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INSULATOR EDGE VOLTAGE GRADIENT EFFECTS
IN SPACECRAFT CHARGING PHENOMENA

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by N. John Stevens,* Carolyn K. Purvis,* and John V. Staskus*

ABSTRACT

Insulating surfaces on geosynchronous satellites have been charged by geomagnetic substorms to a point where discharges occur. The electromagnetic pulses from these discharges couple into satellite electronic systems disrupting operations. Laboratory tests conducted on insulator charging have indicated that discharges appear to be initiated at insulator edges where voltage gradients can exist. An experimental investigation has been conducted to measure edge voltage gradients on silvered Teflon samples as they are charged by monoenergetic electron beams. It has been found that the surface voltage at insulator edges can be approximated by an exponential expression based on an electron current density balance. Using this expression at known breakdown conditions results in a discharge voltage gradient down the insulator edge to ground of about 1.5×10^5 V/cm. Seams between insulation strips and imperfections in insulation can intensify voltage gradients and contribute to discharges. It appears that such discharges can occur on satellite surfaces in space.

INTRODUCTION

Spacecraft charging occurs when geosynchronous satellite exterior surfaces interact with geomagnetic substorm particle fluxes.[1] This interaction results in surfaces being charged to substantial negative voltages relative to the space plasma potential. It is believed that discharges can result from this surface charging and that electromagnetic pulses from such discharges can couple into spacecraft harnesses.[2-4] This discharge-generated pulse is believed to cause the electronic switching anomalies commonly associated with spacecraft charging.

The data from the ATS-5 and 6 Auroral Particles Experiments have been used to obtain the characteristics of geomagnetic substorms and the response of satellite electrical grounds to this environment.[5,6] In sunlight, the ground surfaces rarely are charged to negative voltages larger than a few hundred volts (-2 kV is the larges value reported).[7] During eclipses, the grounded surfaces can be charged to negative voltages in the kilovolt range. ATS-6 has been charged once to -19 kV[7] but charging in the -8 to -10 kV range is common.[8]

There are no direct measurements, in space, of insulator surface voltage responses to the geomagnetic substorms. However, the exposed insulator surfaces should be charged to levels similar to those of exposed satellite ground surfaces. This gives rise to the concept of differential charging of spacecraft: shaded insulators are charged to high negative voltages while sunlit spacecraft ground surfaces remain at low negative voltages. This differential charging could result in voltages across insulators of 8 to 10 kV commonly and of about 19 kV in very severe substorm conditions.

The insulator films used on spacecraft (e. g., silvered Teflon and aluminized Kapton) are typically from 0.005 to 0.013 cm (2 to 5 mils) thick; cover slides on solar arrays are 0.015 to 0.020 cm (6 to 8 mils) thick. The dielectric strength of these insulators should be high enough to prevent bulk electrical breakdown. Yet, data on spacecraft transients[9,10] indicates that surfaces discharge frequently in space and that transients do couple into spacecraft harnesses. Hence, a discharge other than bulk breakdown seems to be indicated: one that would result in discharges at the lower voltage gradients anticipated in space.

Experimental studies have been conducted in ground simulation facilities to determine the response of typical spacecraft insulators to electron fluxes.[11-15] It has been found that discharges can be induced at voltages considerably below bulk breakdown stress. Photographs of these discharges indicate that discharges are triggered at sample edges or at imperfections in the insulator. Typical photographs are shown in figures 1(a) and (b). The samples shown are 0.013 cm silvered Teflon with the silver layer grounded and the Teflon irradiated by an electron beam. The sample in figure 1(a) is a 15- by 20-cm single sheet of 0.013 cm silvered Teflon while the sample in figure 1(b) is made up of three strips of 5 cm wide by 20 cm long silvered Teflon (the center strip was deliberately cut in half). The photographs are time exposures of several discharges during irradiation by 20 keV electrons. Note that all discharges appear to originate at sample edges or at imperfections. At breakdown the insulator surface voltage is between -10 and -13 kV, well below the expected breakdown for 0.013 cm Teflon.[22] Similar results have been found for aluminized Kapton, optical solar reflectors (0.02 cm fused silica with a thin silver layer) and solar cell cover slides. These results indicate, therefore, that voltage gradients at sample edges may be a key to understanding discharge phenomena on spacecraft.

