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# CURRENT FLOW IN A PLASMA CAUSED BY DIELECTRIC BREAKDOWN

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## ABSTRACT

Spacecraft with a thin dielectric coating on the outer surface of the structure which are biased (~ 200 V) negative relative to the atmospheric plasma are susceptible to dielectric breakdown. This paper will present experimental tests designed to measure the electron current flow from the structure through the plasma during the arc. The current path was examined in three parts: the electrons supplied through the structure and the arc to the outer structure, the expansion of the arc into the ambient plasma and the return current through the ambient plasma. The measured electron current either flowing from the plasma or supplied to the plasma by the arc in each case was compared to the random thermal electron current which could be collected. The results of the tests show a spacecraft is capable of supporting arcs with peak currents greater than thermal electron currents, and these currents will be dependent upon the amount of stored charge in the structure (i.e. the structure's surface area and dielectric thickness). Also, the results of these tests show that it is possible for structures with a self capacitance of 10 microFarads to see peak currents of 90 A and structures with 1000 microFarads (i.e. capacitance of one Space Station Freedom module) to produce peak currents of 1000 A.

## INTRODUCTION

All spacecraft to date, including communications satellites, interstellar probes, and the proposed space station, have or will use solar arrays to harness the sun's energy for power. Most of the solar arrays used in the past have been of the low power variety, generating voltages near 30 volts. One exception to this was Skylab which flew a 90 V solar array [1].

As spacecraft become larger and more complex they need more power to operate. In an effort to increase the power available to the spacecraft, the voltage of the solar arrays had to be increased to prevent the need for developing electrical distribution systems capable of handling large currents. This has placed these new larger spacecraft in a regime where the physical interactions between the high voltage solar array [2-5] and the plasma have become significant.

A generating solar array in low earth orbit (LEO) must come to an equilibrium point such that it collects an equal number of ions and electrons. Because electrons are more mobile than ions and easier to collect, the potential of the solar array will be split to collect equal numbers of ions and electrons. This means that a large portion of the solar array will be negative of the ambient plasma, which is the ultimate reference point, in order collect the needed number of ions. Laboratory and flight data have shown this to be the case [6-9]. Because the common practice is to ground or reference the spacecraft to the negative side of the solar array, the potential of the spacecraft will be at the same potential relative to the plasma as the negative side of the solar array. For these new higher powered spacecraft, this places the spacecraft at a high voltage negative of the ambient plasma potential. In the case of Space Station Freedom the structure will be approximately 140 V negative of plasma potential [10].

Some spacecraft have been designed with a thin dielectric coating on the outer surface to protect the spacecraft from the LEO environment. For Space Station Freedom the selected coating is anodized aluminum with an anodic thickness of 0.05 mils to 0.2 mils. A spacecraft immersed in the plasma with this thin dielectric material will build up charge like a large capacitor. The electrons which are collected by the solar array are stored near the surface of the anodic film and the ions from the ambient plasma will be collected on the space side of the anodic film. If the dielectric strength of the coating is not sufficient to withstand the applied voltage stress, dielectric breakdown will occur. Dielectric breakdown has been observed in the laboratory at applied voltages of -80 V for anodized coatings with a thickness of 0.05 mils and -120 V for 0.1 mil thick anodized aluminum [10].

Dielectric breakdown in a conductive plasma has been shown to produce large currents in a short time [10]. The peak currents observed in the laboratory were 90 A at 10 microFarads and 1000 A at 0.1 Farads. In order for currents of this magnitude to be possible the ambient plasma and the spacecraft in question must interact to maintain charge neutrality. If the spacecraft dumps large amounts of electrons into the plasma, the ions that built up on the surface must be neutralized to maintain charge neutrality. This paper will present experimental results describing the current paths needed to neutralize the ions on the surface to support these large currents.

The tests were separated into three parts, which are shown in Fig. 1, to examine the entire current flow path. The current path begins by forming a dense arc plasma by vaporizing and ionizing the aluminum metal that expands into the ambient plasma. The expansion rate of the arc plasma has been measured and it's significance will be discussed. Also, evidence of the arc plasma's ability to discharge the anodized surface will be presented.

