages. Reference 3 in particular observed that current leakage to space (per unit area) would increase at high voltage by orders of magnitude over that experienced by present day low voltage systems, based on extensive laboratory test and analysis using small (1-20 cm) surfaces at high voltages. Assuming certain scaling laws observed to be approximately true on the 1-20 cm scale (in effect, assuming some constant sheath conductance per unit area between the array and the plasma), they calculated the power losses due to these parasitic currents shown in figure 1. The projected loss for the 15 kw array would exceed solar cell output for voltages exceeding +2 kV or -16 kV for a typical Shuttle orbit near the F2 ionospheric maximum.

An alternative theoretical analysis indicates that quite different scaling relations should be expected to apply. By this analysis, current collection by large solar arrays should be controlled by (plasma) charge separation fields, which should form space charge limited "sheaths" that confine the current collecting voltages on the arrays within these sheaths. Distinct outer boundaries to the current collecting sheaths surrounding a high voltage surface should be expected to reach a limiting size of the order of 1 meter/kilovolt, nearly independent of the size of the high voltage surface. When the assumptions in this analysis are valid, total current collected depends only on the outer surface area of sheath available to intercept ambient (drift) currents existing in the undisturbed plasma outside the objects' sheath. The resulting current multiplication factor at any voltage would be the ratio of outer sheath surface area to object surface areas, as illustrated by figure 2. (In effect, sheath "conductance" per unit area becomes a function of both voltage and size, rather than a constant as in some oversimplified lumped circuit element analogies.) For illustration, we assume plasma parameters such that the resulting sheath thickness grows from 10 cm at ±100 V to 10 meters at ±10 kV. This sheath becomes very large compared to the 10 cm sphere, the total current collected increasing by nearly 10^4 (a very high "conductance" sheath). The same plasma sheath, around a 1 km "SPS" array, has a very small ratio of sheath to object size. The total current collected should increase by only a few percent, a very low sheath "conductance" which becomes even lower with increased voltage.

Operating in the large chamber at JSC, it is possible to observe the growth of these sheaths around a 1x10 meter object with 0.1-10 kV applied. This permits a test of their behavior in "free space" without the inevitable wall effects due to sheath growth in smaller chambers.

TEST SET-UP FOR SHEATH STUDIES

The performance of an actual test on the scale of 10 meters available in the large chamber was needed to determine which (if either) scaling relations are applicable to large solar arrays. Figure 3 shows the layout of the basic configuration used for most tests. The high voltage panel ("SPS") was hung near the center of the chamber, with 7-10 meters of free space available in all directions for unobstructed development of the high voltage plasma sheaths. The expected extent of sheath development is illustrated for an SPS model in series connected configuration, with high voltage at top and bottom at ground, for two typical sheath thicknesses of 1 meter and 3 meters. The three probes labeled 22-24 can be moved horizontally from outside the sheath to locate the outer sheath boundary (point of first observed change in plasma conditions). The sheath and associated effects could also be observed visually using low light TV cameras at the first and third floor levels. Large solenoid coils around the chamber provided control of the vertical magnetic field from 0-1.5 gauss. Plasma density and electron temperature measurements were obtained from 15 half inch spherical Langmuir probes located at various points around the chamber.

Plasma Generation

Plasma generation was available from three devices. A 30 cm Kaufman thruster borrowed from LeRC was used with argon gas to generate flowing plasma densities of 10^4 to 10^6 (cm^{-3}), directed either horizontally (across the magnetic field) from the third level into the face of the panel or vertically from the center of the floor (along the magnetic field) along the length of the panel. Plasma electron temperatures varied from 0.5-2 ev, being typically 1 ev. Ion temperatures and flow velocity were not directly measured, flow energy is estimated to have varied from 15-25 ev. Predominately (monatomic) Ar^+ ions were observed in the chamber, however significant numbers of N_2^+, H_2O^+, and HO^+ and some other species were observed. These may constitute a significant (thermal?) population of charge exchange or other secondary ions in the plasma, created from the residual gas.

A 6 inch Kaufman thruster device was fabricated at JSC to provide a lower density source, using H_2, N_2, and He as well as argon as the input gas. Plasma densities of 10^2 to 10^4 (cm^{-3}) were observed, either flowing vertically from center floor or diffused from a horizontal flow across the one meter level above the floor. Electron temperature was typically slightly less than 1 eV.

The third source of plasma employed was a large 5 meter loop antenna, driven at 1-5 MHz to excite an irregular plasma from the residual neutral chamber gases. Properties of this plasma were quite different, densities estimated at 10^3-10^5 (cm^{-3}) with electron temperature about 2-4 eV (based on 1/2" spherical Langmuir probe currents).

SPS Model for Test

Figure 4 shows the physical dimensions of the "SPS" model as tested, as well as location and identification of available test connections to the copper contact strips. The actual dimensions differed slightly from the nominal 1x10 meter design for ease of fabrication. For test purposes, the array was operated in each of three electrical configurations shown. The "series connected (floating)" configuration is the actual case which would be obtained in space; with currents closing from the positive voltage (V_+) end of the array, through the conducting plasma, to the negative portion of the array. The chamber walls and lab ground are not involved in the circuit at all (except in determining the roughly uniform "plasma potential" outside the sheaths). The relative potential of the entire test array and floating power supply will adjust itself relative to the plasma potential so that the total electron current collected along the positive voltage portion of the array exactly equals the total ion current collected along the negative portion. The location of the point along the array which is at "plasma ground" potential will be inversely proportional to the relative ambient current densities of ions and electrons in the free plasma. For typical conditions, this will result in the array "floating" 97-99% negative with respect to plasma potential.

Since operation in the fully floating configuration was physically awkward, most "series connected" testing was done with the power supply and one end of the array grounded to the chamber walls. This was equivalent to testing the negative or positive portions of a floating array individually, with the return current path closing through the chamber wall (via the plasma). In either case, all voltage drops from array surface potential to plasma potential are contained within the sheath. The outer surface of the sheath is at plasma potential. The plasma is effectively a perfectly conducting medium with constant internal potential (within a factor of kT).

A third configuration frequently employed, for maximum simplicity of operation and data analysis, was "constant HV" with the entire surface of the array at the same potential and all current returning through the plasma to the chamber walls.

This test object was designed to produce the extreme values of current leakage possible from a large solar array or other high voltage surface. To eliminate confusion from attempting a correct treatment of the effect of relative surface area and configuration of conductive and insulated portions of the surface of an array, the entire front surface (except the actual solar cell section) was made conductive. The "SPS" model should therefore generate the large scale (outer) sheath configuration believed to be of primary importance in determining its equilibrium interaction with an ambient plasma. The currents collected will not be reduced by any insulation factor.

Test Objectives

In order to test the validity of the proposed approach to scaling calculations of plasma current leakage based on relative sheath to object size, three primary topics were identified for investigation:

(1) Existence, sharpness and size of the expected outer sheath boundary

(2) Equilibrium floating potential of a large panel (array) with fixed voltage differential along its length

(3) Magnitude of leakage currents induced to/from large surfaces as a function of voltage (actually, sheath size)

A secondary topic was the possible existence and behavior of transient current pulses (electrical breakdown or "arcs" to the plasma) reported to occur in smaller scale experiments (refs. 3 and 4).

EXPERIMENTAL RESULTS

The fundamental result achieved was direct observation of the existence, form and dimensions of the plasma sheaths formed about the high voltage panel. Leakage currents between the panel and the surrounding plasma, through the observed sheaths, were recorded for comparison with the theoretically expected current transmission capacities of the sheaths. The existence and form of the sheaths was observed by two independent means, both of which detect the location and "sharpness" of the outer boundary with minimum disturbance of its configuration by physical intrusion of hardware.

Sheath Observation by LLTV

Figure 5 shows a typical LLTV image of the series connected sheath, with surface potential on the SPS increasing from 0 at the bottom end to 1 KV near the top (actually about the center of the panel) of the picture. The sheath is the dark area, seen to increase approximately linearly in thickness from 0 at 0 volts to perhaps 1-2 meters at 1 KV. The outer boundary is generally rather sharply defined in the LLTV image, as expected from the space charge limited thickness hypothesis.

The sheath is frequently visible on LLTV, as a dark region in front of the panel which expands or contracts as a function of voltage on the panel face, when viewed under sufficiently high plasma density conditions against a dark background. We believe the sheath region is dark because with electrons (or ions) excluded, little of the ambient plasma recombination/de-excitation leading to photon emission occurs. In any case, acceleration of ions (or electrons) in the sheath leads to a reduction in number density by more than an order of magnitude. The sheath becomes unobservable when the outer boundary becomes large and curved, not parallel to the line of sight, or viewed against a bright background (such as the aluminized mylar toward the top of fig. 5).

Sheath Detection by Probes

The second method involved watching for an alteration in the observed I vs. V current collection characteristic of a moveable Langmuir probe as it approaches and enters the outer boundary of the sheath from the external plasma (or equivalently, as the sheath expands to envelope the probe as the surface voltage of the panel is increased). After some experimentation, a satisfactory operational technique was developed for recording this information. A series of log I vs. voltage curves were recorded for electron collection from the zero current voltage up to +100 volts, as surface voltage on the panel was increased in steps from zero until the probe (at a particular location) was deep inside the panel's sheath. A representative set of curves is shown in fig. 6. The undisturbed plasma at this point was about 10^6/cc with an electron temperature (T_e) slightly less than 1 eV as deduced from the initial curve recorded with 0 V on the panel. The linear increase in current from (thermal current density) about $1x10^{-5}$ amp at +6 V to $9.5x10^{-4}$ amp at +100 V is consistent with normal orbit limited electron collection in such a plasma.

