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CURRENT FROM A DILUTE PLASMA MEASURED THROUGH HOLES IN INSULATORS

Norman T. Grier and Stanley Domitz

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

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by Norman T. Grier and Stanley Domitz

Lewis Research Center

SUMMARY

The current collected from a plasma through holes in insulated electrodes was measured. Holes of 0.051- and 2.54-centimeter diameters in Kapton H film and plasma number densities of 10^2 and 10^4 electrons per cubic centimeter were used. The current collected by bare electrodes, that is, electrodes with no surrounding insulation, is also presented. For all samples the current at a given voltage was a function of the surrounding insulator area rather than of the hole size or the underlying electrode size.

In addition, at the low plasma density the current-voltage (I-V) characteristic showed very steep rises for voltages below 1 kilovolt. In one case the current jumped by a factor of approximately 70 at 200 volts. Results are given for positive biases to 10 kilovolts. For negative biases, sparking prevented testing most samples to the 10-kilovolt limit.

INTRODUCTION

Future earth-orbiting satellites will require power in the kilowatt range. One of the most efficient means of generating and distributing kilowatts of power is by building solar arrays with output voltages equal to the voltage requirements of the loads. For communication satellites that use traveling wave tubes and ion bombardment thrusters, the requirement is in the kilovolt range.

In order to operate solar arrays in the kilovolt range in space, consideration must be given to the fact that the ambient environment is a dilute plasma. Domitz and Grier (ref. 1) have surveyed the many spacecraft-plasma interaction phenomena that may occur on orbiting satellites. Kennerud (ref. 2) presents laboratory results for many of the phenomena described in reference 1. One plasma phenomenon that required further investigation is current collection through pinhole imperfections in an insulator covering an electrode that is at a potential much greater than the plasma potential. Kennerud (ref. 2), Grier and McKinzie (ref. 3), Cole, Ogawa, and Sellen (ref. 4), and Herron, Bayless, and Worden (ref. 5) all have made laboratory tests which indicate that the current through pinhole imperfections is a strong function of the surrounding insulator area. According to these tests, the current is many times that predicted from thick-sheath probe theory. This phenomenon is investigated more extensively in this report, and more data are presented to substantiate this. In addition, the effects of electrode size and hole size on the collection current are presented.

Kapton H film (a polyimide) was used as the insulator material. Two "pinhole" sizes were used: diameters of 0.051 and 2.54 centimeters. The plasma was generated by bleeding nitrogen gas into a Penning-type discharge chamber. The pressure at which tests were conducted was approximately 4×10^{-6} torr.

Kapton H film was chosen because lightweight solar arrays use this film as the substrate. Previous tests (refs. 2 and 3) indicated that the pinhole current is not a strong function of the type of insulator. Therefore, the results should also be applicable for other insulators.

SAMPLES AND INSTRUMENTATION

Test Samples

The test samples were chosen to determine the effect of hole size, electrode size, sample size, and Kapton insulator on the collection current. Figures 1 and 2 show a typical test sample with the terminology used in this report. In order to demonstrate these effects, the samples were constructed with and without Kapton covering. Eight Kapton-covered and three uncovered samples were tested. Table I gives the sample, electrode, and hole dimensions.

All but two Kapton-covered samples and all uncovered samples, with the exception of the glass rod, were constructed as shown in figures 1 and 2. Of course, in the uncovered samples the Kapton film was not used. The Kapton film was bonded to the fiberglass substrate with Dow Corning A4000 silicone adhesive. An epoxy adhesive (Shell Oil Co. Epon 828 resin with General Mills Versamid 140 catalyst in ratio 70/30 percent by weight) was used to mount the copper electrodes on the fiberglass substrates and also to pot the wires on the reverse sides of the samples.

The other two Kapton-covered samples were square in shape (45.7 cm by 45.7 cm). A cross-sectional view of their construction is shown in figure 3. In one square sample, a 26.7-centimeter-diameter copper foil was sandwiched between the Kapton and the fiberglass substrate. The other 45.7-centimeter-square sample did not have the copper foil. For both square samples, a 2.54-centimeter-diameter by 0.051-centimeter-thick copper disk was mounted on top of the Kapton surface to serve as the collection-current electrode. The electrode was electrically connected to the copper foil. The current collected with the two square samples was compared with the current from the other samples to further determine the effect of the size of the electrode beneath the Kapton on the collection current.

For the glass-rod sample, a 0.12-centimeter-diameter tungsten rod was fitted snugly inside a 0.64-centimeter-diameter hollow glass rod. The end was ground flat and served as the sample. This sample was the smallest tested.

In table I, samples 1 to 6 with the 0.051-centimeter-diameter collection hole and samples 2 to 8 with the 2.54-centimeter-diameter collection hole were used to determine the effect of specimen size on collection current. Current collected from samples 5 and 6 was compared, and current collected from samples 7 and 8 was compared to determine the effect of the size of the electrode beneath the Kapton insulator on the collection current. The bare-electrode samples, that is, samples 9 to 11, were used to show whether or not the collection current depended on the type of insulation surrounding the current collection area. The glass rod, sample 12, was used as a sample of a very small insulator surrounding the current collection area.

Vacuum Tank

The tests were performed in a 1.8-meter-diameter by 3-meter-long cylindrical vacuum tank at a pressure of approximately 4×10^{-6} torr. The experimental samples were mounted on a Lucite rod located at one end of the tank, and the plasma source was mounted at the other end. A sketch of the experimental setup is shown in figure 4.

Plasma Source

The plasma was generated by bleeding nitrogen gas through a leak valve into a Penning-type discharge chamber. A coil was wound so as to produce an axial magnetic field in the discharge chamber. The discharge chamber was 5.1 centimeters in diameter and 7.6 centimeters long. A cross section of the plasma source is shown in figure 5. The source was operated at an anode potential of 40 volts relative to the cathode, which was grounded to the tank walls. A 10.2-centimeter-diameter baffle was placed 15.2 centimeters in front of the discharge exit so as to assist in spreading the plasma throughout the vacuum tank.

Instrumentation

The current collected by the samples was measured with a battery-powered electrometer (Keithley 602), which was connected between the high-voltage power supply and the test samples. In order to keep stray currents through the electrometer to a minimum, coaxial cables were used between the test samples and the electrometer. The outer and inner conductors were connected to the high-voltage terminal of the power supply. The electrometer and samples, however, were only connected to the inner conductor. The outer conductor served as a guard.

Plasma Density

The plasma number density n_e was found by using the slope of the current-voltage (I-V) characteristic of a 1.9-centimeter-diameter sphere located 1.1 meters along the tank axis from the plasma source. Thick-sheath spherical probe theory was used. The sphere was left in place during all runs and was not disturbed during sample changes. The plasma number density was checked in two ways: (1) by applying thick-sheath probe theory to the I-V characteristic for a 0.32-centimeter-diameter by 20-centimeter-long cylinder, and (2) by using the measured current to this same cylinder at plasma potential in the equation for the thermal flux. Each of these methods gave electron densities within a factor of 3 of each other. The electron temperature was found by using the cylindrical Langmuir probe and was between 5 and 10 electron volts.

RESULTS AND DISCUSSION

Experimental Procedure

The samples were tested at plasma number densities of approximately 10^2 and 10^4 electrons per cubic centimeter. The plasma number densities were found by the procedure given in the preceding section. The two densities were chosen to show more clearly the effect of plasma number density on the results. The lower density, namely 10^2 electrons per cubic centimeter, corresponds to the maximum density a satellite experiences at synchronous altitude (35 900 km). The higher density, namely 10^4 electrons per cubic centimeter, corresponds to an altitude of approximately 1000 kilometers (ref. 6).

For all tests the tank pressure was approximately 4×10^{-6} torr. Check runs were made to find the effect of tank pressure on the results. For tank pressures between 2×10^{-6} and 1×10^{-5}, the effect was less than 1 percent.

The samples were run at both positive and negative voltages to 10 kilovolts. Some samples when biased negatively, however, started sparking at voltages less than 10 kilovolts. At this point the tests were terminated for these plasma number densities. There was no particular voltage at a given plasma number density that marked the inception of sparking for all samples. On most samples, sparking occurred at a negative voltage greater than 1 kilovolt. In general, sparking occurred at a lower voltage for the high-number-density plasma than for the low-number-density plasma.