Remote areas of the spacecraft structure, which are isolated from the arc plasma will not be able to interact with the expanding plasma. The ambient plasma will only see the structure undergo a significant positive voltage transient during the arc. The ability of this voltage transient to extract electrons from the ambient plasma has been examined, and experimental data will show the current to the surface of the structure to be much higher than thermal electron current collection.

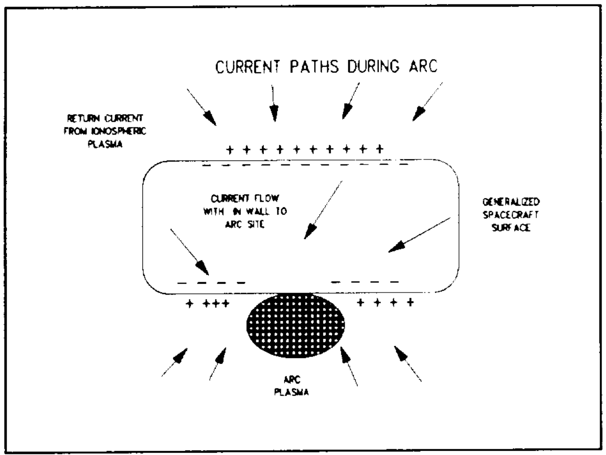

**Figure 1 Example of Electron Flow in the Plasma**

## EXPERIMENTAL TEST APPARATUS

The tests were performed in a 4 ft diameter by 6 ft long cylindrical vacuum chamber capable of a base pressure in the high $10^{-8}$ torr range. An argon plasma was produced in the chamber using a hollow cathode plasma source [11]. A hollow cathode plasma source was chosen for these tests because of its ability to produce a fairly uniform unperturbed plasma. Because hollow cathode plasma sources require a flow of gas to operate, the pressure during operation of the plasma source was in the low $10^{-4}$ torr range.

The spacecraft surface was simulated in these tests with chromic acid anodized aluminum plates with an anodic thickness layer ranging from 0.05 mils to 0.10 mils. This material was chosen because of the direct implication it has as the baseline material for Space Station Freedom. The back side of the 7.6 cm by 12.7 cm samples were coated with kapton to insulate them from the plasma. By insulating the back side of the samples from the plasma, it was easier to understand how the ambient plasma was interacting with the samples. The samples were biased negative with a DC power supply which was current isolated from the samples by a 10 K ohm resistor.

Schematics of the various test configurations are shown in Figs. 2,3 and 4. All test configurations were identical in chamber size, type of plasma source, and bias supply. Below, is a description of the variations in each test configuration.

### Arc Expansion into the Ambient Plasma

Figure 2 shows the test configuration used to measure the arc plasma expansion rate. A single anodized aluminum plate was

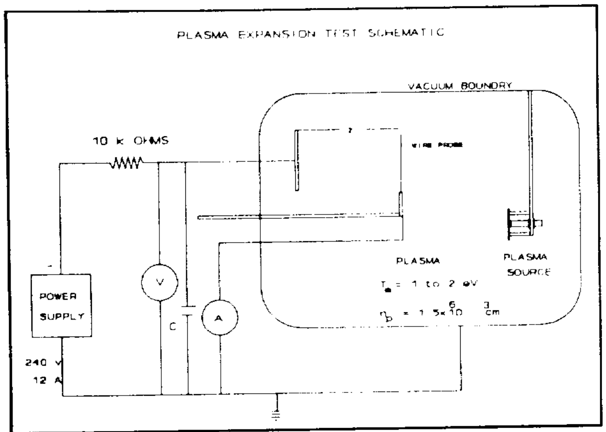

**Figure 2** **Arc Plasma Expansion Test Schematic**

placed in the center of the chamber and biased 160 V negative of ground and allowed to arc. Because the plates themselves did not have sufficient charge capability, an 8 microFarad capacitor was placed in the circuit to provide a small amount of charge. A 0.025 cm (0.01 in) diameter and 12.7 cm (5 in) long cylindrical Langmuir probe which could be moved axially was placed into the chamber. The probe was grounded through an ammeter to measure the current surge from the arc. One channel of an oscilloscope was connected to the ammeter to measure the current surge as a function of time and the other to the voltage bias on the plate. The oscilloscope was triggered off the voltage bias on the plate to signal the start of the arc.