As voltage is applied to the panel, no effect is seen at the probe location (still outside the growing panel sheath) until the applied voltage (V_{OP}) reaches -800V, when a slight displacement of the curve at higher probe voltages is first detectable. Increasing V_{OP} by 100v to -900v causes a clearly noticeable reduction in probe current at +100v bias, more than resulted from the previous 800 volt change. There is as yet no change below the linear portion of the curve. We interpret this as indicating the probe is still (just) outside the panel's sheath boundary but near enough for the probe's expanding effective radius of electron collection (about 5 inches for a ½ inch probe at +100v) to partially contact the region of sheath disturbed ambient electron currents. (A partial "shadowing" of the probe location by the growing plasma absorbing sheath may also be expected, particularly when the panel is located between the probe and the plasma source.) The sheath has probably just passed the location of the probe when -1,000v is applied to the panel, the current zero-crossing voltage has shifted. As the panel voltage is increased further, moving the location of the sheath edge further beyond the probe location, even greater positive voltages are required on the probe before its electron attracting field is strong enough to reach beyond the electron depleted sheath boundary to an undisturbed plasma region containing electrons which it can then draw to its surface. When panel voltage has increased to -1500v, the probe is so deep inside the panel's ion sheath that +100v on the probe is able to draw less than 0.1% of the electron current available outside the sheath (+70v is required to attract any measurable electrons at all into this electron depleted region).

A set of curves similar in appearance is obtained for positive (electron collecting) sheaths. The causes are probably quite different, since there are electrons present to be collected inside this sheath. The probe current zero crossing voltage will still shift to progressively higher positive voltages as the sheath is entered, since the probe will repel electrons until it exceeds the local (positive) potential inside the sheath. The current collected will then be reduced due to the combined lower density and higher energy of the available electrons, and their essentially unidirectional velocity distribution.

Sheath Size

The test results show a distinct limitation to sheath growth, as a function of voltage and (ambient plasma) current density. Within present limits of experimental error, the observed sheath thicknesses follow the $V^{3/4} \div n^{1/2}$ dependence expected for space charge limited current flow with d (sheath thickness) the free variable. Figure 7 shows the applied voltage required at various plasma densities for the outer sheath surface to reach a Langmuir probe (#23 in fig. 3) located 1 meter from the surface of the array. The reference line is the theoretical thickness calculated for a one-dimensional planar geometry case (Appendix A) with an effective electron or ion "temperature" of 1 eV. Notice the electron sheath (shown as ⊕) is about the same size as the ion collection sheaths (shown as ○).

Sheath Current Leakage vs. Voltage

The resultant leakage current multiplication factor was observed to be much lower than observed on previous small scale tests. Figure 8 shows current leakage from "SPS" to the plasma observed from -10 to -3000 volts in four ambient plasma densities ranging from 10^4 to 10^6 per cubic centimeter. The observed rate of increase in leakage current with voltage is seen to increase as the resulting sheaths become large compared to panel width, as expected from figure 2. The regions of sheath size shown are rough estimates, based on the calculation in figure 20 normalized to an actual measurement for each data set.

Floating Potential

Recalling the requirement that total current flowing to an electrically isolated panel in series connected configuration be zero for voltage equilibrium with the ambient plasma to exist, we expect values of V- and V+ relative to the plasma shift so that (fig. 9)

$$J_{oi} A_- = -J_{oe} A_+ \qquad (1)$$

where j_{oi} and j_{oe} are the ambient ion and electron current densities across the outer sheath boundaries, and A- and A+ are the effective surface areas of the negative and positive potential sheaths. We neglect current contributions from other sources such as secondaries, and the area (± a few kT) immediately around the V = 0 (w.r.t. Vp) point along the panel. For reasonably thin sheaths, relative to panel dimensions, we can use the approximation

$$\frac{A-}{A+} = \frac{L(-)}{L(+)} = \frac{V-}{V+} \tag{2}$$

where L(-), L(+) are the lengths of the panel sections floating negative, positive with respect to plasma potential. $\Delta V/\Delta L$ along the panel is assumed constant. (We note the assumption j_{oi}, j_{oe} constant along the sheaths does not require j_i, j_e constant along the panel. Current density along the panel should vary due to focusing effects, without affecting our assumptions so long as the relative geometric shapes of A- and A+ are the same. This should be true for thermal velocity distributions and approximately valid for ion streaming velocities oriented perpendicular to the face of the panel. For other orientations, more careful account must be made for both the effective intercept cross-section (A-) and effective reduction in j_{oi} due to screening by both the panel and the positive (A+) sheath.)

In the case of thermal electron currents and directional streaming of ions with mean energy

$$E_i = \frac{1}{2} m_i V_i^2 \tag{3}$$

We can use (1-D calculation)

$$j_e = n_e q_e \overline{V}_e = -n_e e \sqrt{\frac{kT_e}{m_e}} \tag{4}$$

$$j_i = n_i q_i \overline{V}_i = +n_i e \sqrt{2E_i/m_i} \tag{5}$$

Therefore

$$\frac{-j_e}{j_i} = \sqrt{\frac{m_i}{m_e}} \sqrt{\frac{kT_e}{2E_i}} \tag{6}$$

For an Ar+ plasma, $\sqrt{m_i/m_e} = 270$. Typical values for electron temperature of lev and ion beam energy of 20 ev give

$$\frac{-j_e}{j_i} \approx 43 \tag{7}$$

Using (7) in (1) and (2)

$$\frac{-j_e}{j_i} = \frac{A-}{A+} = \frac{L_{(-)}}{L_{(+)}} = 43 = \frac{V-}{V+} \quad (8)$$

We therefore expect the panel to float about 2.3% positive, the remainder (97.7% of L, V_{op}) negative under these conditions. Representative current density and voltage values expected along an array are shown in fig. 10(a).

Comparison with Observation (Ion flow perpendicular to panel face)

This was verified experimentally. The 30 cm thruster was operated from the third level catwalk, aimed horizontal directly into the face of the panel. Average plasma density along the panel is estimated to exceed $10^6/cm^3$, based on supply current of 21 mA at V_{op} = 2000 V compared to 15 mA (at -2000 V) observed earlier when probe measurements indicated densities decreasing from $1.1x10^6$ at the bottom to $2.2x10^5$ at the top of the panel. The experiment configuration was series connected (floating) as shown in fig. 4. Using a pair of electrically isolated power supplies in series, voltages (V_{op}) from 500 to 5500 V were applied to the panel while monitoring the voltage at lead #8 using a DVM referenced to lab ground. (The plasma potential was +5 - 10 V referenced to lab ground.) As long as the panel floated more than 90% negative wrt ground, the DVM at #8 would read -0.167 V_{op} less V+. Readings of V+ directly at lead #10 were also recorded at V_{op} = -3 kV and -4 kV. Values observed are plotted in fig. 11. V+/V_{op} at 3-4 kV is 2.6-2.3%, very nearly the expected value.

The behavior of V at lead #8 indicates this is probably true at lower values of V_{op}, but the high leakage currents cause a loading down of the resistive panel such that $\Delta V/\Delta L$ is no longer constant and a large fraction of the panel surface between #8 and #10 is in effect left out of the circuit at V_{op} = 500 - 1000 V. At these voltages the entire current supplied at the ends of the panel is carried part of the length entirely through the plasma, leaving zero current in the panel. Therefore $\Delta V/\Delta L$ = 0 in this section, which floats slightly negative so as to repel (97%) of the electrons and draw no net current from the plasma. This is illustrated in fig. 10(b).

Power Loss

Total current supplied to the panel was recorded for each voltage. This allowed calculation of current leakage estimates and the resultant power lost to the plasma as a function of V_{op}. The calculated current leakage values were obtained under assumptions which may be in error ±25%. These errors cancel in further calculation of total power lost. Results are shown in Table 1. The 56 watts estimated lost in driving plasma currents at V_{op} = 4,000V is significant, but well under the roughly 1 kilowatt available from a solar array this size.

This result is plotted in fig. 12 for comparison with the earlier estimates in ref. 3 using constant leakage per unit area and reducing the total by 90% to allow for relative insulator/conductor areas. The "error bars" show our estimated uncertainty in plasma conditions and possible reduction in total currents due to 90% insulation (our measurements were for a 100% conductive surface).

Arcing to Plasma

Arcing, defined here as any sharp and transient increase in current drain to the plasma was frequently observed. Most measurements of current loss vs. voltage were limited to voltages less than 2-3 KV because arc induced transients became so severe that useful meter readings could not be made. Although some arcs were "small" and did not affect the rest of the panel except for small pulses in the current meter, many resulted in complete discharge of the panel voltage, which required 1-5 seconds to rebuild. This was visible both in the collapse of the sheaths to much smaller dimensions (observed both in the LLTV dark image, see fig. 13, and with any Langmuir probe located inside the sheath, see fig. 14) and as a voltage drop indicated by the power supply meter. The time and electrical power required to restore the sheath could be appreciable (estimate typically 2 seconds and 50 joules). This collapse of the entire sheath was observed, by LLTV, to occur even in cases where the discharge was observed to come from an insulator surface located 1-2 meters out in the sheath and having no contact with the conductive panel surface other than the plasma (fig. 15).