Effect of Hole Size

In order to determine the effect of hole size, hole diameters of 0.051 and 2.54 centimeters were used in the Kapton-covered samples. The overall sample diameters were 5.1, 20.3, and 30.5 centimeters. For these tests, the 2.54-centimeter-diameter electrode was used only with the 5.1-centimeter-diameter sample, and the 5.1-centimeter-diameter electrode was used with the 20.3- and 30.5-centimeter-diameter samples. The results are shown in figure 6 for the low-plasma-number-density tests and in figure 7 for the high-plasma-number-density tests. Shown on each figure are the results for both positively and negatively biased electrodes.

From figures 6(a) and 7(a), for positive biases on the 5.1-centimeter-diameter Kapton-covered sample, the current ratio between the 0.051- and the 2.54-centimeter-diameter holes is greater than a factor of 3 over the complete voltage range. While for the 20.3- and 30.5-centimeter-diameter positively biased samples (figs. 6(b) and 7(b) and 6(c) and 7(c), respectively), the current ratio is large only at the low voltages. In some cases the spread is greater than a factor of 10^3 at low voltages but becomes almost 1 at 10 kilovolts.

This decrease in current ratio as a function of increasing voltage may be an effect of tank size. The source was mounted at one end of the tank and the samples were mounted at the other end. At 10 kilovolts the electric field from the 20.3- and 30.5-centimeter-samples probably extended to the walls of the tank and possibly to the source. This condition would occur at a lower voltage at the low density because of the larger Debye length. Therefore, the 20.3- and 30.5-centimeter-diameter samples were collecting all the electrons possible for the finite and confined plasma in the tank. This tank-size effect would result in decreased spread between the curves and the flattening in the curves at high voltages. To give further credence to this explanation is to note that, if both the positively and the negatively biased curves are extended to higher voltages at their respective slopes at 10 kilovolts, they will eventually intersect. Thus, the absolute magnitude of the electron collection current would equal the absolute magnitude of the ion collection current at the same voltage. This condition is unreasonable because of the larger mass of the ions.

Another point shown by the positively biased curves in figures 6 and 7 is the large increase in current below 2 kilovolts. This increase is larger for the smaller diameter hole and begins at lower voltages as the sample size is increased. These results indicate that the collection current before saturation is a function of sample size. This phenomenon is known as the "area effect" and is discussed later in this report.

For negatively biased electrodes, one characteristic that was noticed for all samples was the straight-line behavior on the log-log plot with slopes between 1 and 1.5. This behavior implies that the current is proportional to voltage to some power between 1 and 1.5. For large probes and high voltages, Linson (ref. 7) and Al'pert (ref. 8) show that the current should vary as $V^{6/7}$. Parker (ref. 9) argues for a linear behavior in voltage. The Child-Langmuir law for fixed electrodes (ref. 10) for space-charge-limited flow gives $V^{3/2}$. Since none of these theories exactly predicts the behavior presented in the figures, other phenomena such as secondary emission, ionization of gas evolving from the surface, and photoconductivity of Kapton may be occurring. In any event, the results for the negatively biased electrodes seem to obey some analytical power-law function.

Also in figures 6(a) and 7(a) for negative biases, there is a large spread in the data between the 0.051- and 2.54-centimeter-diameter holes for the 5.1-centimeter-diameter sample for both plasma densities. Although the spread is a factor smaller than the area difference may infer, it is much larger than the difference in the curves for the 20.3- and 30.5-centimeter-samples (figs. 6(b), 6(c), 7(b), and 7(c)). One would expect the collection current to be proportional to the hole area. Therefore, the small difference in the negatively biased curves, especially for the 20.3- and 30.5-centimeter-diameter samples is unexplainable except for possible surface effects. Kennerud (ref. 2) found no variation in current for hole diameters of 0.038 and 0.38 centimeter for a plasma density of 1.3×10^{4} ion per cubic centimeter. His Kapton sample was 3.5 centimeters in diameter.

One last point to be noted from figures 6 and 7 is the spread in current between the positively and negatively biased electrodes. One would expect from the mass ratio between a nitrogen ion and an electron that the magnitude of the electron current (i.e., positively biased electrodes) would be $I_{ion} \sqrt{m_{N_i}/m_e}$, or $\sim1.6\times10^{2}\ I_{ion}$. From the figures, this is approximately true for the 2.54-centimeter-diameter hole at voltages less than 100 volts. It is not true for the 0.051-centimeter-diameter hole. Kennerud (ref. 2) obtained similar results in a plasma of 1.3×10^{4} electrons per cubic centimeter. No adequate explanation exists for this behavior.

Effect of Electrode Size

Four samples were run to determine the effect of electrode size on collection current. They were two 30.5-centimeter-diameter samples, one with a 15.3-centimeter-diameter electrode and the other with a 5.1-centimeter-diameter electrode, and two 45.7-centimeter-square samples, one with a 26.7-centimeter-diameter electrode and the other with a 2.54-centimeter-diameter electrode. The collection areas were 0.051- and 2.54-centimeter diameter holes for the 30.5-centimeter-diameter and 45.7-centimeter-square samples, respectively. Results are shown in figure 8 for low and high plasma number densities. The figures show that the electrode size has little, if any, effect on the collection current for both positively and negatively biased electrodes. The little difference that is noticed indicates that the smaller electrode collects more current at the same plasma number density. This tendency seems to be more pronounced at the higher density. However, because of the scatter in the data and the possibility that the plasma source changed from one run to the next, this conclusion is not substantiated by these data.

One interesting phenomenon noticed for the 45.7-centimeter-square samples at low density (fig. 8(c)) is the sharp rise in the collection current for positively biased electrodes at voltages between 150 and 200 volts. The current jumps by almost a factor of 10^3 within a 50-volt range. At higher voltages it seems to saturate. The saturation is probably due to the overall facility and source effects as mentioned previously. Comparing figures 8(c) and (d) shows that, although there is a steep rise in electron current, it is not discontinuous. This comparison, along with a comparison of figures 6(a) and 7(a), 6(b) and 7(b), and 6(c) and 7(c), leads to the conclusion that the lower density results in a steeper rise in electron current.

Effect of Sample Area

In the results presented previously, it was seen that for a given size hole in the Kapton-covered sample the collection current increased with increases in the sample area at constant plasma number density. In order to verify this conclusion, five different-size samples were placed in the tank and tested at two plasma number densities. The samples were the end of a 0.64-centimeter-diameter cylindrical glass rod with a 0.12-centimeter-diameter electrode completely exposed (no Kapton); a 2.54-centimeter-diameter Kapton-covered sample with a 0.64-centimeter-diameter electrode and a 0.051-centimeter-diameter hole; and 10.2-, 20.3-, and 30.5-centimeter-diameter Kapton-covered samples each with a 5.1-centimeter-diameter electrode and a 0.051-centimeter-diameter hole. Collection current as a function of sample radius squared is shown at four different voltages in figures 9(a) and 10(a) for positively biased electrodes and figures 9(b) and 10(b) for negatively biased electrodes.

Figures 9(a) and 10(a) show that there is a sharp rise in collection current for positively biased electrodes to a sample diameter of approximately 10.2 centimeters. For diameters of 10.2 centimeters and larger the collection current continues to increase with area but at a lower rate. From figure 9(a) for the low-density plasma the ratio between the 1000- and 6000-volt curves is only a factor of 3 or 4 for a given sample radius. This again is probably due to the current saturation at this density. For the high-density plasma (fig. 10(a)) the ratio between the 1000- and 6000-volt curves is approximately a factor of 10 or greater.

Also it is interesting that the 30.5-centimeter-diameter Kapton-covered sample collected over 100 times as much current as the glass rod even though the collection areas differ by approximately a factor of 5. This result has implications for high-voltage solar arrays in that small pinholes in their Kapton substrates may collect enormously large currents and cause local heating.

The area effect for negatively biased electrodes is shown in figures 9(b) and 10(b) for the same voltages. One unexpected result for the low-density plasma (fig. 9(b)) is the decrease in collection current for radii out to 3.8 centimeters at all voltages. From this minimum value the current increased by about two orders of magnitude for the 30.5-centimeter-diameter sample. No minimum was noticed for the high-density plasma (fig. 10(b)).

In all the curves in figures 9 and 10, there seems to be a leveling out of the collection current when the sample diameter reaches 30.5 centimeters. This is as expected since it is reasonable that beyond a certain size the collection current should not increase if the sample size increases for a fixed collection area.