Current and voltage data were recorded at 5 cm increments over a 50 cm range. The data collected were analyzed in terms of the time for the current surge to reach a given probe position.

## Current Supplied by the Structure

Tests to examine the current flow through the structure during an arc were performed (Fig. 3) by placing two anodized aluminum samples of identical size and anodization condition approximately 36 cm (14 in) apart in the vacuum chamber. Each plate was isolated from the other as well as the tank wall. The two plates were connected to each other outside the tank and an inductive current probe was placed around the line between them to measure current transferred during an arc. The arrow shown in the figure indicates the direction of positive electron current. Both plates were biased to the same potential in the tank and allowed to arc. One channel of an oscilloscope was connected to the current probe to measure current transients between the two plates and the other to monitor the voltage bias. The oscilloscope was triggered from the plate voltage to signal the start of the arc. The current and voltage data were then numerically analyzed to measure the total integrated charge transferred to the other plate during each arc.

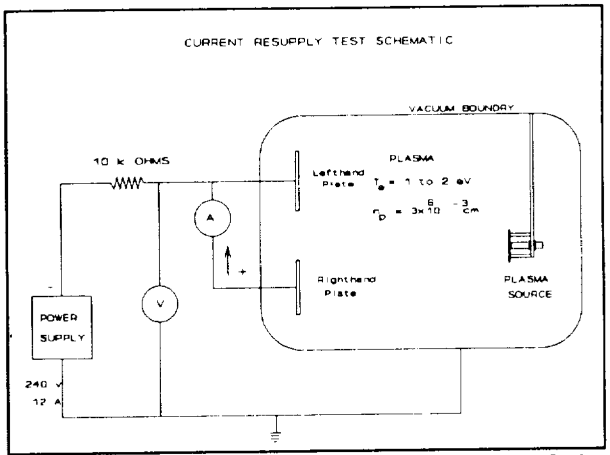

**Figure 3** **Schematic of Two Plate Experiments**

## Return Current from the Plasma

A single anodized aluminum plate was placed in the center of the chamber and biased -140 V to -160 V. In this set oftests the plate shown in Fig. 4 was not allowed to arc but was instantaneously grounded using a switch to simulate the voltage transient the structure would see if an arc occurred. An ammeter was connected to the plate, which has a known capacitance, to measure the amount of electron current caused by the neutralization of ions by the ambient plasma electrons. In this set of tests the plasma source which was allowed to float in all other tests, was grounded to simulate the infinite well of electrons one would see in space. One channel of an

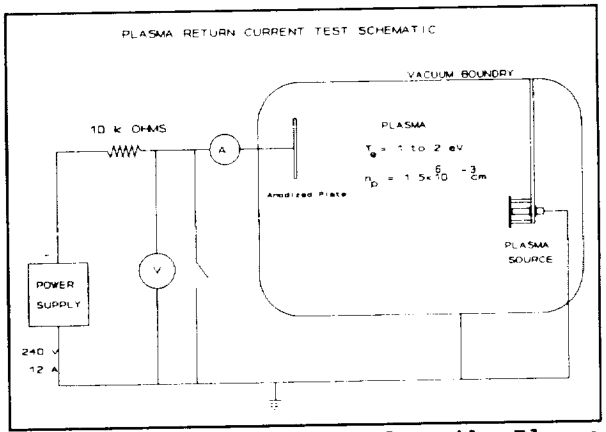

**Figure 4** **Return Current from the Plasma Test Schematic**

oscilloscope was connected to the ammeter the other to the plate bias. The oscilloscope was triggered off the plate bias. Once the voltage transient was applied, the current data were recorded as a function of time. The recorded current data were numerically integrated and the amount of charge flowing calculated.

## EXPERIMENTAL RESULTS

After the initiation of an arc by dielectric breakdown, electron current flows from the structure to the ambient plasma while the ambient plasma is returning electrons to the structure. The flow of electrons through the plasma begins with the production of a dense arc plasma by vaporization and ionization of the bulk aluminum metal. The electrons stored in the structure which is negative of the ambient plasma provide the necessary energy to produce a plasma during the arc. The arc plasma then expands into the ambient plasma in all directions neutralizing the part of the structure it contacts.