The arcs were observed to occur at positive voltages over +400V, and negative voltages over -1,000V. There appears to be no particular dependence between plasma density and minimum voltage for the onset of arcing. At any given density, arcing would occur at -1KV on some days and then not occur at voltages up to -3 KV the next day. The appearance of the arcs, as observed by LLTV, varied greatly. However, arcs occurring at negative voltage tended to appear as point discharges, even when occurring from an extensive flat surface. Positive voltage arcs more often would involve most or all of a large surface in a sudden (less than 1/30 sec) bright discharge.

A very interesting finding is that every arc observed by the LLTV system to date occurred from an insulator surface. We have not yet observed a single instance of a visible arc occurring from the conductive surface area of the panel. It would appear that the arcs are the result of a local charge build-up due to sheath currents impinging on a nonconductor in their path in a process similar to that occurring with satellites in GEO during substorms. Most of the resulting current drain from the panel biasing power supplies must be due to large scale currents within the collapsing (space charge) sheath, not directly due to the small area of visible flash region currents.

Surface Glow: Ion Focusing

A very noticeable effect occurs at negative panel voltages, where a distinct surface glow pattern is observed by LLTV to form along the face of the panel (see fig. 16). This pattern has a shape suggestive of a flow along the panel and was originally thought to be due to secondary electrons cascading along the surface voltage gradient. This was ruled out when the voltage gradients were found not necessary for formation of the pattern. The pattern is observed to become brighter and narrower as panel voltage increases (fig. 17). We now believe it is due to focusing of the incoming ions by the plasma sheath, which acts as a large cylindrical lens in front of the panel. As the size and curvature of the sheath potential surfaces increase with voltage, the degree of focusing also increases as illustrated in fig. 18. This focusing effect is present at both ends of the panel when operated in constant high voltage configuration (see figs. 16 and 17) but vanishes at the grounded end (fig. 19) for a series connected panel. This is probably due to the sheath size there flattening out to zero.

CONCLUSIONS

We conclude that estimates based on calculations of space charge limited sheath dimensions provide a promising working model for calculating design estimates of high voltage plasma current leakage from large solar arrays and similar objects. It would appear necessary that all such estimates be verified by a carefully developed sequence of plasma-vacuum tests progressing from small lab chambers to full scale flight tests, due to large differences in applicable scaling relations which are observed to result from subtle differences in assumed conditions. Large scale tests of the sort described here, together with adequate math models to provide continuity between different design or test details, will be an important element in any development test sequence for systems involving large surfaces or high voltages.

The present results are preliminary, based on exploratory measurements intended to determine the feasibility of this type of investigation and order of magnitude of the experimental quantities to be measured. Detailed verification and extension of these results is the first objective of our next series of tests. Development of math models to include the space charge effects is needed. Detailed cross-checking of the predictions of such models with actual measurements within the 1-5 meter sheaths during tests in the large chamber should be very useful to aid further development of both models and tests.

The present results indicate that equilibrium high voltage leakage currents to the plasma should be much less than some earlier predictions had indicated, particularly for very large solar arrays. The power loss, and other effects, due to the observed arcing phenomena threatens to be much more significant unless adequate means are developed to understand and control it. More detailed and complete study of the large scale high voltage sheaths around a solar array appears basic to an adequate treatment of both problems. While the dense plasma present in LEO will bleed off any natural charge build-up from passive surfaces, the plasma sheath formed around any high voltage surface envelopes all surrounding structure in an environment very similar to that at GEO during intense storm conditions. Within the sheath, strong flows of the collected species of charge are accelerated to kilovolt energies while most charge of the opposite sign is excluded from the sheath area and cannot act to bleed off areas of surface charge build-up and prevent eventual arcing.

APPENDIX A

CALCULATION OF SHEATH THICKNESS

The size of the sheaths is expected to vary in such a manner that space charge limited flow conditions prevail. The calculation is somewhat different from the usual case considered, in that the current density available across the virtual "electrode" formed by the outer sheath surface is considered as fixed (by the ambient thermal motion or orbital velocity current flow across that boundary) while the separation of the two "electrode" surfaces (the outer sheath boundary and the panel face) is freely variable. For example, we calculate the expected sheath thickness, d, for the case of planar geometry by equating the random thermal current of the attracted particle species (electron or ion)

$$j_o = 1/4\ N_o q \sqrt{\frac{8kT}{\pi m}} \tag{1}$$

or for directed (1-D) flow

$$j_o = N_o q \sqrt{\frac{kT}{m}} \tag{1a}$$

to the Langmuir-Child Law expression for planar diode space charge limited current

$$j_{sc} = \frac{4\epsilon_o}{9} \sqrt{\frac{2q}{m}}\ \frac{V^{3/2}}{d^2} \tag{2}$$

Therefore, defining $kT = E$ (expressed in electron volts) and k^* to incorporate the appropriate velocity distribution function in a general expression for

$$j_o = k^*\ N_o\ q \sqrt{\frac{kT}{m}}$$

We obtain

$$d = \frac{5.89\text{x}10^3}{\sqrt{k^*}}\ \frac{|V|^{3/4}}{N_o^{1/2}\ E^{1/4}} \tag{3}$$

Where $\sqrt{k^*} = 1.0$ for 1D flow and $\sqrt{k^*} = .63$ for Maxwell distribution. In most cases of interest, k^* is probably close to 1. Even the thermal electrons must have their velocity distribution altered significantly from Maxwellian near the sheath boundary, as there exists flow in but none out.

Notice that the particle mass (m) does not appear in (3). For a given plasma density (singly ionized), the electron sheath will be the same size as the opposite polarity ion sheath if their temperatures are the same. The current densities across the sheath outer boundaries will be higher for electrons in the ratio

$$\frac{j_{oe}}{j_{oi}} = \sqrt{\frac{T_e m_i}{T_i m_e}} \qquad (4)$$

For the case of streaming flow velocities greater than mean thermal velocity (usually the case for ions in low earth orbit) it is necessary to use a carefully selected equivalent temperature, or the direct expression

$$j_{oi} = Nq \langle v \rangle \cos\theta \qquad (5)$$

where $\langle v \rangle$ is the average velocity (i.e., orbital velocity or velocity of thruster beam energy) and θ is the angle between flow vector and sheath normal.

The resulting relation between plasma density and voltage required to cause a given sheath thickness d is plotted in fig. 20 for several values of d. The calculation should be reasonably good for d << 1 meter. For d ≈ 1 meter and d >> 1 meter, similar expressions can be obtained for cylindrical and spherical geometry respectively, using

cylindrical
$$j_{oe} = \frac{4\epsilon_o}{9}\sqrt{\frac{2q}{m}}\,\frac{V^{3/2}}{ra\beta^2} \qquad (6)$$

spherical
$$j_{os} = \frac{4\epsilon_o}{9}\sqrt{\frac{2q}{m}}\,\frac{V^{3/2}}{r^2 x^2} \qquad (7)$$

where α^2 and β^2 are quantities tabulated by Langmuir (refs. 5 and 6). For thick sheaths we use an approximation from ref. 3:

$$x^2 \simeq 1.16 \left(\frac{r_o}{a}\right)^{3/2} \qquad (8)$$

where r_o = outer radius of sheath, a = probe radius. Therefore (3) becomes

$$(d + a) = r_o = 137 \frac{(aV)^{3/7}}{N_o^{2/7} E^{1/7}} \qquad (9)$$

The result for d = 3m (with a = ½m, E = 1ev) is also plotted on fig. 20 for comparison with the planar calculation at 10 ft. The actual, roughly cylindrical geometry, value should lie somewhere between these extremes.

REFERENCES

1. Rosen, A. (ed.) Spacecraft Charging by Magnetospheric Plasmas, Progress in Astronautics & Aeronautics, Vol. 47, MIT Press, Cambridge, MA, 1976.

2. Pike, C.P. and Lovell, R.R. (eds), Proceedings of the Spacecraft Charging Technology Conference, Air Force Geophysics Laboratory, AFGL-TR-0051, 1977 (also NASA TMX-73537).

3. Kennerud, K.L., "High Voltage Solar Array Experiments," NASA CR-121280, 1974.

4. Stevens, N.J., et al., "Investigation of high voltage spacecraft system interactions with plasma environments", AIAA Paper 78-672, April 1978.

5. Langmuir and Blodgett, "Currents limited by space charge between coaxial cylinders", Phys. Rev. 22, 347-356 (1923).

6. Langmuir and Blodgett, "Currents limited by space charge between concentric spheres", Phys. Rev. 23, 49, 1924.

TABLE I. - POWER LOSS WITH OPERATING VOLTAGE

[Series-connected, 9-m^2 floating array; no insulation; $N_o > 10^6/cm^3$.]