An investigation has been undertaken at the Lewis Research Center (LeRC) to measure edge voltage gradients as insulating films are charged to various levels up to and including discharge conditions. In this paper, the initial results of the investigation are discussed. The results of this study will be used to develop a model of discharge processes in insulators.

EXPERIMENTAL INVESTIGATION

Test Procedure

The test samples were 0.013 cm thick silvered Teflon, 5 cm wide, bonded to 15 by 20 cm aluminum plates with conductive adhesive. Silvered Teflon was chosen as the initial test surfaces because there was a considerable body of test results at the LeRC that could be used to support the results of the current tests. The two sample configurations used are

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shown in figure 2. With these configurations, the effect of a grounded metal boundary on the insulator edge voltage gradient could be determined. Gap voltage gradients at the seams between the Teflon strips could also be evaluated.

All tests were conducted in the LeRC Geomagnetic Substorm Simulation facility.[16] The facility is shown in figure 3 for a typical set up. The vacuum chamber is 1.8 m diam by 1.8 m long and operates typically in the 10^{-7} to 10^{-8} torr range. The electron gun, mounted in the chamber door on axis with the sample, can be operated as a monoenergetic source of electrons accelerated to any voltage between 2 kV and 25 kV. The shield with the Faraday cup is lowered over the sample when the electron gun parameters are set. The shield is raised at the start of a test, exposing the uncharged insulator sample. This allows charging rate data to be obtained until steady-state conditions have been reached. At the conclusion of a test run, the sample is discharged by a low energy plasma source.

The surface voltage of the sample is measured by sweeping two electrostatic voltmeter probes (manufactured by TREK, Inc.) across the sample. These probes are noncontacting capacitance coupled devices and they traverse the sample 2 to 3 mm above the surface. The two probes are mounted on a single arm so that surface voltage profiles at two different locations on the same sample are obtained simultaneously. The probes function while the electron beam is operating so that continual charging curves can be obtained.

Test Results

Typical surface voltage profiles across the test surface as a function of electron beam accelerating voltage are shown in figure 4(a) for the completely covered substrate sample (three strips of silvered Teflon) and in figure 4(b) for the sample with the 2.5 cm grounded metal boundary (two strips of silvered Teflon). Note that the probe readings indicate zero volts over the grounded metal surfaces, show sharp voltage gradients at the insulator edges, and clearly indicate changes in surface voltages at the insulator seams. The incident beam current density for all tests is 1 nA/cm^2 at the test surfaces.

The profiles characteristically exhibit sharp voltage gradients at the edges of both samples. This surface voltage approaches a constant value towards the central portion of the insulator. The seam in the insulator introduces only a perturbation in this trend. That the voltage at the seam does not go to the zero substrate voltage is probably due to the size of the seam joint or the probe sweep speed. The trend towards sharper edge voltage gradients as the beam accelerating voltage is increased is clear.

The surface voltage probes are finite in size (1.1 cm square with a 0.13 cm aperture) and move across the 15 cm dimension of the sample in about 18 seconds. The accuracy of the probe in determining the surface voltage is of concern. Throughout the test the probes are calibrated. At one end of the arm sweep probe readings are checked against a grounded plate allowing the probe electronics to be zeroed, if necessary. At the other end of the arm sweep there is a metal

plate that can be biased by a laboratory power supply. This allows a probe electronic system calibration against a known voltage reading. The calibration checks are typically run before and after test sequences on the silvered Teflon samples. The probes have been found to be stable.

The data obtained for the edge voltages as a function of beam accelerating voltage is shown in figure 5(a) for the completely covered substrate sample and in figure 5(b) for the grounded metal edge sample. The error bars represent the range of voltages obtained at each position indicated by both probes at both edges of the sample. The solid line, then, represents the average voltage gradient obtained for each sample. Comparison of the two sets of average values indicates that there are no significant differences between them. Therefore, having an exposed, grounded metal boundary does not significantly change the edge voltage characteristics of the insulators used in these tests.