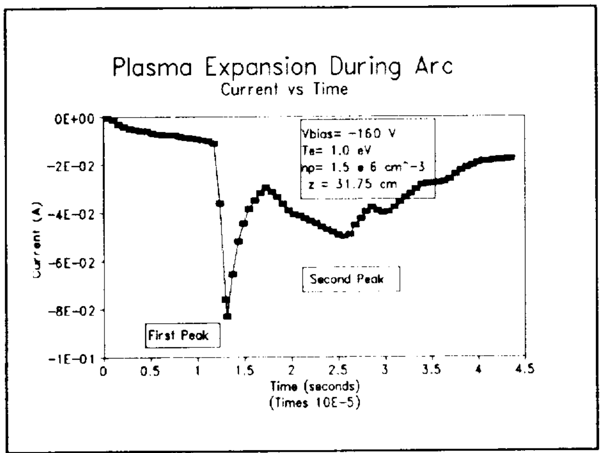

**Figure 5 Typical Arc Plasma Expansion Data**

Typical data collected while measuring the expansion rate of the arc plasma are shown in Fig. 5. The current trace presented in this figure was recorded with the Langmuir probe approximately 32 cm from the anodized aluminum sample. All current traces recorded showed the two peak structure observed in Fig. 5. This figure shows an intense plasma wave front passes the probe first followed by a second less intense wave. The intensity of both fronts (i.e. 80 mA and 50 mA)is greater than the thermal electron current (0.1 micro Amps) that could be collected by the probe from the ambient plasma. The first peak is the actual arc plasma wave front passing the probe. The significance of the second peak is not known at this time. This type of wave structure was typical of all data recorded during these tests.

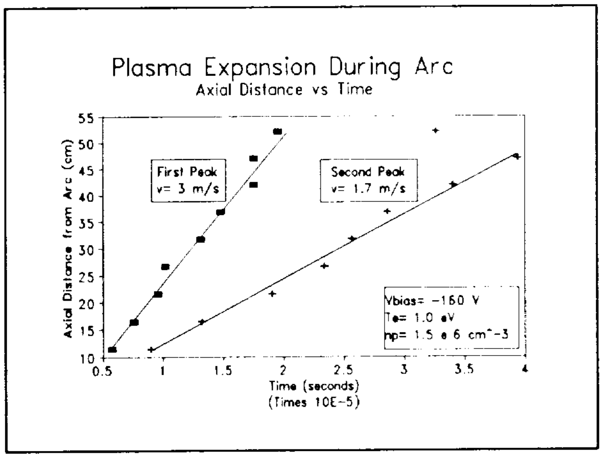

**Figure 6 Arc Plasma Expansion Rate**

The time for the arc plasma wave front to reach the Langmuir probe was plotted as a function of axial position and is shown in Fig. 6. This figure provides an indication of the velocity or the rate of expansion of the arc plasma into the ambient plasma. The electrons in the plasma which are more mobile than the ions are controlled by the electrostatic interaction of the ions. The velocities shown in Fig. 6 were computed by calculating the best linear fit to each set of data. The calculated velocities are an order of magnitude higher than ion acoustic velocities at these plasma conditions.

The average kinetic energy of an ion in the arc plasma can be calculated assuming every ion has the velocity shown in Fig. 6. Using the velocity of the first peak to calculate the kinetic energy in the first wave front assuming aluminum ions, an energy of 127 eV is obtained. The calculated kinetic energy is close to the energy one would expect a particle would obtain from the plate bias (i.e. -160 V). The difference between the calculated kinetic energy and the plate bias is an indication of the energy required to vaporize and ionize the aluminum to produce a plasma.

The intense arc plasma as seen from the data expands at a rate given by the amount of energy provided to the arc plasma by the electrons. The arc plasma expands at a velocity sufficient to cover large surface areas of the anodized aluminum structure over a short period of time. The ability of the arc plasma to discharge the surface of the anodized aluminum structure was examined by placing two plates in a plasma (See Fig. 3). The plates were isolated from each other inside the chamber, but connected outside. When one plate arced, the arc plasma would discharge the other plate passing current between the two.