Bare-Electrode Results

The previously discussed results, with the exception of the glass rod, were for samples with Kapton surrounding the current collection hole. In most cases the Kapton also covered some part of the electrode. Three samples were run without any Kapton covering. They were two 30.5-centimeter-diameter samples, one with a 10.2-centimeter-diameter electrode and the other with a 25.4-centimeter-diameter electrode, and a 25.4-centimeter-diameter sample with a 5.1-centimeter-diameter electrode. The results are shown in figure 11 for the low and high plasma number densities, respectively.

For the low-density plasma (fig. 11(a)) the electron current (positive bias) saturated when the bias was approximately 100 volts for the 25.4-centimeter-diameter electrode. Because of this current saturation at a low positively biased voltage, the shape of the curve is probably not representative of a true I-V characteristic for voltages above 200 volts. This is confirmed also by the very small spread between the electron collection current (positive bias) and the ion collection current (negative bias) for the 25.4-centimeter-diameter electrode at 6 kilovolts. The electron current is only about 25 times the ion current as compared with a factor of approximately 250 in their mass ratios.

For the high-density plasma (fig. 11(b)), the "area effect" for positively biased electrodes is quite noticeable, being smallest for the 25.4-centimeter-diameter electrode and largest for the 5.1-centimeter-diameter electrode. This result substantiates that the area effect is not peculiar to Kapton. This conclusion is also substantiated in the results of Kennerud (ref. 2).

For the negatively biased electrode (ion collection current), no saturation occurred at either density. However, sparking occurred at voltages less than 1 kilovolt for the 10.2-centimeter-diameter electrode in the high-density plasma. Also for negatively biased electrodes the curves are clearly separated according to electrode size for both plasma densities. This is contrary to Kennerud's results (ref. 2). All his data for current collectors fell on one curve even though his areas differed by a factor of 100. The electrode areas for the results presented in figure 11 differed by factors of 4 and 25. The difference in the collection current for these samples also differs by approximately these same factors.

CONCLUDING REMARKS

Results have been presented which show that the current collected from ambient plasma through small holes in Kapton insulators covering biased conductors is independent of the size of the electrode beneath the Kapton but increases rapidly with the size of the insulator surrounding the hole. This large increase in current with surrounding insulator area is known as the "area effect." According to Kennerud (ref. 2) and Grier and McKinzie (ref. 3), the area effect is independent of the type of insulator. It is more pronounced for positively biased than for negatively biased electrodes.

Plausible explanations are given here for the area effect when the electrode diameter is larger than the collection hole diameter and for the bare-electrode results. Also given is a plausible explanation for the jump in the current-voltage characteristic for the low-plasma-density cases. Finally, the implications of the area effect are discussed.

Electrode Size

The results showing that collection current is independent of electrode size may imply that the electric field from the Kapton-covered portion of the conductor is canceled at the Kapton surface. In order for the field to be canceled, a charge layer or sheath of polarity opposite that of the biased electrode must exist on the Kapton surface. That is, an electron sheath must exist for positively biased electrodes, and an ion sheath for the negatively biased electrodes. This leads to a plausible explanation of the area effect as follows: With a hole in the insulator and a biased conductor beneath the insulator, the charges that would normally be on the surface surrounding the hole are now being diverted and collected by the conductor. The plasma replenishes these charges continuously. This process causes the current to be larger than probe theory may predict even at low voltages. As the voltage of the conductor is increased, more and more of these "surface charges" are collected through the hole. Thus, the current rises with voltage faster than expected. However, the electric field from the hole decreases as the square of the distance from the hole until eventually the field is too weak to divert more electrons to the hole. So a tapering off of the current occurs as the insulator size increases. Eventually, there would be no increase in current with insulator area. This may explain the area effect for biased electrodes that are larger than the hole.

Bare Electrodes

Similar reasoning also explains the area effect for the positively biased bare-electrode samples. These samples had no Kapton covering on the top surface, so the insulator surface was flush with the electrode surface. In a plasma an electron sheath forms on the insulator surface. This sheath forms because the mobility of the electrons is much greater than the mobility of the ions and the net current to the insulator has to be zero. The sheath tends to retard the flow of electrons and to slightly enhance the flow of ions such that the net current to the insulator is zero. At low positive voltage on the electrodes, some of the electrons that normally would be in the sheath are diverted and collected by the electrode. As the voltage increases, more and more of the sheath electrons are collected. Thus, the current increases as the insulator area increases. Again because the field varies as the inverse square of the distance from the electrode, the current eventually stops increasing with increasing insulator area.

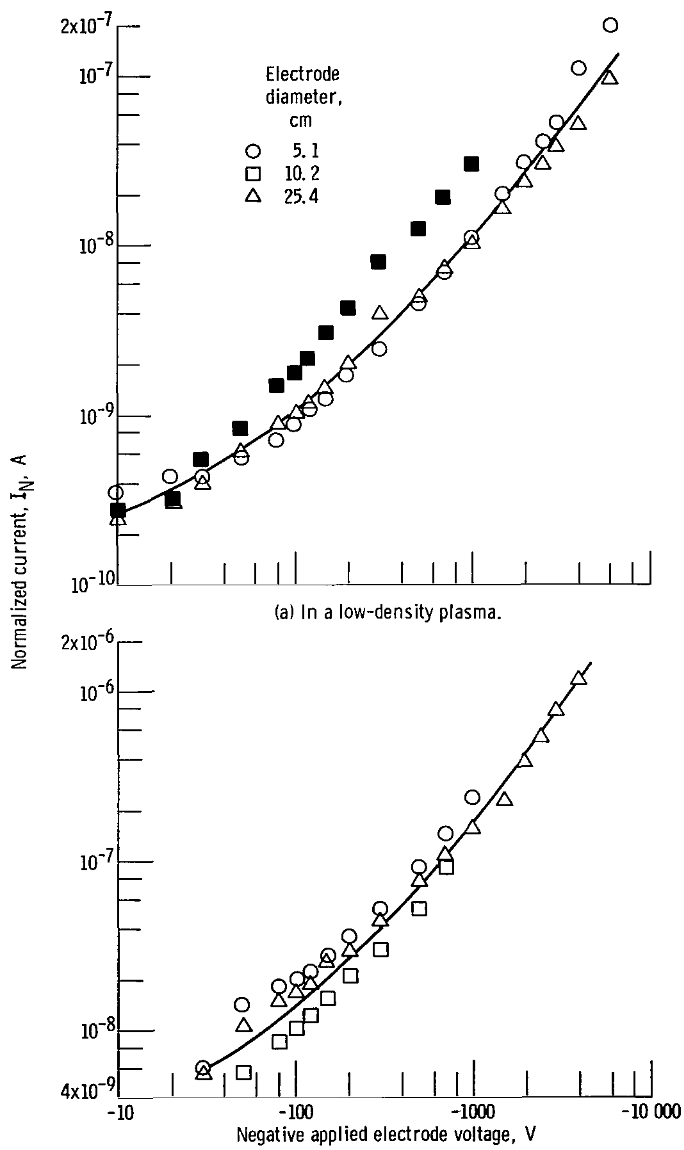
For the bare-electrode samples that were negatively biased, no area effect was noticed; that is, the current densities through the holes were equal. To show this, the current for each sample was normalized with the electrode area for the 5.1-centimeter-diameter sample, the smallest bare electrode. The equation for the current I as a function of the electrode area A is

$$I = jA$$

where j is the current density. Normalizing with the 5.1-centimeter-diameter electrode

$$I_N = I \frac{A_{5.1}}{A} = I \left(\frac{5.1}{d}\right)^2$$

where d is the diameter of the sample electrode. In the following figure, I_N is shown for the negatively biased bare-electrode samples in the low- and high-density plasmas,



(b) In a high-density plasma.

respectively. In this figure the normalized-current data for each sample fall very close to a single line. This result implies that the insulator surrounding the electrode has very little effect on the collection current. Thus, for negatively biased electrodes, the area effect occurs only when an insulator is covering the electrode in a plasma.

Current Jump

The preceding description gives a plausible explanation of the area effect at high plasma densities. However, it does not adequately explain the jump in electron current observed at some voltages less than 1 kilovolt when the plasma density is low. This jump may be caused by the electric field from the positively biased electrode punching through the repulsive field from the negative charges on the insulator surrounding the hole. As shown by the current-voltage characteristics the current jump is pronounced for low plasma densities and large samples.