DISCUSSION OF RESULTS

Edge Gradient Model

A simple one-dimensional model for the voltage gradient at the edge of an insulating slab has been developed based on a suggestion proposed by Parks and Mandel.[17] The predictions from this model have been compared to the experimental data.

The geometry used in the model is depicted in figure 6. An insulating slab of thickness, d, is mounted on a grounded metallic substrate. This configuration has an edge at $x = 0$. The sample is irradiated by a beam of monoenergetic, normally incident electrons with energy, eV_B, where V_B is the beam voltage. Under steady-state conditions, a voltage, $V_S(x)$, exists on the insulator surface. Because some current is assumed to flow around the corner and down the edge at $x = 0$, V_S is not zero at $x = 0$. Thus, a voltage will exist beyond the insulator surface (in the $y = 0$ plane). For purposes of this model, the voltage along $y = 0$ is assumed to reach zero at some distance ℓ to the left of $x = 0$, i.e., at $x = -\ell$.

An expression for $V_S(x)$ can be obtained from an electron current density balance on a surface element of the insulator. The current densities are:

$$-\Delta j \equiv -j_e + j_{se} + j_{Bs} \ \text{(A/cm}^2\text{)} \begin{matrix}\text{(assumed to be a constant and a}\\ \text{negative value)}\end{matrix}$$

$$j_L = \frac{-V_S}{\rho d} \ \text{(A/cm}^2\text{)}$$

$$j_x = \frac{1}{\rho_x} \frac{dV_S}{dx} \ \text{(A/cm)}$$

where j_e, j_{se}, and j_{Bs} are current densities due to incident electrons, secondary and backscattered electrons, respectively; j_L is the bulk leakage current density through the sample; j_x is the surface leakage current (i.e., current per unit length) flowing along the insulator surface; ρ and ρ_x are the bulk and surface resistivities (ohm-cm and ohm per square), respectively; and d is the insulator thickness (cm). The electron current density balance is obtained by

equating the electron flow into an elemental region dx to the flow out of the region (see insert in fig. 6). This current density balance is

$$-\Delta j \, dx + j_x = j_L \, dx + j_{x+dx}$$

$$\left. -\Delta j \, dx + \frac{1}{\rho_x}\frac{dV_s}{dx} = \frac{-V_s}{\rho d}dx + \left[+\frac{1}{\rho_x}\frac{dV_s}{dx} + \frac{1}{\rho_x}\frac{d}{dx}\left(+\frac{dV_s}{dx}\right)dx \right] \right\} \quad (1)$$

or

$$\frac{1}{\rho_x}\frac{d^2V_s}{dx^2} - \frac{V_s}{\rho d} + \Delta j = 0 \quad (2)$$

The general solution to equation (2) is:

$$V_s(x) = C_1 e^{-ax} + C_2 e^{+ax} + \rho d \, \Delta j \quad (3)$$

where $a = (\rho_x/\rho d)^{1/2}$ cm^{-1} and C_1 and C_2 are arbitrary constants determined from the boundary conditions.

Since the insulator surface is being charged by a finite energy electron beam, the surface voltage must also remain finite. In order to satisfy this condition the positive exponential must disappear, so C_2 is zero. The second boundary condition is that the surface voltage, $V_s(x)$, is zero at $x = -\ell$. This can be satisfied by letting the exponential be $-a(x + \ell)$ and $C_1 = -\rho d \, \Delta j$. Therefore

$$V_s(x) = -\rho d \, \Delta j \, e^{-a(x+\ell)} + \rho d \, \Delta j = \rho d \, \Delta j \left[1 - e^{-a(x+\ell)}\right] \quad (4)$$