V_{op}	I_{supply}	$I_{leakage}$	Power Leakage
500	6 ma	4 ma	1.3 watts
1000	12	7.5	5
1500	15	7	7
2000	21	10.5	14
3000	31	15	30
3500	36	17	40
4000	41	21	56
-4000	44	24	64

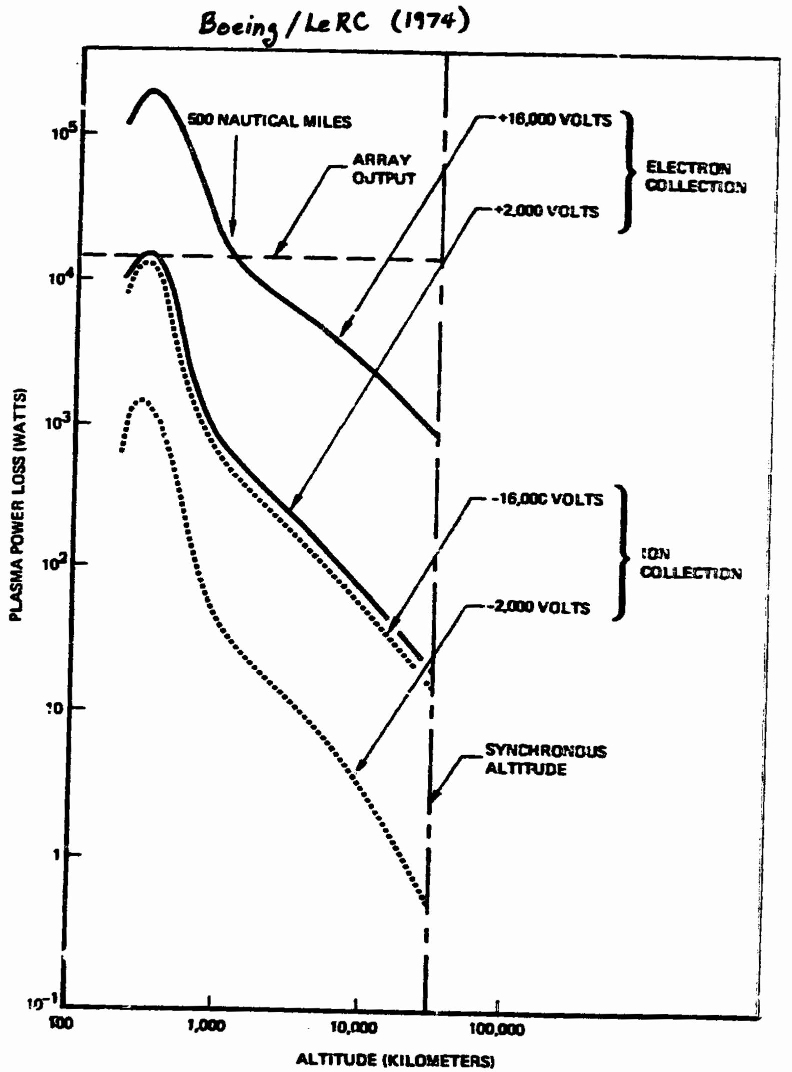


Fig. 1 - Plasma power losses of biased, 15-kilowatt solar array with 90% insulating surface. (From ref. 3.)

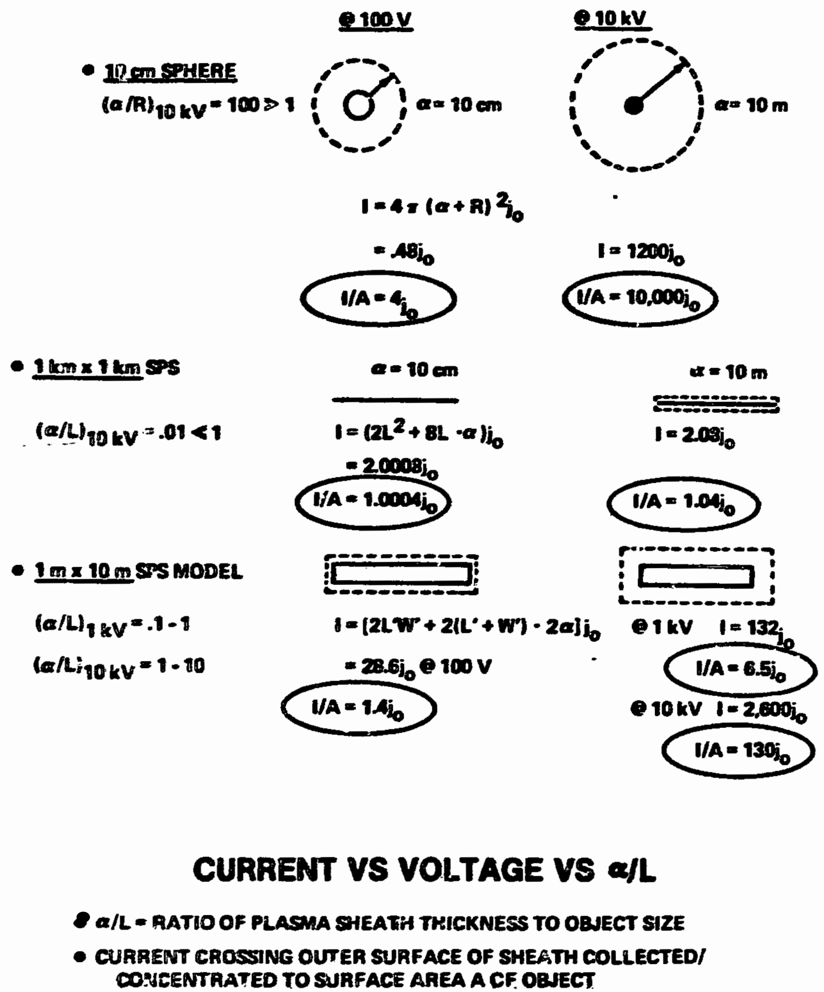


Fig. 2a - Effect of sheath size relative to object size on plasma current collection.

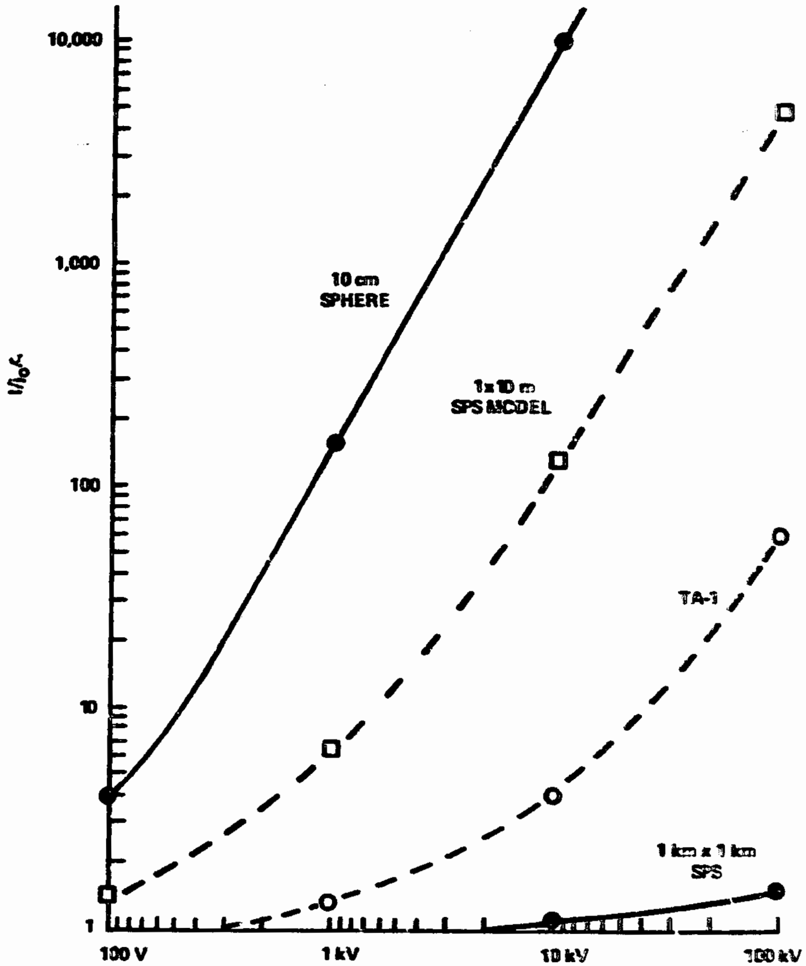


Fig. 2b - Limitation of current multiplication ratio vs voltage expected for collecting objects of increasing size, assuming sheath size limited.