Typical current and voltage data recorded during the two plate experiment are shown in Fig. 7. When this data was acquired, an arc occurred on the lefthand plate shown in Fig. 3. The beginning of the voltage trace indicates the inception of the arc. In this figure the current is positive which was positive proof of electron flow from the righthand plate.

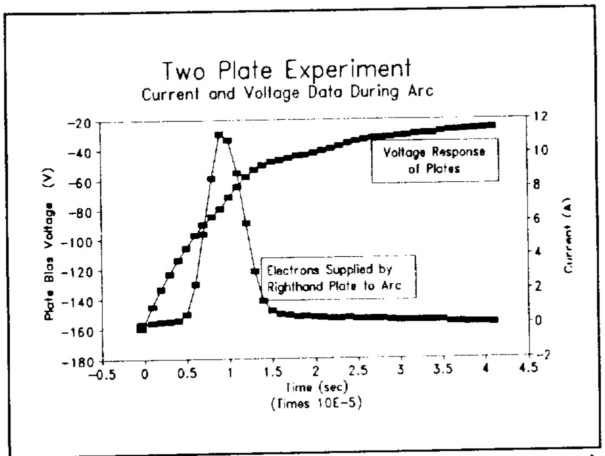

**Figure 7 Two Plate Experiment Current and Voltage Data**

The time lag between the initiation of the arc and the peak in the current trace represents the time required for the arc plasma to be emitted from the lefthand plate and fully discharge the righthand plate. A simple calculation of the time for the plasma to travel the distance from the righthand plate to the left was performed. The two plates are 36 cm apart from the center of one plate to the center of the other. Because an arc could occur anywhere on the lefthand plate a range of distances must be considered. The range considered in this calculation was 32 cm to 40 cm, which is the distance from the near edge of the lefthand plate to the center of the righthand plate and the far edge to the center of each respective plate. Using the velocity indicated in Fig. 6, the time for the plasma to reach the center of the second plate ranged from 10 to 13 microseconds. This time is close to the lag time between the start of the arc and the peak in the current trace. This suggests that the arc plasma can expand and discharge the neighboring anodized aluminum plate.

The level electron currents being transferred between the two plates was also significant. The data presented in Fig. 8 is the current being supplied between the plates by either the right or lefthand plates, as indicated, after being discharged by the arc plasma. The plates, from which the data shown in this particular figure were measured, were both anodized aluminum with a 0.1 mil (2.54 microns) oxide layer. The current traces shown in Fig. 8 can be numerically integrated to calculate the charge transferred between the plates at a given voltage. From that information the experimentally measured capacitance can be computed. Also, the theoretical capacitance of the two plates can be calculated using flat plate theory assuming the aluminum as one conductor and the plasma as the other.

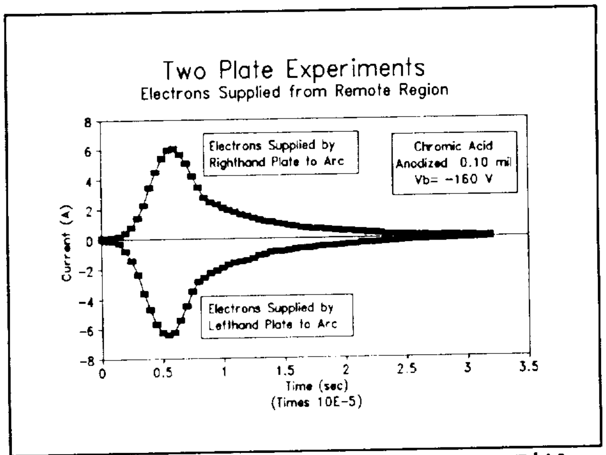

**Figure 8 Current Traces from Either Plate**

The numerical integration program used to compute the experimentally measured capacitance was calibrated by measuring the current response to several capacitors which were biased -160 V and shorted to ground. Current and voltage data similar to that shown in Fig. 7 were recorded and numerically analyzed to calculate an experimentally measured capacitance. The capacitors experimentally measured were on the order of a few microFarads which is close to the capacitance of the plates in question. The experimentally measured capacitance agreed to within 10 % of the value listed on the label of the capacitors.