As x becomes very large compared to the thickness, the surface voltage becomes a constant value. This constant surface voltage can be related to the incident beam voltage by use of existing experimental and analytical results.[15, 20] It has been found that, for very good insulators such as Teflon (bulk resistivity of $\sim 10^{17}$ ohm-cm[19]), the constant surface voltage is approximately the difference between the beam voltage and the "second crossover" voltage for secondary emission, V_1 (i.e., the voltage for which the secondary emission yield is unity). Therefore, equation (4) for the silvered Teflon samples tested becomes:

$$V_s(x) = (V_B + V_1)\left[1 - e^{-a(x+\ell)}\right] \ (V)$$

or

$$V_s(x) = (V_B + 1900)\left[1 - e^{-a(x+\ell)}\right] \ (V) \quad (5)$$

where $V_1 = 1900$ V from the literature values for Teflon[18] and

$$a = \left(\frac{\rho_x}{\rho d}\right)^{1/2} \ cm^{-1}$$

It is recognized that the constant voltage term in equation (4) ($\rho d \, \Delta j$) has apparent inconsistencies. Since it was assumed that the bulk resistivity was constant and that Δj was also constant (to solve eq. (2)), then the surface voltage could depend on the insulator thickness, d. The experimental data for very good insulators like Teflon indicates that the surface voltage at the center of insulators depends on surface parameters and is independent of thickness.[15, 22]

This implies that there are multidimensional effects and possibly a variable Δj that must be considered in a rigorous model of edge voltage gradient phenomenon. However, the simplified one-dimensional model developed here will be used to compare with the experimental data and to illustrate possible effects at insulator edges.

Comparison to Experiment

The voltages computed from equation (5) were compared to the experimental data given in figure 5. The parameters a and ℓ were adjusted to give the best fit to the data. Since the data obtained appeared to be independent of configuration, the edge voltages for both samples were averaged and plotted as functions of position, x, and beam voltage, V_B. The voltages computed from equation (5) with $a = 2$ cm^{-1} and $\ell = 0.1$ cm agree very well with these data (see fig. 7).

While there are published values of bulk resistivity for silvered Teflon of about 10^{17} ohm-cm, the values for surface resistivity are not well-defined; values that can be between one order of magnitude and four orders of magnitude less than the bulk resistivity have been reported.[19, 20] From this experiment the ratio of surface to bulk resistivity is:

$$\frac{\rho_x}{\rho} = 4d = 4(0.013) = 0.05 \ cm^{-1}$$

which is at least within the ranges reported.

The voltage gradient at the seams between the silvered Teflon strips was compared to the predictions of equation (5) with $\ell = 0$, $x = x_1$, and $a = 15$ cm^{-1}. It is assumed that x_1 is positive in both directions (a mirror image solution is assumed). This comparison is shown in figure 8. The agreement here also is good. A value of a of 15 seems to indicate that surface currents are negligibly small at the seams.

Therefore, it appears that the surface voltage characteristics of silvered Teflon insulators can be computed from a simple exponential expression. It is anticipated that similar relationships can be obtained for other insulating films (i.e., aluminized Kapton).

Discussion

The results of this study indicate that there is a pronounced edge effect in the charging of insulator surfaces on grounded metal substrates. The concept of zero surface voltage at $x = -\ell$ was introduced into the simple model to allow for current flow down the edges of insulators. If the surface resistivity on the edge were the same as the irradiated surface, then current continuity would require ℓ to be the insulator thickness, d. However, to match the data, ℓ was found to be 10 times greater than the thickness. This implies that there is additional resistance down the insulator edge or that charge "collects" at the corner. The edge voltage gradients become progressively steeper as the electron beam accelerating voltage increases until breakdown occurs.

Prior experiments have shown that 0.013 cm thick silvered Teflon samples in similar configurations will break down when the surface voltage is -12 kV (± 1.5 kV).[15] The

computed surface voltage for the edge of the insulator at this breakdown condition (V_B + 1900 = -12 000) is shown in figure 7. The computed surface voltages at the seam at breakdown conditions is shown in figure 8.