What happens during a current jump may be described as follows: As explained previously, the surrounding insulator surface in a plasma obtains a negative bias to retard electron flow to the surface. The electric field from the insulator extends from the surface to a distance comparable to the Debye length. For a very tenuous plasma, this distance may be quite large. At very low positive electrode voltages, the field from the positive electrode is masked by the field from the surrounding negatively charged insulator surface. Sherman and Parker[1] calculate the electrostatic fields for two concentric disks as a function of the ratio of their radii. The inner disk has an attractive potential, and the outer disk has a repulsive potential. For large values of outer radii as compared to the inner radius, a large attractive potential is required to break through the repulsive barrier caused by a small negative potential on the outer disk. If we assume this phenomenon occurs for the samples used in the tests herein, the jump in the electron current may be caused by the attractive (positive) potential on the electrode breaking through the repulsive potential barrier of the insulator. In other words, at this voltage the plasma "sees" the hole in the insulator for the first time.

Implications

The area effect has implications for any large insulator covering a biased conductor in the environment of space. In this environment the insulator is subject to small holes due to micrometeorite penetration, insulator breakdown, and other phenomena. When

[1]Sherman, Christopher; and Parker, Lee W.: Potential due to a Circular Double Disk. Air Force Cambridge Res. Labs. (AFCRL-70-0568; AD-715889), 1970.

this occurs the power passing through the hole may be orders of magnitude larger than expected. On a high-voltage solar array, hot spots or local pitting may occur on the back side of the array, and the interconnecting tabs may collect more current than expected. Both phenomena represent power losses and possible catastrophic failure.

One possible advantage of the area effect in space may be in reducing differential spacecraft charging. Many spacecraft use metalized insulator blanket materials such as aluminized Teflon or Kapton. During magnetic substorms, insulators may become negatively charged to 10 kilovolts or higher from high-energy electrons. If the spacecraft becomes differentially charged, arcing may occur and send unwanted pulses through the electronic systems. However, if the metal backing can be grounded and small pinholes spaced judiciously throughout the insulator, it may be possible to prevent large voltage buildup on the insulator surface and thereby prevent arcing.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 5, 1975,
506-23.

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TABLE I. - SAMPLE, ELECTRODE, AND HOLE DIMENSIONS

Sample	Type	Sample diameter, cm	Electrode diameter, cm	Diameter of collection hole or area, cm
1	Kapton covered	2.54	0.64	0.051
2		5.1	2.54	0.051 and 2.54
3		10.2	5.1	
4		20.3	5.1	
5		30.5	5.1	
6		30.5	15.3	
7		[a]45.7 by 45.7	2.54	2.54
8		[a]45.7 by 45.7	26.7	2.54
9	Without Kapton[b]	25.4	5.1	5.1
10	Without Kapton[b]	30.5	10.2	10.2
11	Without Kapton[b]	30.5	25.4	25.4
12	Glass rod	.64	.12	.12

[a]Square.
[b]Bare electrode.

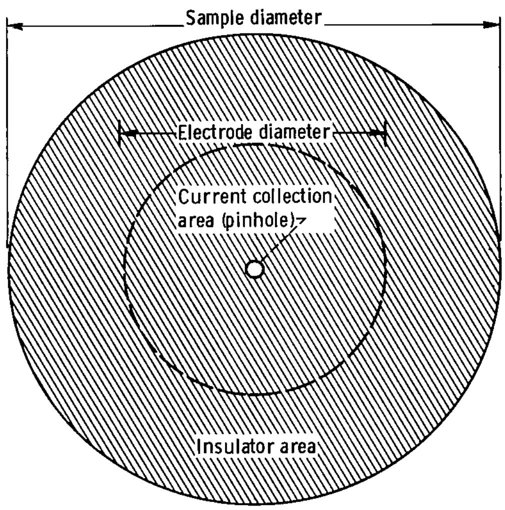


Figure 1. - Top view of sample showing sample diameter, electrode diameter, and hole or current collection area.

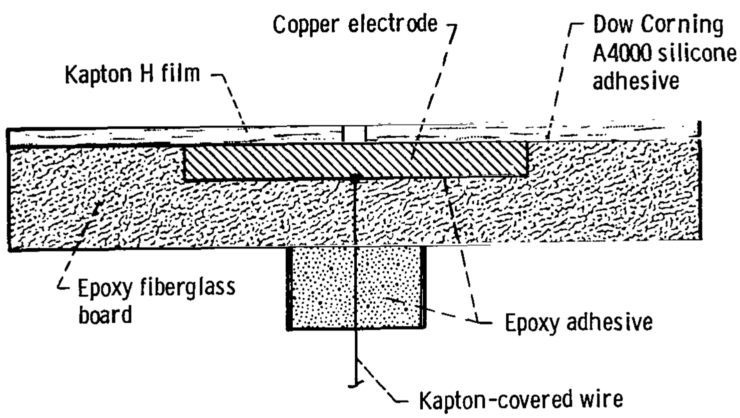


Figure 2. - Typical cross section showing construction of Kapton-covered test samples.

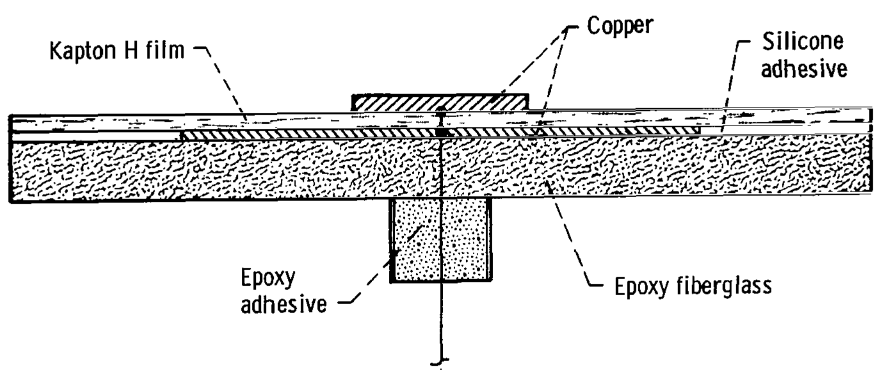


Figure 3. - Cross section of 45.7-centimeter-square sample with copper foil beneath the Kapton.

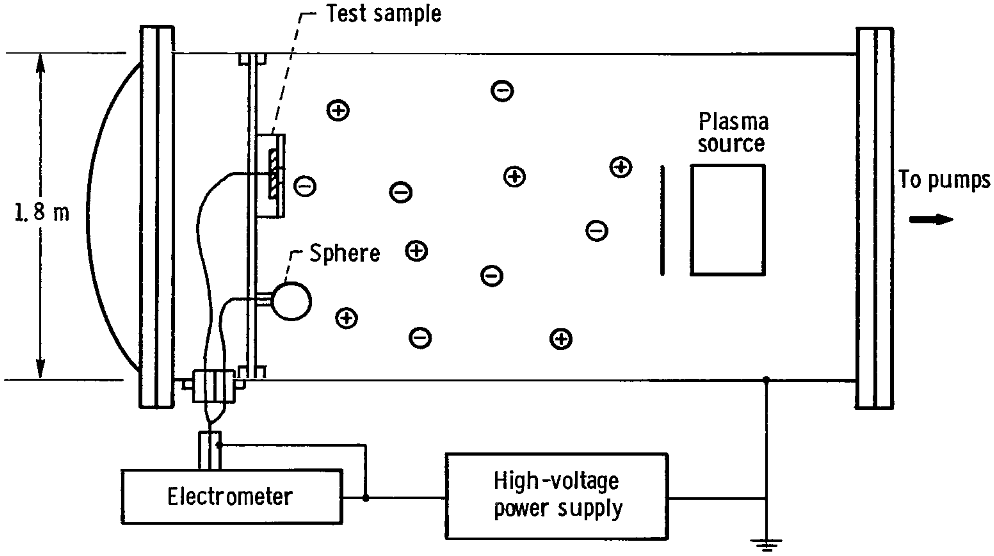


Figure 4. - Space-plasma simulation chamber.