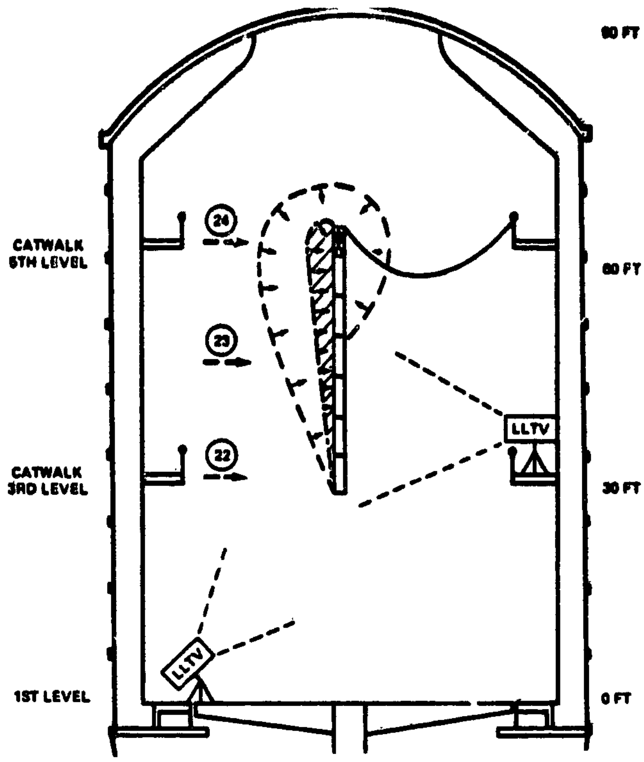


Fig. 3 - High Voltage "array" test lay-out in Chamber A

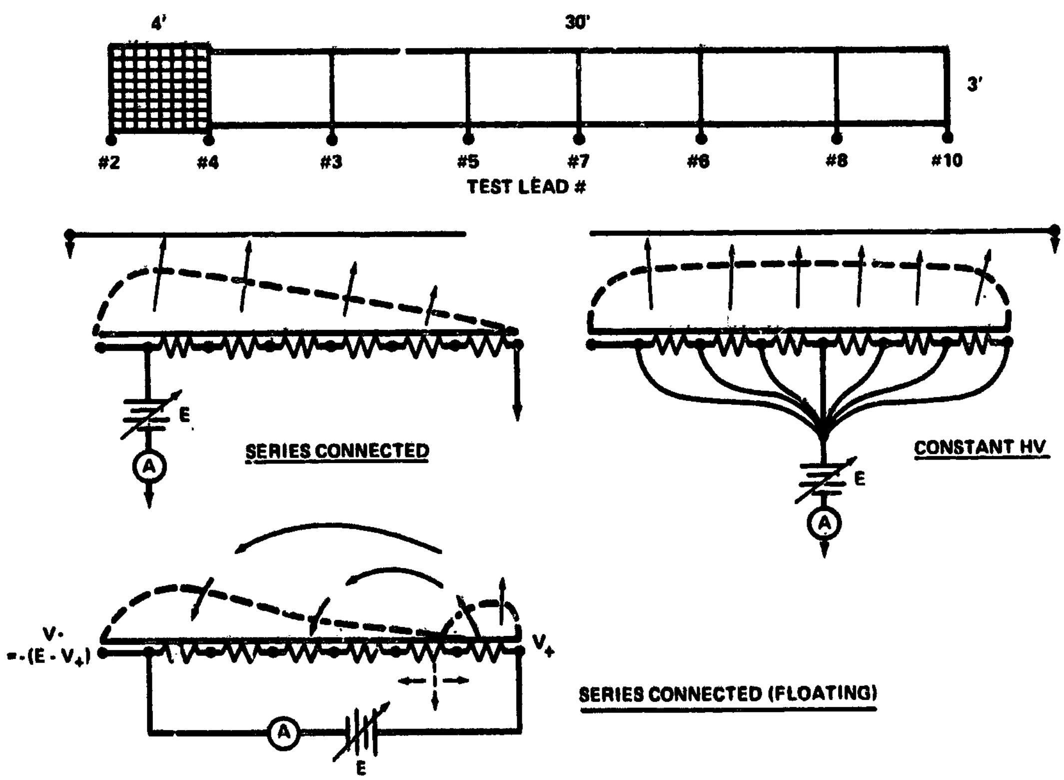


Fig. 4 - Simulated high voltage array electrical configurations (SPL-1; 1977).

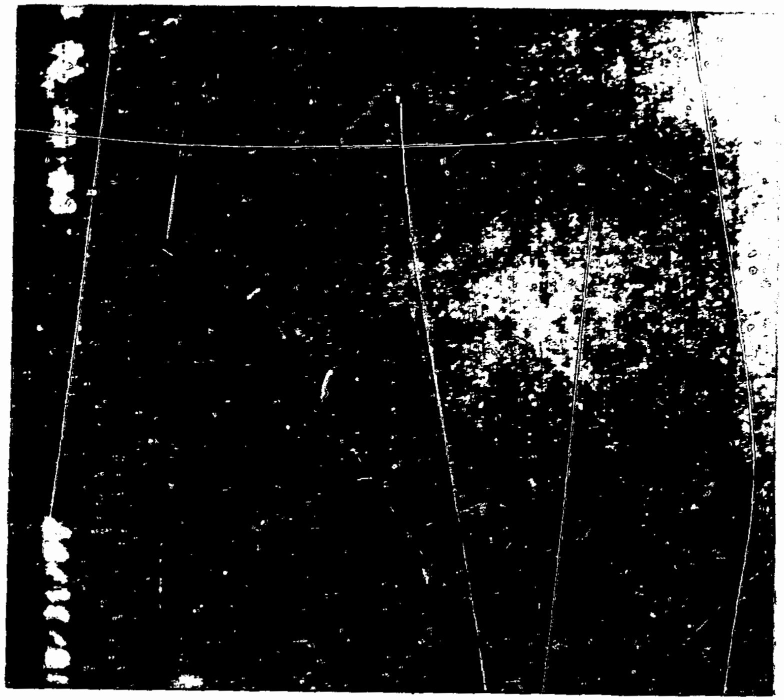


Fig. 5 - LLTV image of HV plasma sheath.
"SPS" edge-on, series connected.

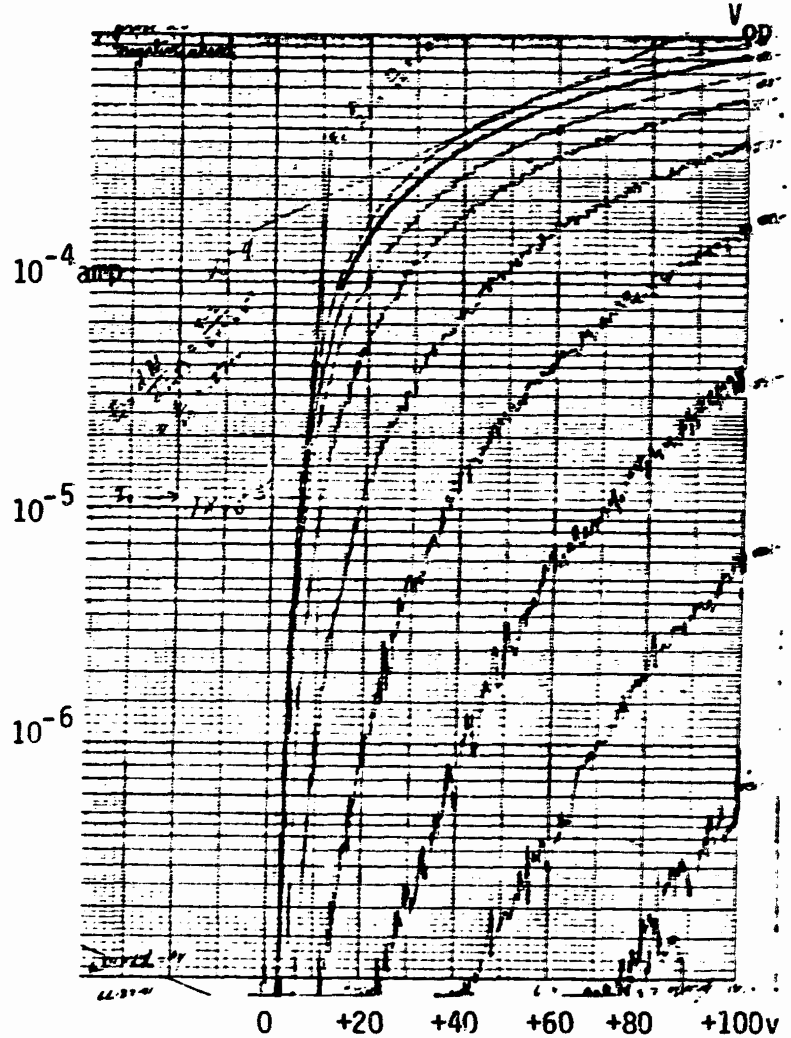


Fig. 6 PROBE BIAS VOLTAGE vs Log I
Change with V_{op} as sheath expands past probe.

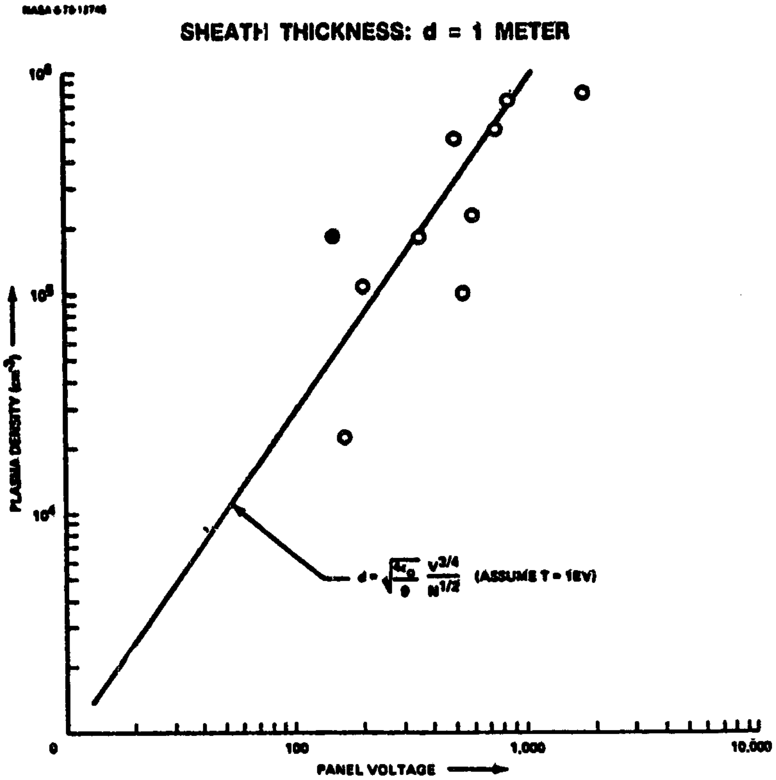


Fig. 7 - Applied voltage required for outer sheath surface to reach Langmuir probe located 1 meter from surface of array.