The electric field at the sample edge can be calculated. The x component of the field (along the surface) can be found from equation (5) with ℓ = 0.1 cm and a = 2 cm^{-1}:

$$E_x = -\frac{dV_s}{dx} = -(V_B + 1900)\left[+2e^{-2(x+0.1)}\right]$$

$$= -1.6\,(V_B + 1900)\ \text{V/cm}\ \text{at}\ x = 0$$

If it is assumed that the voltage gradient down the thickness of the insulator is linear, then this field is simply (with ℓ = 0.1 cm and a = 2 cm^{-1}):

$$E_y = -\frac{V_s}{d} = -\frac{(V_B + 1900)\left[1 - e^{-2(x+0.1)}\right]}{0.013}$$

$$= -13\,(V_B + 1900)\ \text{V/cm}\ \text{at}\ x = 0$$

Hence, the electric field down the thickness of the insulator (the y-component) will be dominant. The computed relationship for the edge voltages and the y-component of the electric field as a function of the central insulator surface voltage is shown in figure 9. It appears that breakdown will occur when the edge voltage gradients are about 1.5×10^5 V/cm, a value not inconsistent with results from other experiments.[13]

This concept of edge or seam breakdown is supported by two additional experimental results. First, it is known that a grounded metal frame covering the edges of an irradiated insulator surface prevents discharges.[21,22] The voltage gradients from the insulator surface to the frame are as severe as those found in this study. The only difference is a lack of an exposed edge or seam.

The second result, based on LeRC experiments, is that insulating surfaces with edges and seams mounted on electrically floating metal plates do not discharge. The insulating surface can be charged. However, without the grounded surface, there are small edge or seam voltage gradients and no discharges (at electron beam accelerating voltages up to 20 kV).

Results reported in the literature[13,22] indicate that both positive and negative particles are ejected in the discharge. The existence of plasma particles in a discharge could be explained by an ionization process occurring during edge breakdowns. The residual gas from adhesives or from the insulator surface could be ionized and these particles expelled by the fields surrounding the insulator.

The results obtained in these tests can be applied to spacecraft conditions. In space the absolute ground is the space plasma potential. Both the spacecraft structure (electrical ground for all spacecraft systems) and the insulator surfaces (which are primarily capacitively coupled to the structure) will be at some voltage relative to the plasma. When the spacecraft experiences a substorm flux of particles while in sunlight, the structure will become only slightly negative due to photoemission.[1] The shaded insulators,

however, can be charged to large negative values. The conditions then would be similar to those in the tests. Discharges at edges, seams, and imperfections would then be expected. When the spacecraft experiences a substorm flux of particles while in eclipse, then both the insulators and conductors would "float" at some value depending on their material properties. LeRC tests have indicated that there may not be discharges under these conditions.

CONCLUDING REMARKS

It has been observed from discharge photographs that the discharge appears to originate at insulator edges, seams, and imperfection. A study has been undertaken to evaluate surface voltages at edges and seams in insulators under steady-state conditions to determine the edge voltage at breakdown conditions. Silvered Teflon samples, 0.013 cm thick, were used in the study.

It has been found that the x component of the electric field at insulator edges observed in experiments can be approximated by an exponential expression developed from a current density balance concept. This field decays to zero on the insulator surface within 2 to 3 cm of the edge.

It is believed that discharges are caused by a breakdown at insulator edges between the charged insulator surface and the grounded substrate. The electric field at the edge is on the order of 10^5 V/cm which is consistent with the literature data on breakdown across insulators. Furthermore, it is believed that residual gas or parent material from the insulator is ionized in the breakdown and the plasma particles ejected.

From the results of this investigation, it is concluded that discharges on geosynchronous spacecraft could occur at edges, seams, or similar imperfections in insulation mounted over spacecraft ground structures under geomagnetic substorm conditions.