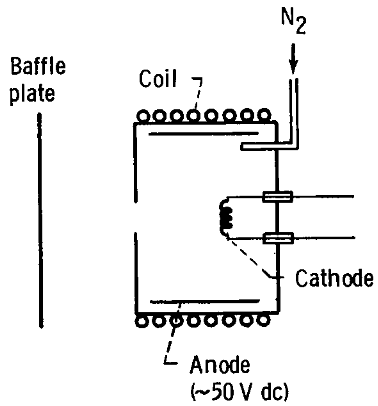
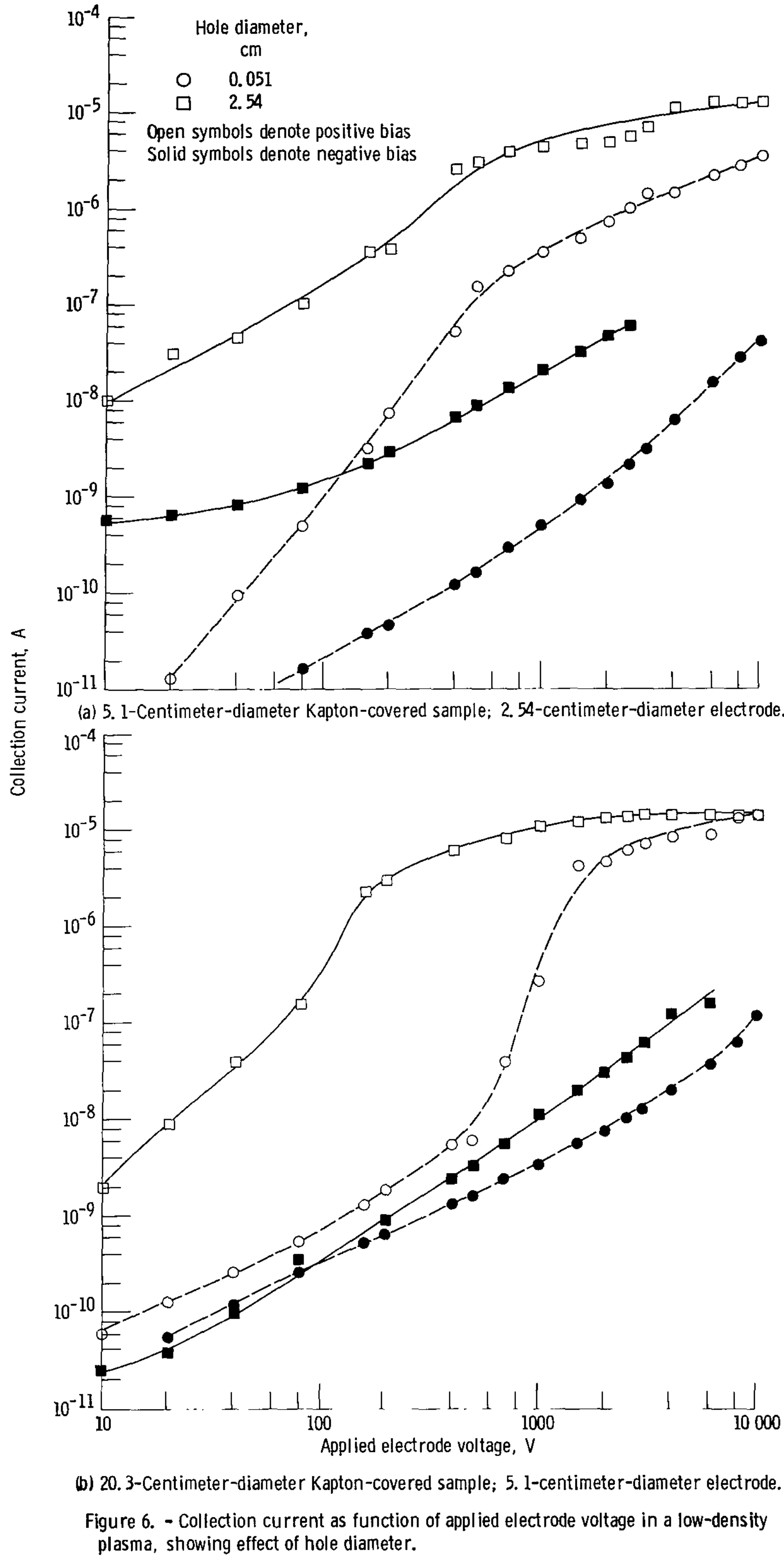


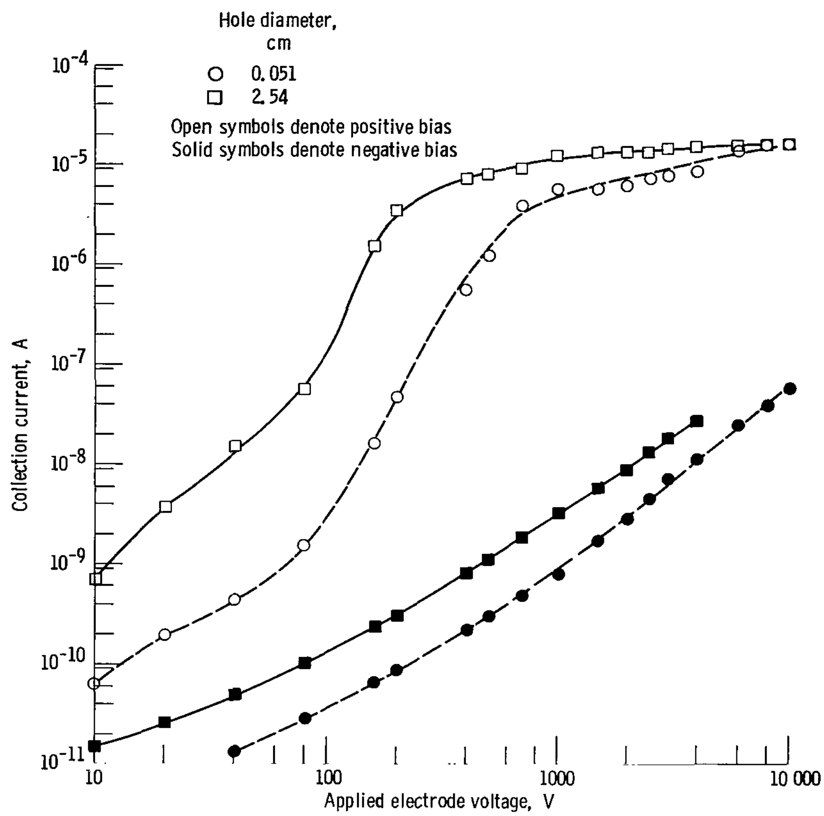
Figure 5. - Plasma-source generator.



(a) 5.1-Centimeter-diameter Kapton-covered sample; 2.54-centimeter-diameter electrode.