The results of the numerically calculated capacitance values obtained from the two plate experiments are compared with those calculated from flat plate capacitance theory in Table I. The capacitance data shown in Table I were computed for aluminum plates identically processed with two different anodic coating thicknesses which are indicated in the table. The experimental capacitance data are within 20 to 25 % of that calculated from theory. Two reasons for the difference in the two capacitance values are the uncertainty of the dielectric constant and the 10 % error already present in the integration program. The dielectric constant found in the literature was for aluminum-oxide not anodized aluminum. The

**Comparison of Theoretical**
**and**
**Experimental Capacitance**

| **Anodize Cond.** | **Exper. Cap. (uF)** | **Theory Cap. (uF)** |
|---|---|---|
| 0.05 mil Chromic Acid An. | 0.49 | 0.68 |
| 0.10 mil Chromic Acid An. | 0.27 | 0.38 |

**Table I Comparison of Theoretical and Experimental Plate Capacitance Values**

oxide coating produced during the anodization process does have some metallic impurities present. The results show the charge being transferred between the two plates is equal to that being stored in the plates. This suggests the arc plasma can completely discharge the stored charge in the surface once the two come in contact.

The expansion of the arc plasma can discharge a large area in a very short time. The size of the area that can be discharged is the present subject of an ongoing effort. However, it is apparent that physical limitations of spacecraft design (i.e. around corners or on the backside) will prevent the arc plasma from discharging an entire spacecraft. Therefore, experimental tests were performed to examine the interaction of the ambient plasma with the part of a spacecraft isolated from the arc plasma.

When an arc occurs on a spacecraft, the portion isolated from the arc plasma only experiences a positive voltage transient. Tests were conducted to measure the response of the ambient plasma to these simulated arcs by applying the same voltage transient to the anodized aluminum sample. This voltage transient was produced by biasing the sample 160 V negative of ground and immediately grounding the plate through a switch. The ability of the ambient electrons to discharge the surface of the plate was recorded as the amount of electron current flowing from the plate to ground. Because the ground test facility has a limited amount of plasma in the vacuum vessel, it was necessary to ground the hollow cathode plasma source in these tests to simulate the infinite source of electrons present in space. This is a viable approach because hollow cathode plasma sources are capable of several amperes of electron current.

The response of one simulated arc is shown in Fig. 9. This data is typical of all data taken with the hollow cathode grounded. When the hollow cathode was not grounded, the current response to the simulated arc showed some unusual perturbations which suggested the plate was probably collecting all the electrons possible from the limited plasma volume with in the chamber. The peak current shown in this figure is on the order of amperes whereas the amount of thermal electron current the plate could collect is several orders of magnitude smaller (on the order of uA). In this transient case the ions are frozen and the Debye sheath which shields electric fields has not had time to develop. The time response on the current trace shown in this figure appears to be slower and the peak current smaller than data recorded when an arc occurred on a similar type of plate (see Fig. 7) without the hollow cathode grounded. This added time delay is due to the increased impedance caused by the absence of the conductive arc plasma. The data presented in this figure were also numerically integrated to determine the amount of charge measured during the simulated arc. This numerical calculation was then compared to that observed in the two plate experiments.

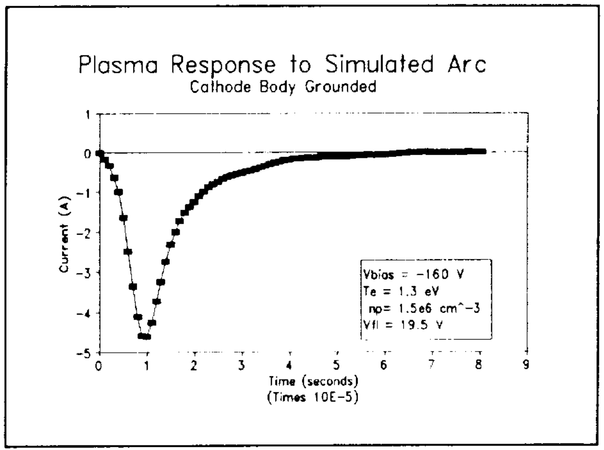

**Figure 9 Plasma Response to Simulated Arc**

Figure 10 shows a comparison of the total integrated charge for both the two plate experiments and the simulated arc experiment. This figure is a plot of the total integrated charge obtained from numerical integration of current traces like those shown in Figs. 7, 8 and 9 versus the bias voltage on the plate minus the floating potential of the anodized surface. Because the hollow cathode was grounded during the simulated arc tests, the plasma floating potential was nearly 20 V. In the case of the two plate experiment the floating potential was about 2 V. The data