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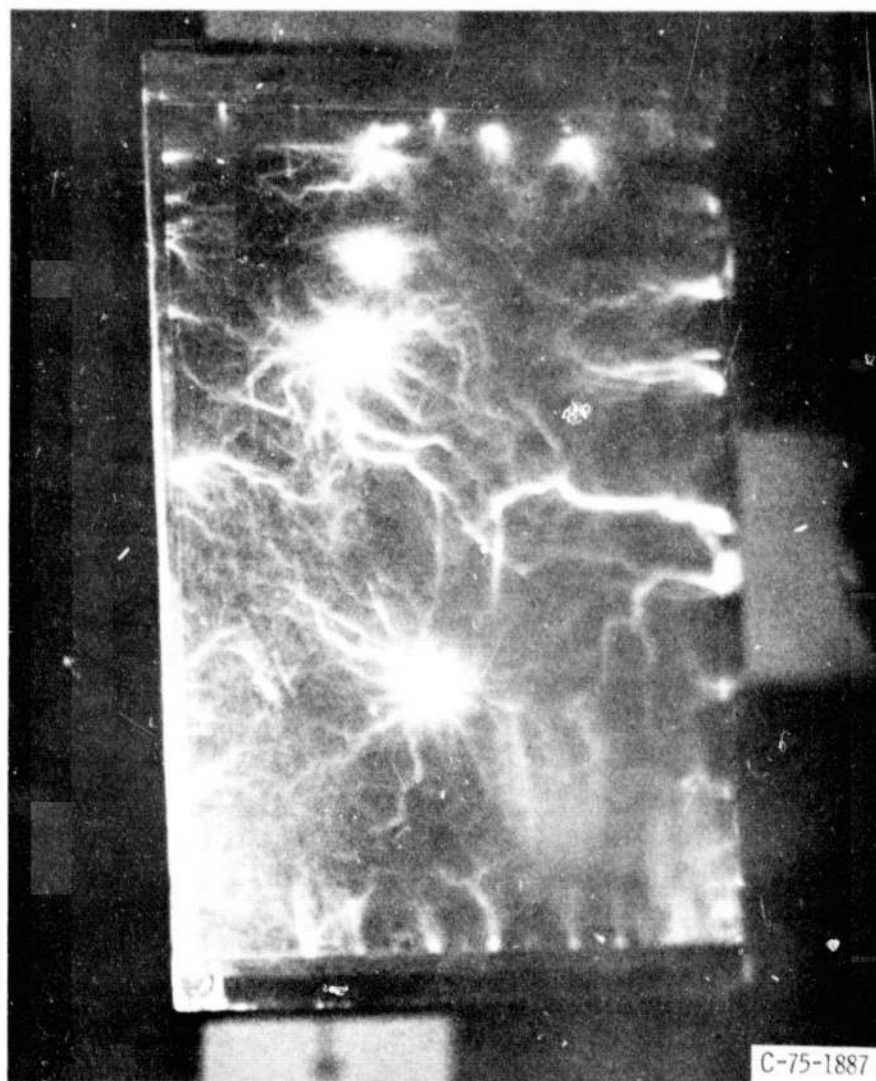
C-75-1887

Figure 1A. - Visible discharges on single sheet of silvered teflon.

C-75-1539
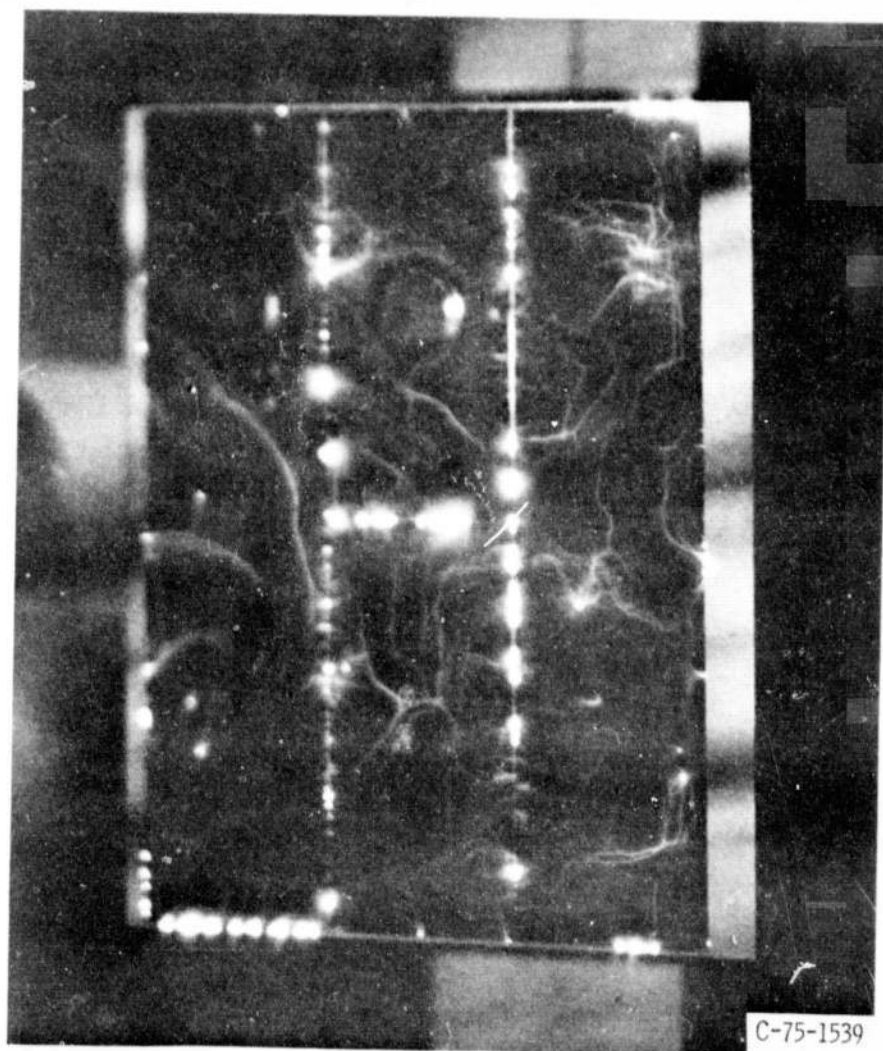
Figure 1B. - Visible discharges on 3-strip sample of silvered teflon.