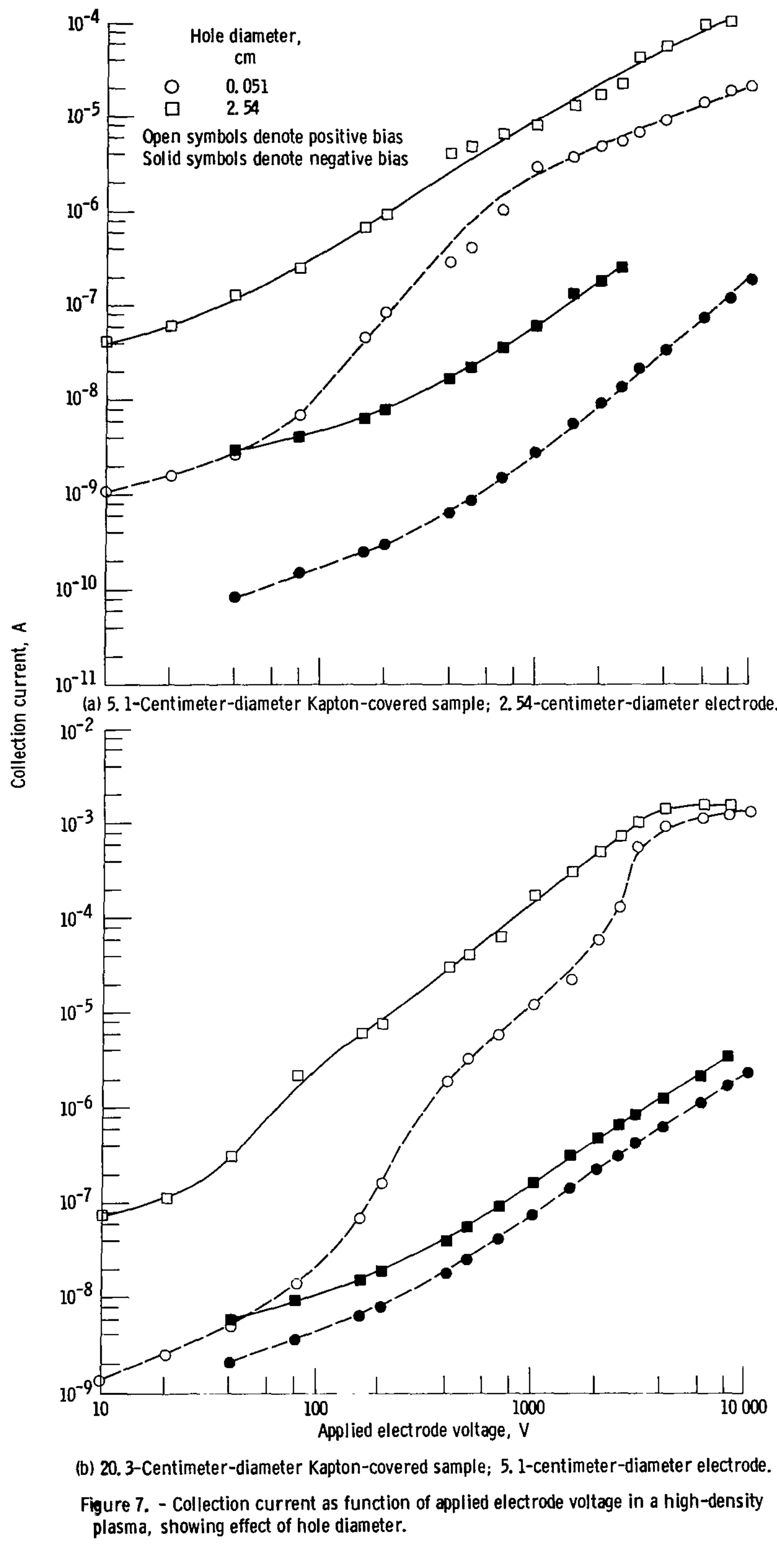
(b) 20.3-Centimeter-diameter Kapton-covered sample; 5.1-centimeter-diameter electrode.

Figure 6. - Collection current as function of applied electrode voltage in a low-density plasma, showing effect of hole diameter.



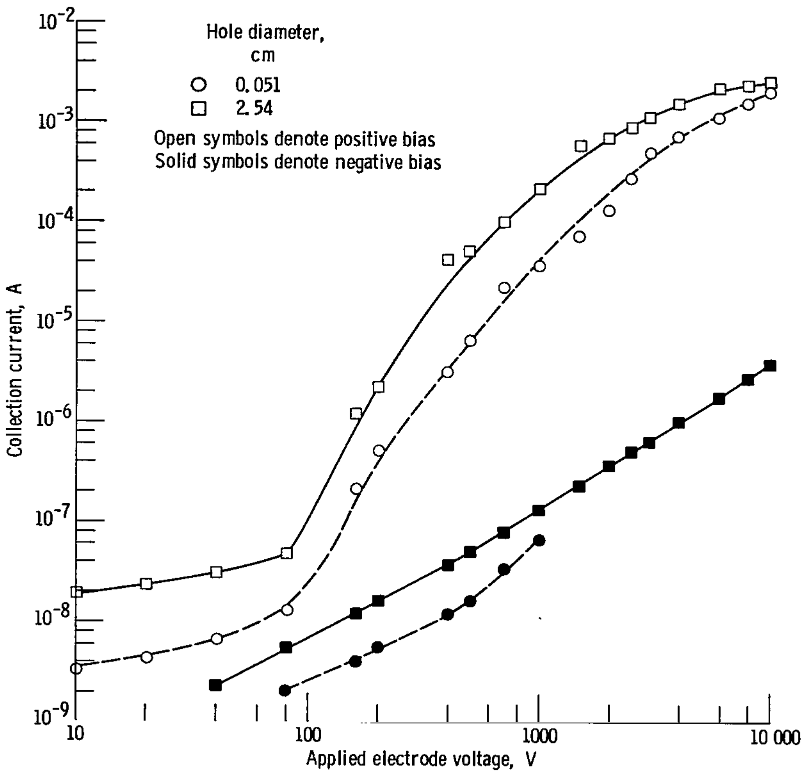
(c) 30.5-Centimeter-diameter Kapton-covered sample; 5.1-centimeter-diameter electrode.

Figure 6. - Concluded.



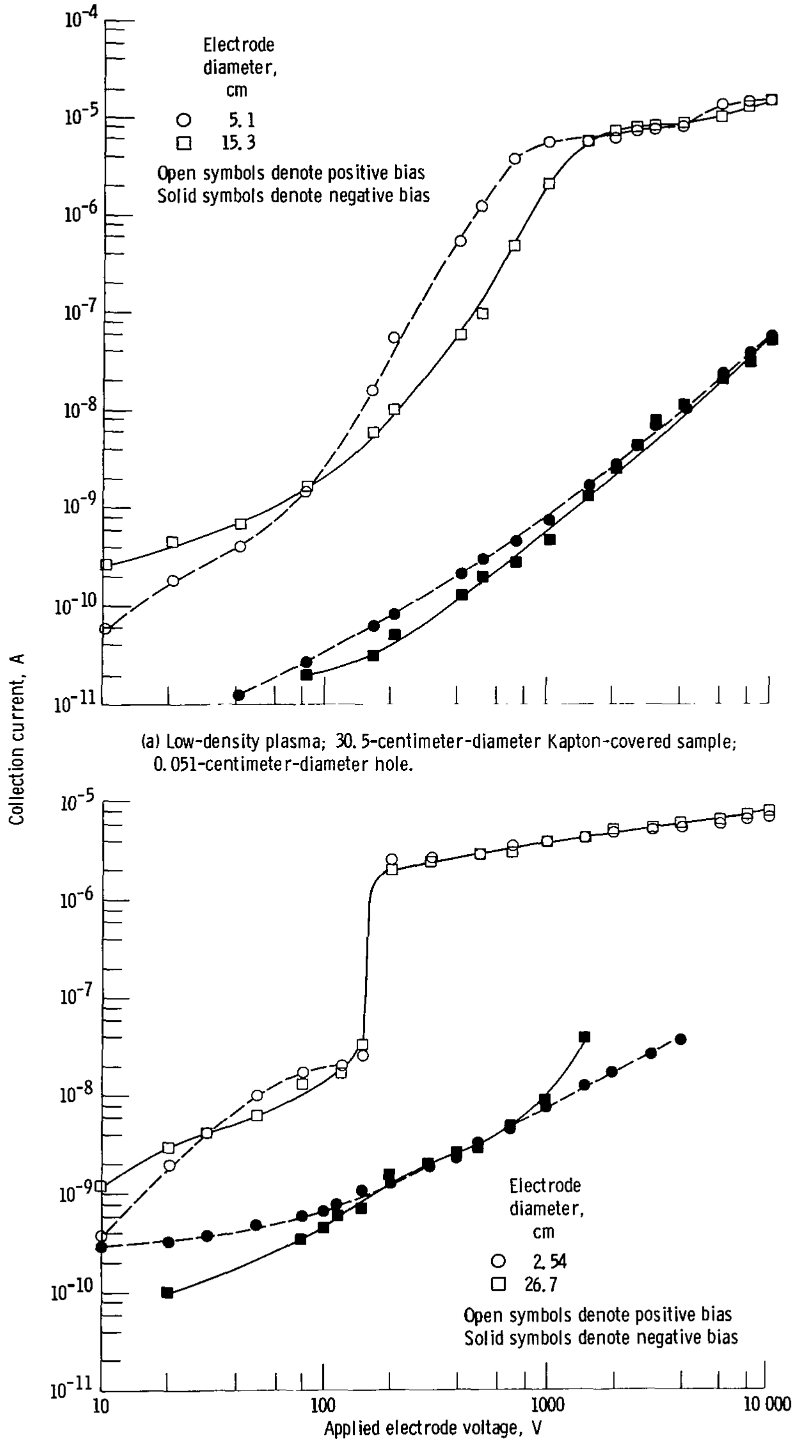
(b) 20.3-Centimeter-diameter Kapton-covered sample; 5.1-centimeter-diameter electrode.