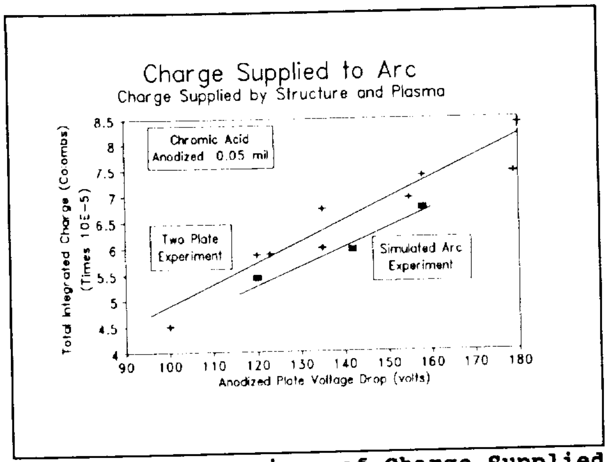

**Figure 10 Comparison of Charge Supplied to Arc Between the Two Plate Experiment and the Simulated Arc Experiment**

in this figure show the charge transferred during each experiment agree within experimental error. This result indicates that the ambient plasma is capable of discharging the entire anodized surface it comes in contact with in a very short period of time provided there is a sufficient supply of charged particles. Because space is an infinite well of charge particles, there should be ample supply to discharge any spacecraft in orbit.

## SUMMARY

The requirement for higher powered spacecraft has produced new environmental interactions between the low earth orbit plasma and the structure. From the results of this work and that presented in [10], under the present design practice which grounds or references the structure to the negative side of the solar array, dielectric breakdown will occur on spacecraft whose potential relative to the plasma is greater than 80 V negative and the LEO plasma will be able to support large currents on the order of 100's or 1000's of amps depending on the capacitive capability of the spacecraft. Figure 11 is a reprint of the data shown in [10] to provide the peak current data versus capacitance that has been measured in the laboratory.

The electrons collected by the solar array from the ambient plasma build up in a capacitive nature in the skin of the structure. During the breakdown of the dielectric coating on the structure, there is sufficient energy to vaporize and ionize the aluminum structure at the arc site, producing a dense arc plasma. The arc plasma expands from the arc site out in every direction at a rate much greater than the ion acoustic velocity. As the arc plasma expands along the structure it neutralizes the ions which have collected along the structure due to its capacitance. The amount of the structure that the arc plasma can discharge is determined by how far the arc plasma can travel in 10's, possibly 100's, of microseconds and have the needed current capacity. The exact distance is not known yet and is a subject of an ongoing effort.

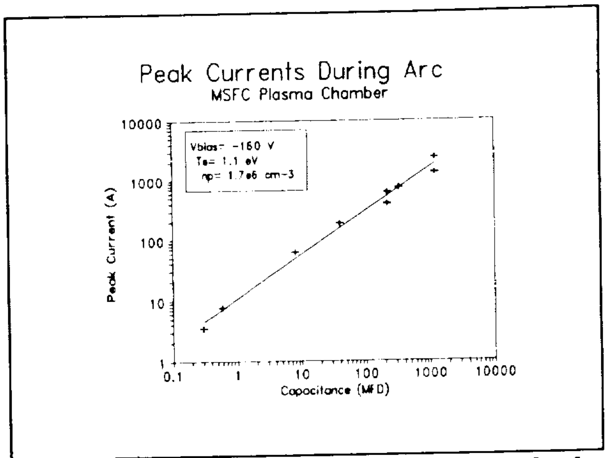

**Figure 11 Peak Currents Caused by Dielectric Breakdown**

The portion of the spacecraft which does not interact directly with the arc plasma will be discharged by the ambient plasma. The voltage transient the spacecraft experiences during the arc is sufficient to attract enough ambient electrons to discharge the entire stored charge in the structure. The arc will have to couple to the ambient plasma to provide a closed current path. The electron current attracted by the voltage transient from the ambient plasma is much greater than thermal electron currents.

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