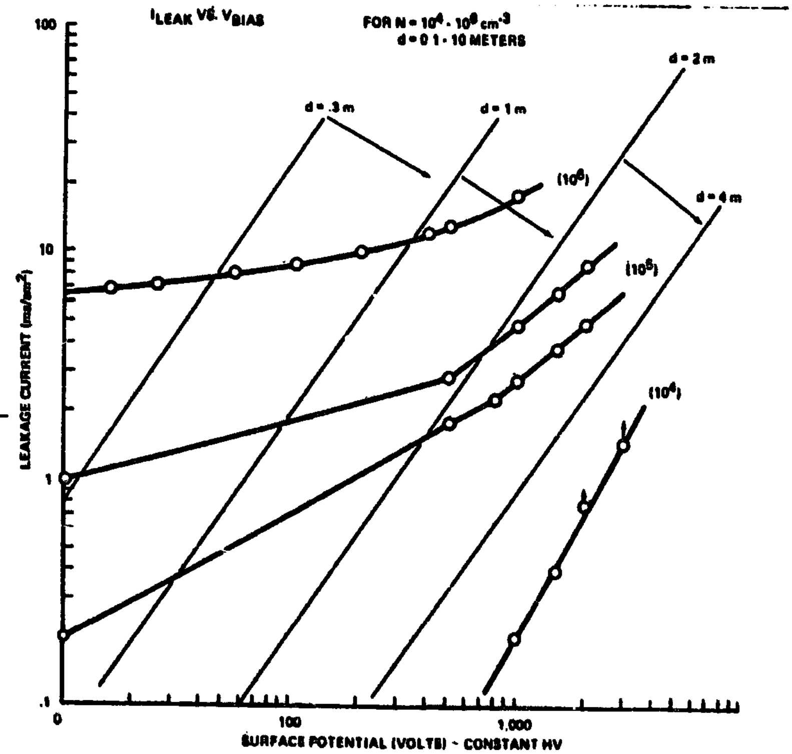


Fig. 8 - Current leakage from SPS to plasma.

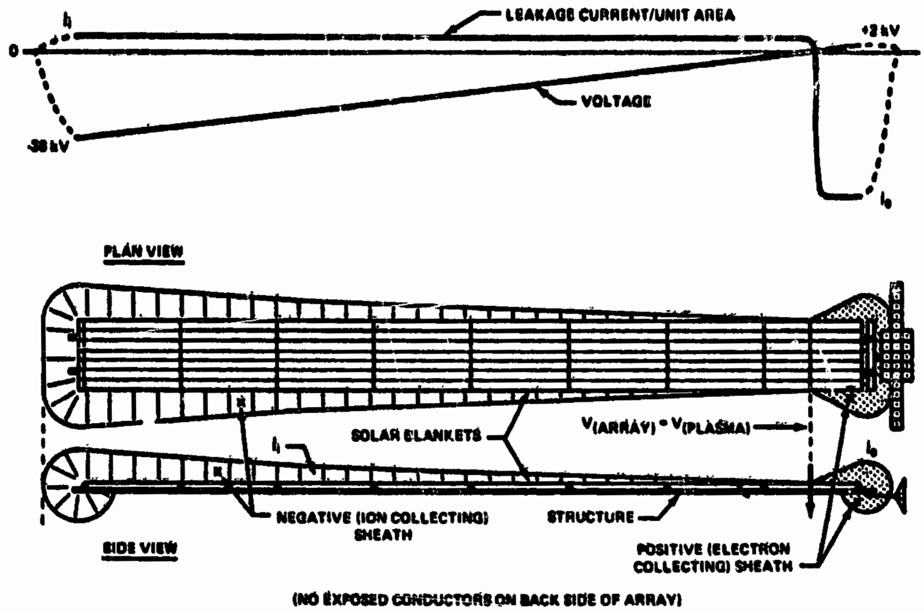


Fig. 9 - Preliminary model of expected space charge limited sheath development around a 10 Mw solar array in LEO. Voltage, with respect to plasma potential, along the array must shift so as to balance ion current against electrons.

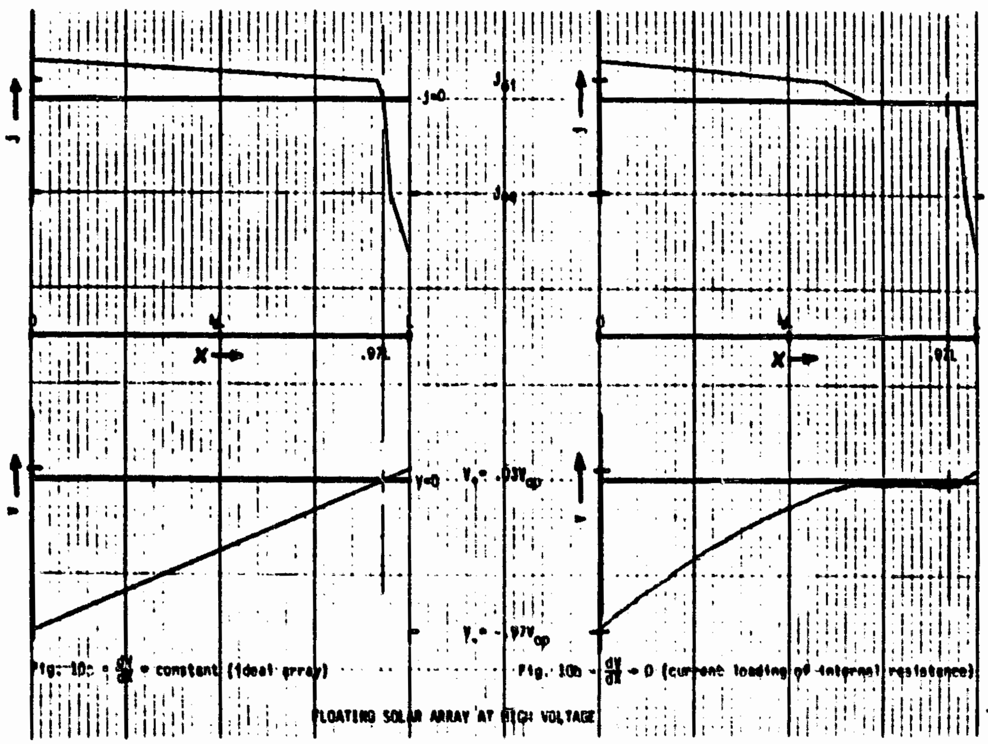


Fig. 10 - Effect of internal loading of series connected (floating) high voltage array due to plasma leakage currents.

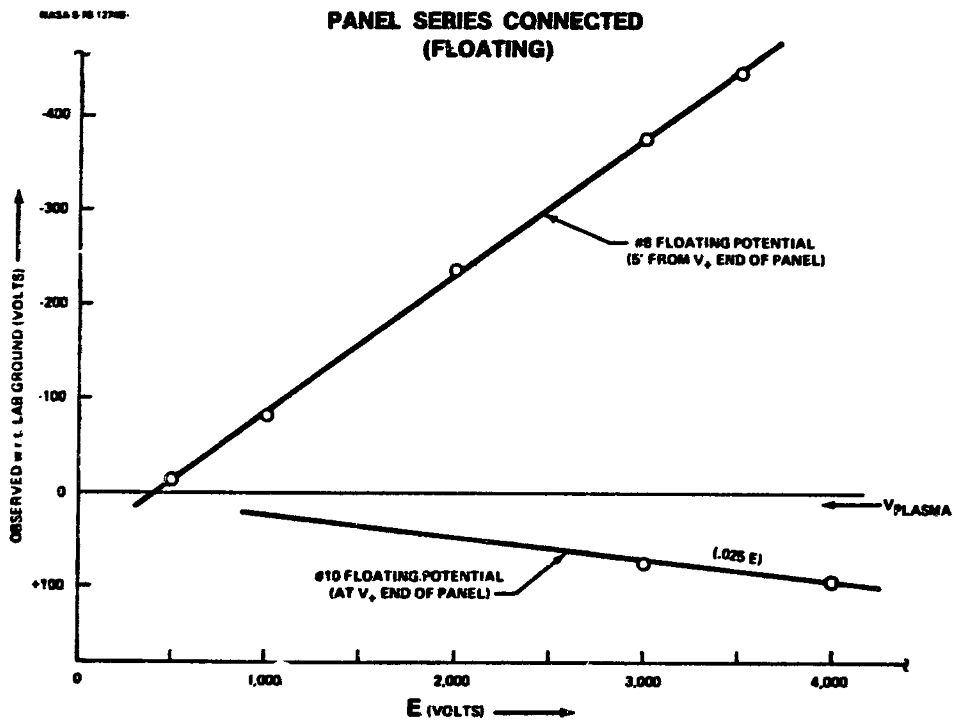


Fig. 11 - Equilibrium floating potential of positive end of simulated high voltage solar array .