Figure 7. - Collection current as function of applied electrode voltage in a high-density plasma, showing effect of hole diameter.



(c) 30.5-Centimeter-diameter Kapton-covered sample; 5.1-centimeter-diameter electrode.

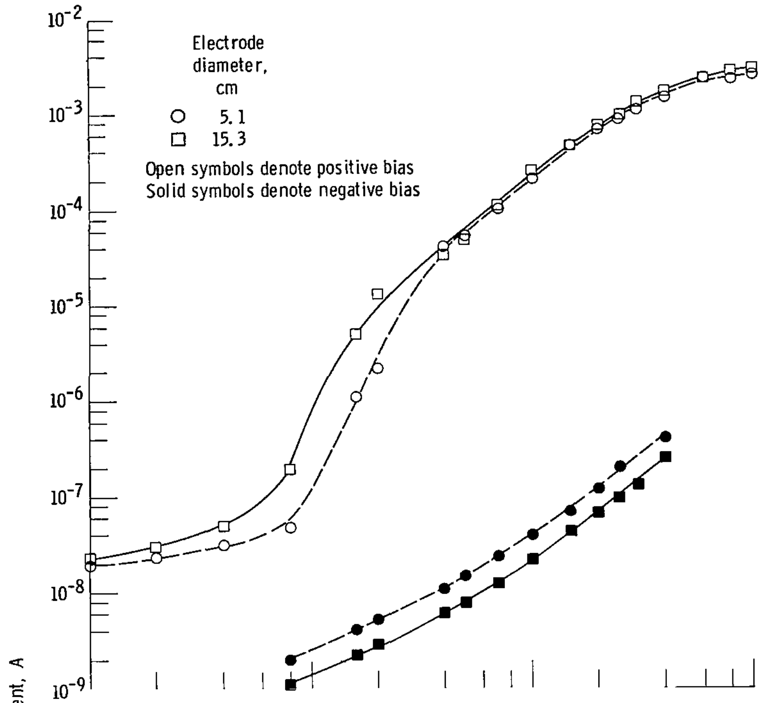
Figure 7. - Concluded.



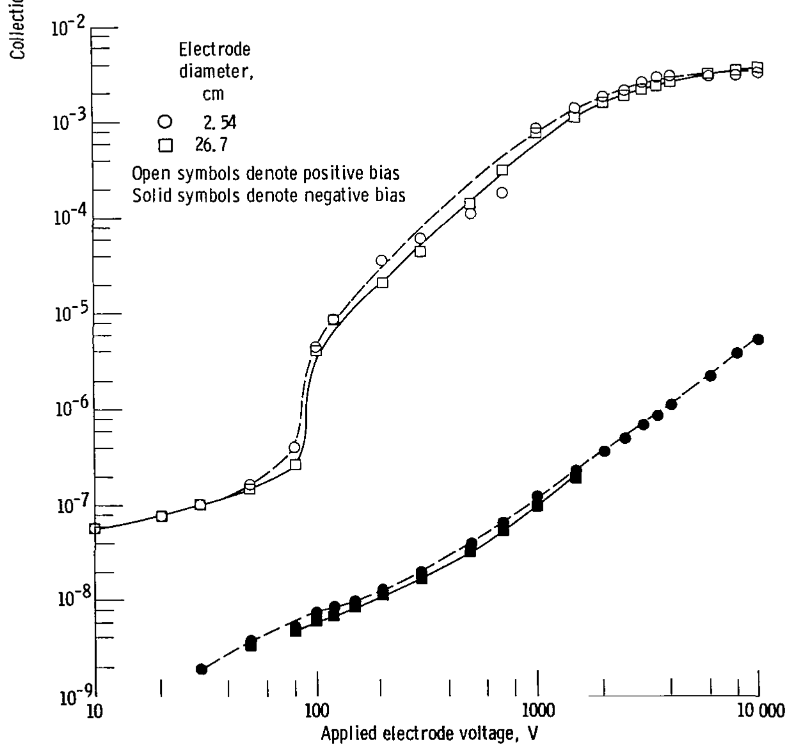
(a) Low-density plasma; 30.5-centimeter-diameter Kapton-covered sample; 0.051-centimeter-diameter hole.

(b) Low-density plasma; 45.7-centimeter-square Kapton-covered sample; 2.54-centimeter-diameter hole.

Figure 8. - Collection current as function of applied electrode voltage, showing effect of electrode diameter.



(c) High-density plasma; 30.5-centimeter-diameter Kapton-covered sample; 2.54-centimeter-diameter hole.



(d) High-density plasma; 45.7-centimeter-square Kapton-covered sample; 2.54-centimeter-diameter hole.

Figure 8. - Concluded.

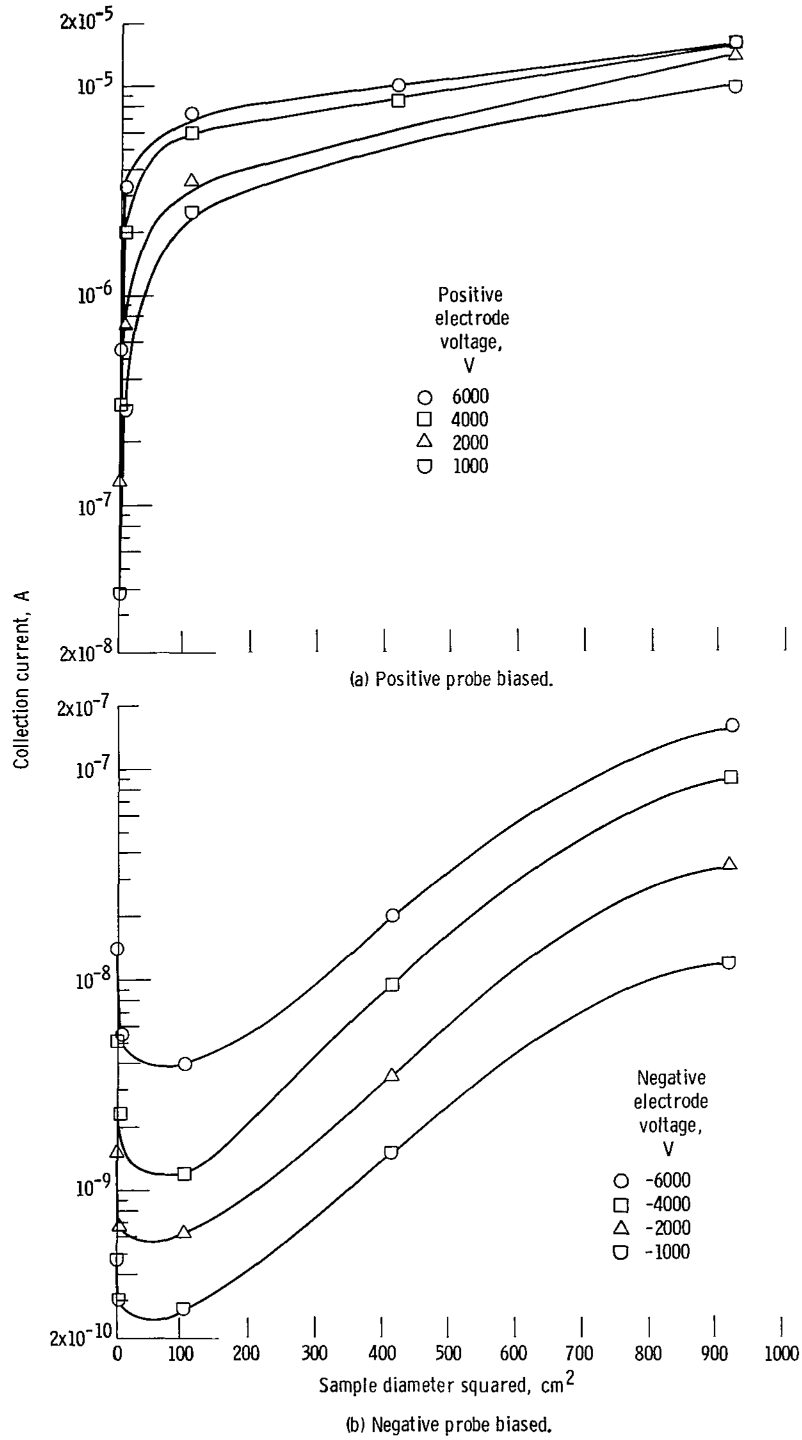
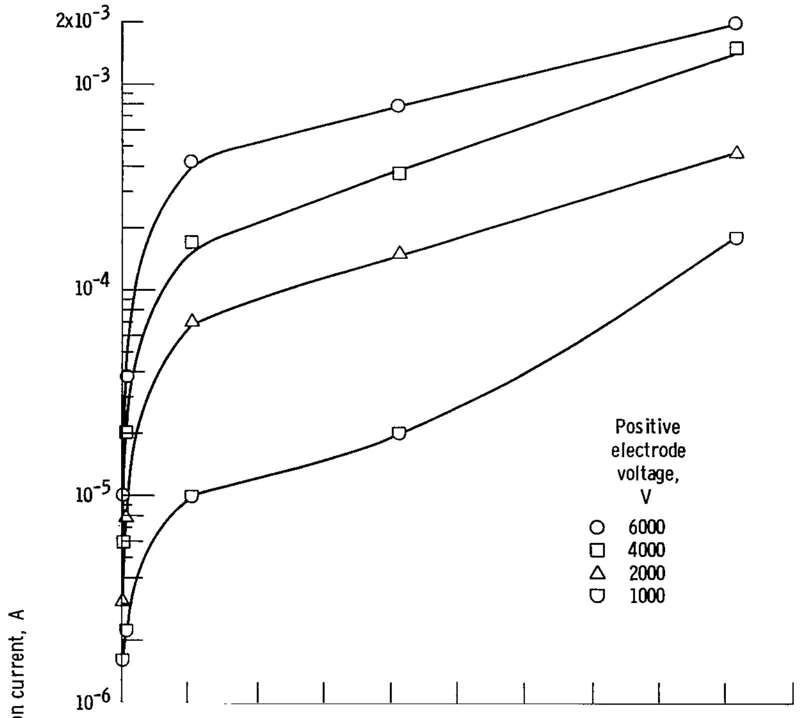
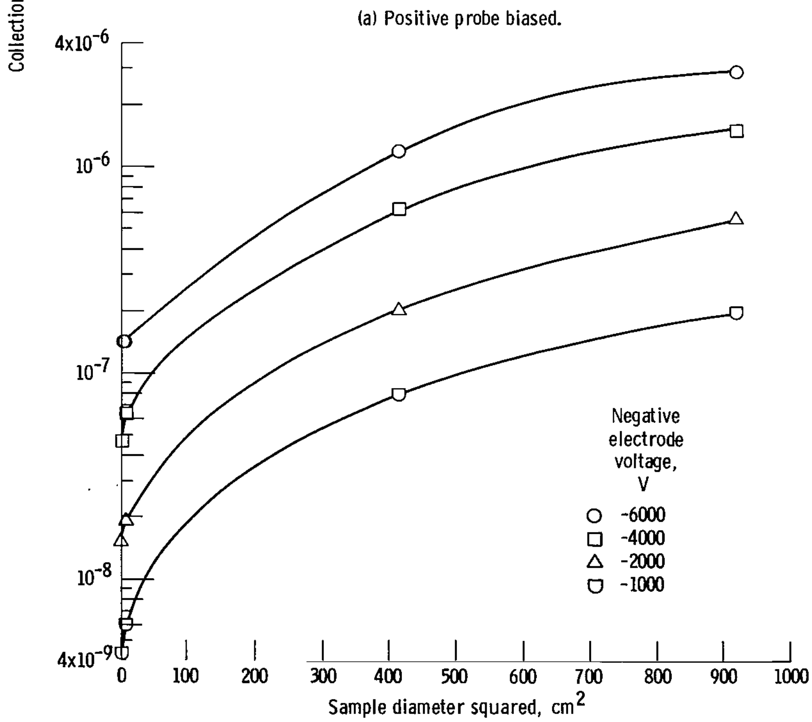


Figure 9. - Collection current as function of sample size (area effect) in a low-density plasma. Hole diameter, 0.051 centimeter.



(a) Positive probe biased.



(b) Negative probe biased.

Figure 10. - Collection current as function of sample size (area effect) in a high-density plasma. Hole diameter, 0.051 centimeter.

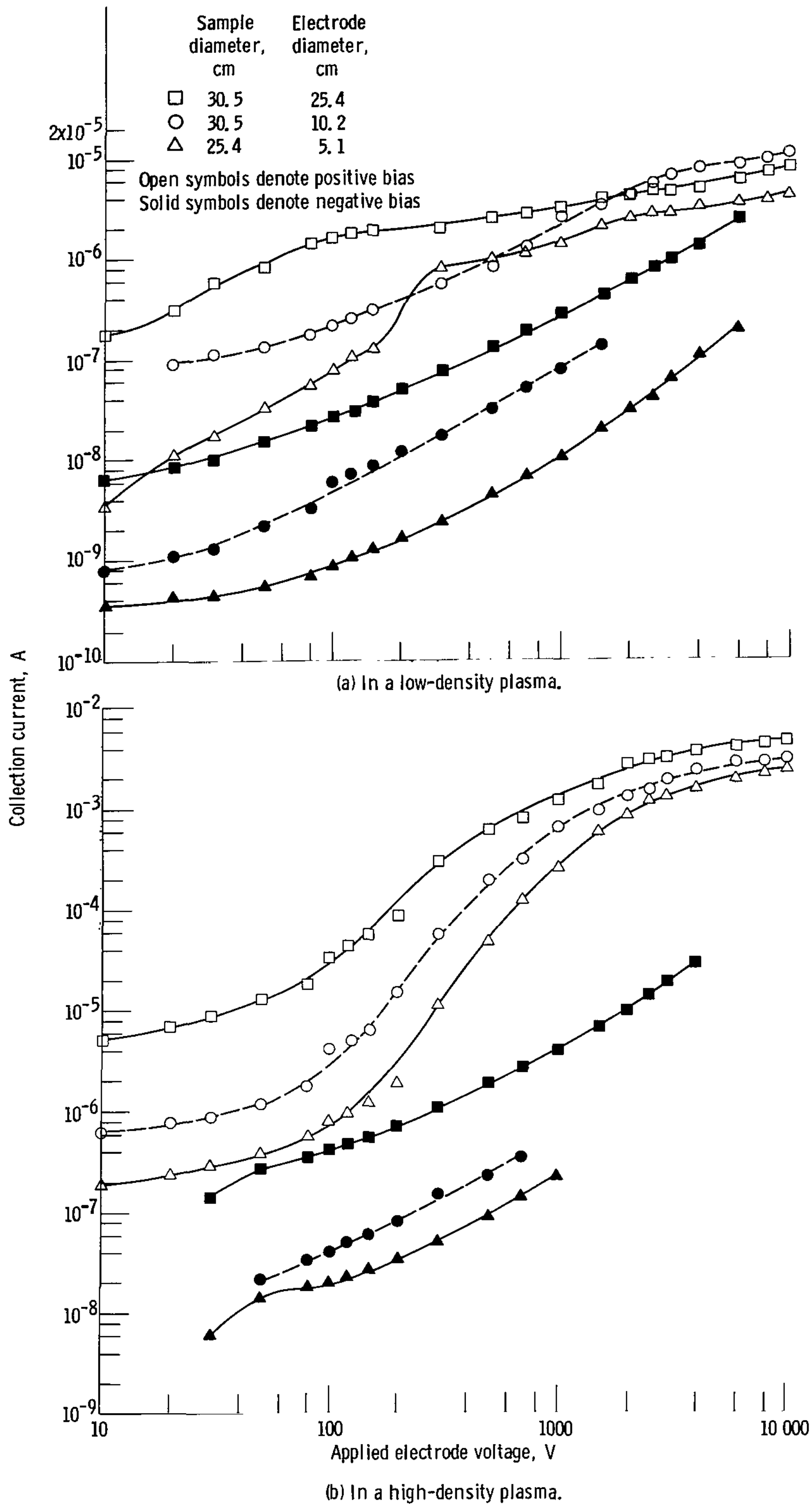


Figure 11. - Collection current as function of applied electrode voltage for bare-electrode samples (no Kapton).

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