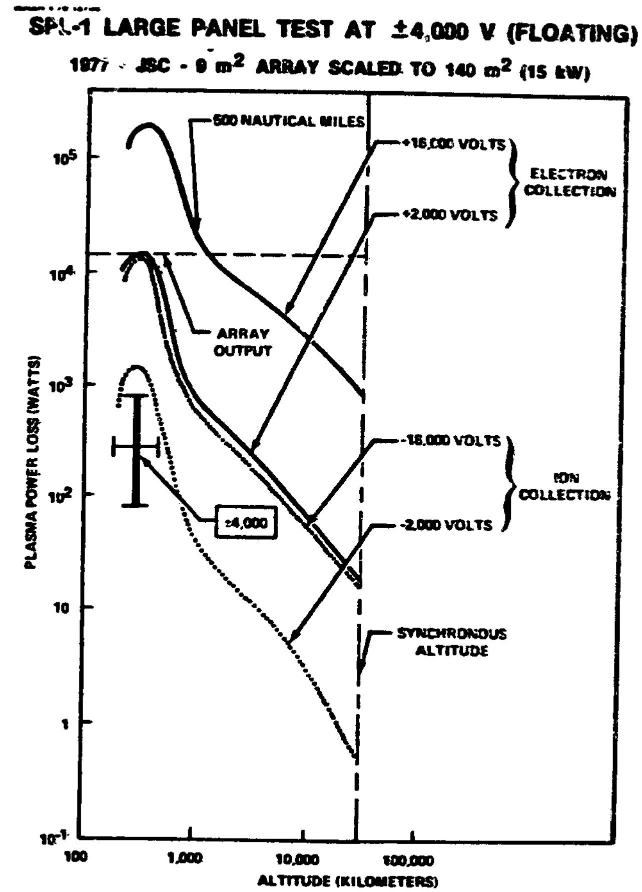
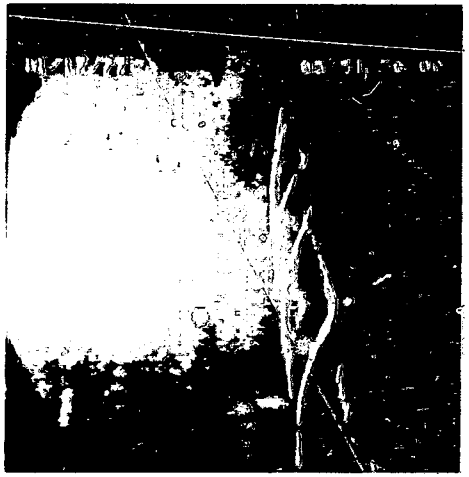
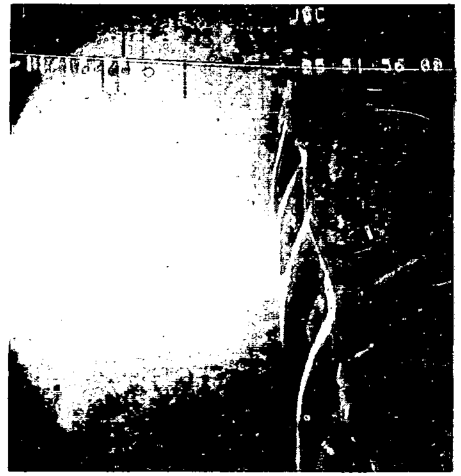


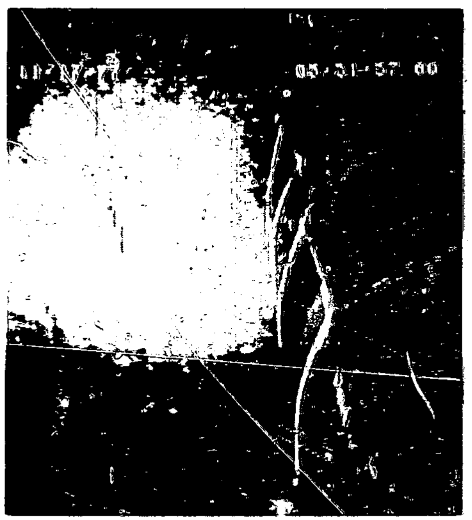
Fig. 12 - Power loss due to plasma leakage currents observed at ± 4000V, from an uninsulated 1 x 10 meter simulated solar array, plotted for comparison with estimated curves shown in fig. 1.



(13a) sheath before arc



(13b) 1/30 sec after arc



(13c) 1/2 sec after arc

(13d) 1 sec after arc

Fig. 13 - LLTV sequence showing sheath collapse and slow recovery following "arc" discharge.

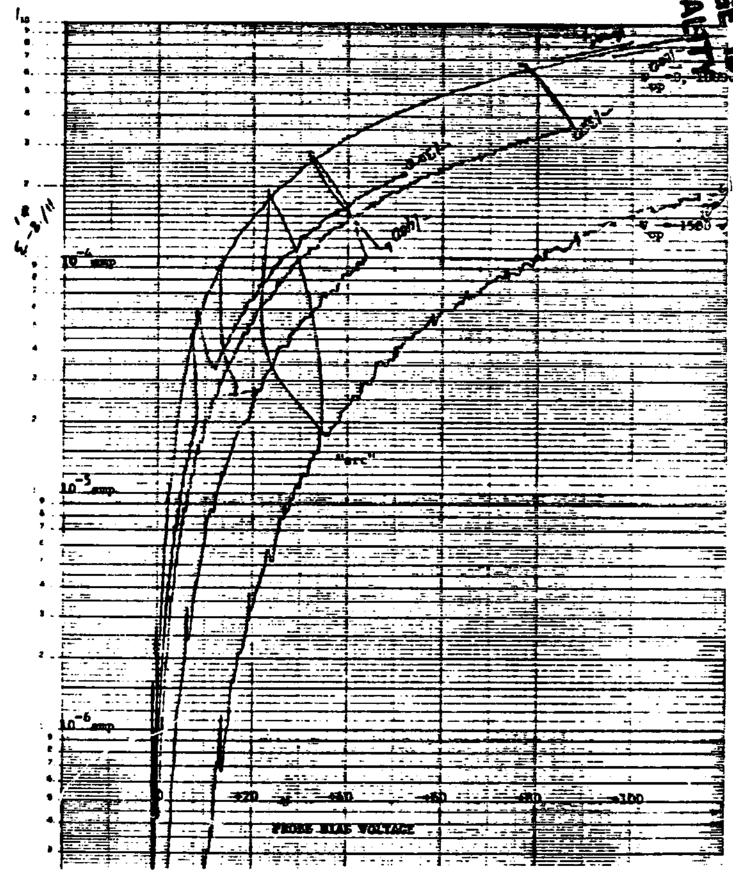


Fig.14 - Set of log I vs V curves showing several arcs with sheath collapse. Probe recorded value I(V) following arc shifts from point along "inside the sheath" curve to a value along original "outside the sheath" curve, then slowly returns to its pre-arc I(V) conditions.

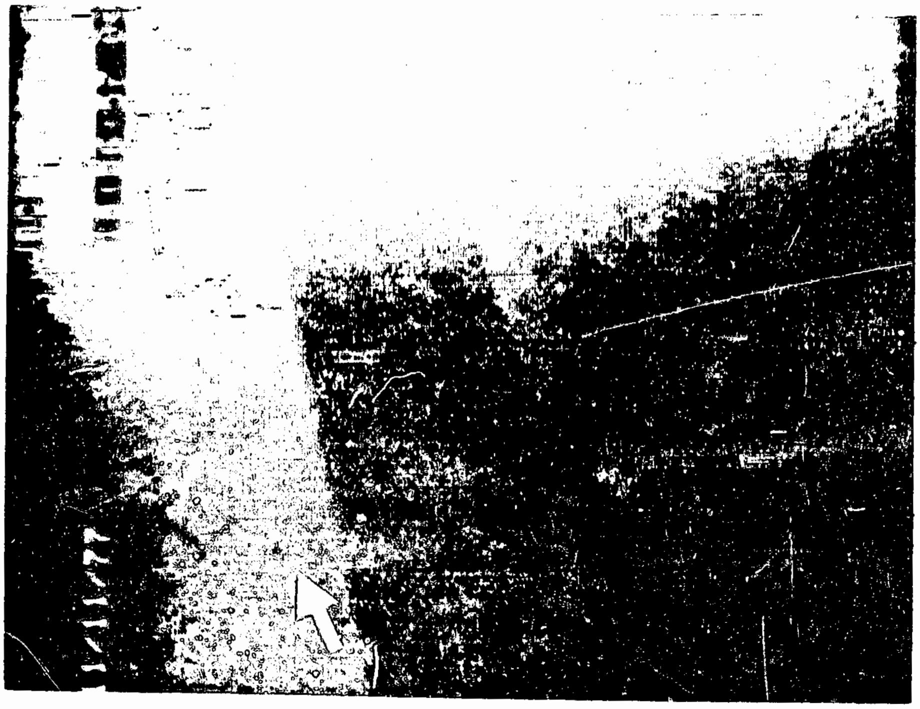


Fig.15a - Arc from mylar tape holding teflon insulated rod to plastic brace, located (arrow) 1-2m in front of "SPS" (@-3000V), inside ion sheath. Edge-on view shows simultaneous collapse of sheath, with no bright glow.

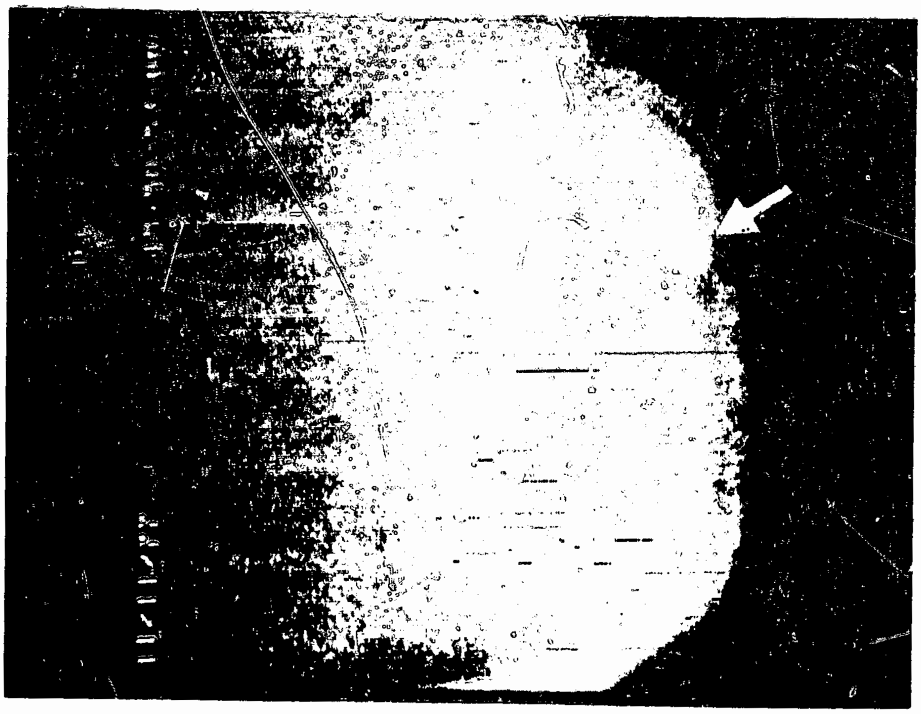


Fig.15b - Arc from teflon insulated/mylar wrapped wire, at point 5m along the wire, 1m behind "SPS" panel (edge on, @+3000V); inside thick electron sheath. Note greatly brighter emission from surrounding region.

Fig. 16 - Surface Glow (Ion Focusing) on face of "SPS" panel. Constant 1.0 kV.

Fig. 17 - Surface Glow (Ion Focusing) on face of "SPS" panel. Constant 2.5kV.

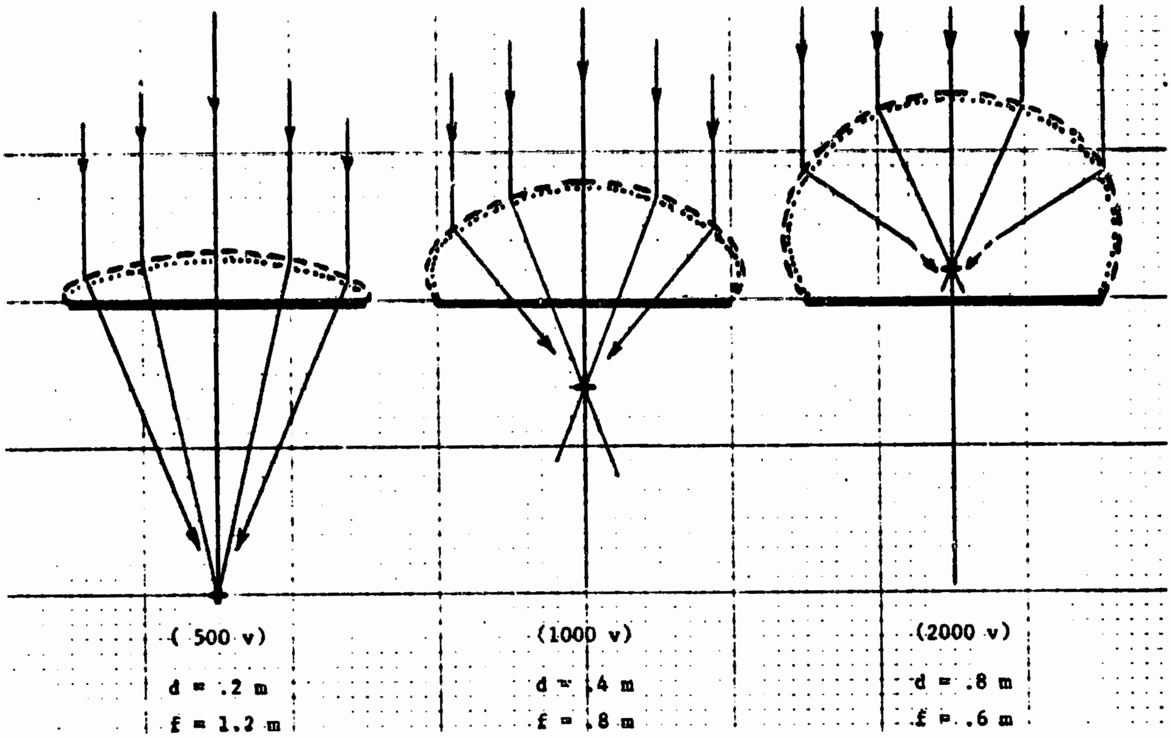


Fig.18 - Ion focusing onto panel by cylindrical lens effect of space charge sheath. Model is qualitative, to illustrate relative behavior to be expected as sheath expands (with increased V, or reduced density).

Fig. 19 - Surface Glow (Ion Focusing) at grounded end of panel (sheath thickness flattens to zero as voltage decreases to ground).

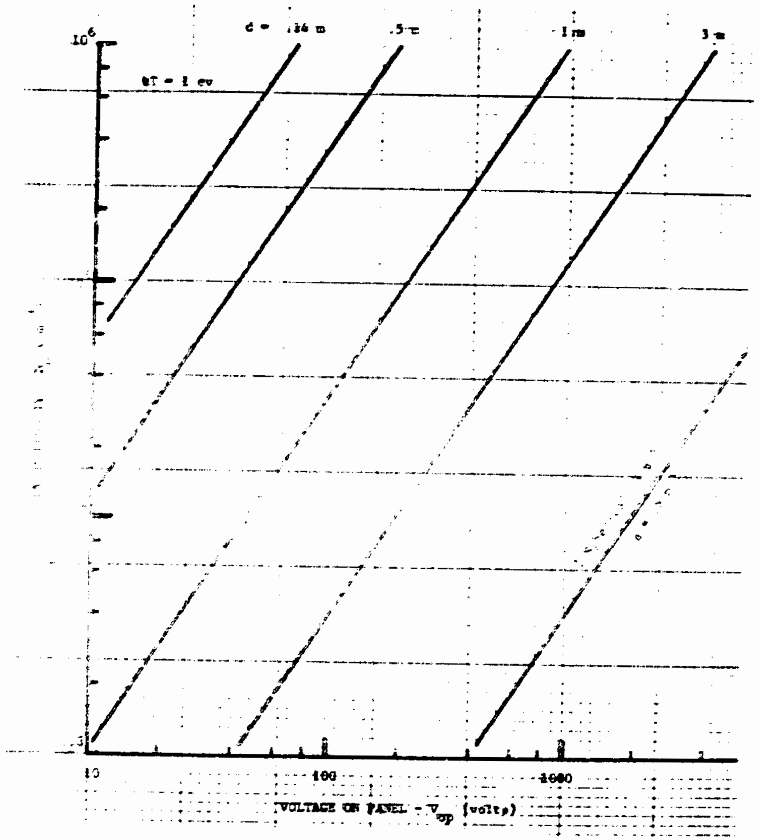


Fig. 20 - Planar space charge limited sheaths, ion or electron collecting. Thickness d vs N_o, V_{op}.

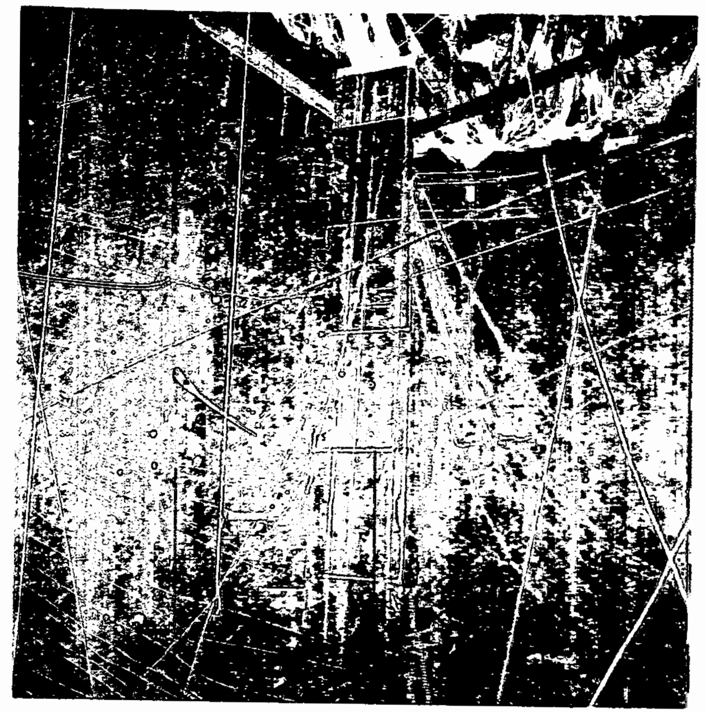


Fig. 21 - "SPS" installed in chamber A for SPL-1 tests. Note movable probes in front.