THREE-STRIP SAMPLE   TWO-STRIP SAMPLE

20 cm

15 cm   15 cm
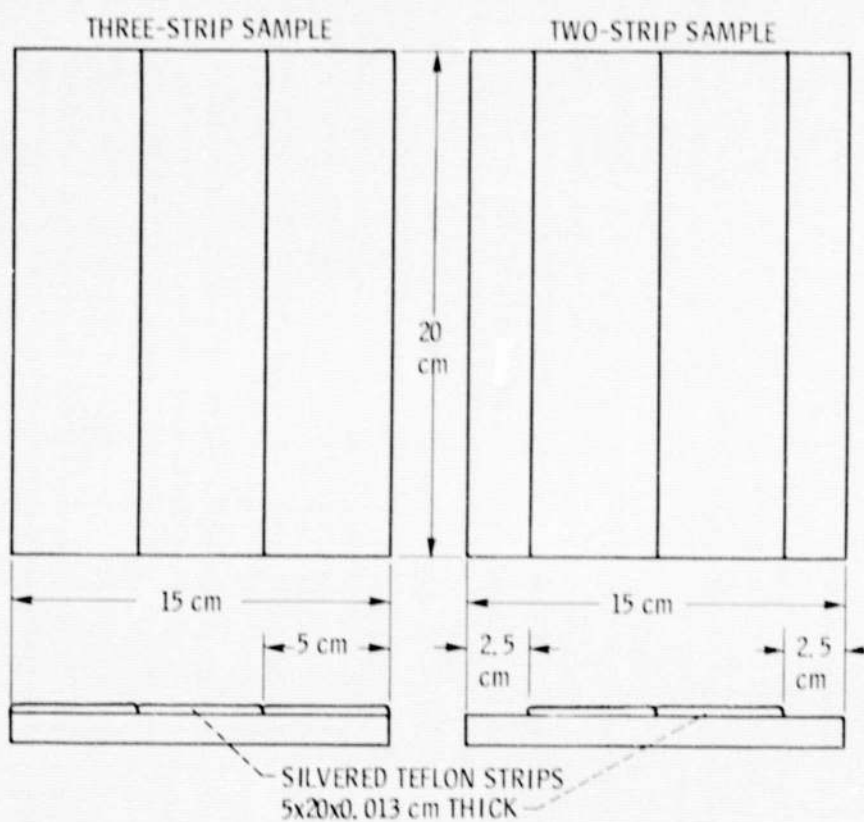
5 cm   2.5 cm   2.5 cm

SILVERED TEFLON STRIPS
5x20x0.013 cm THICK

Figure 2. - Sample configurations. Teflon side to electrons mounted to
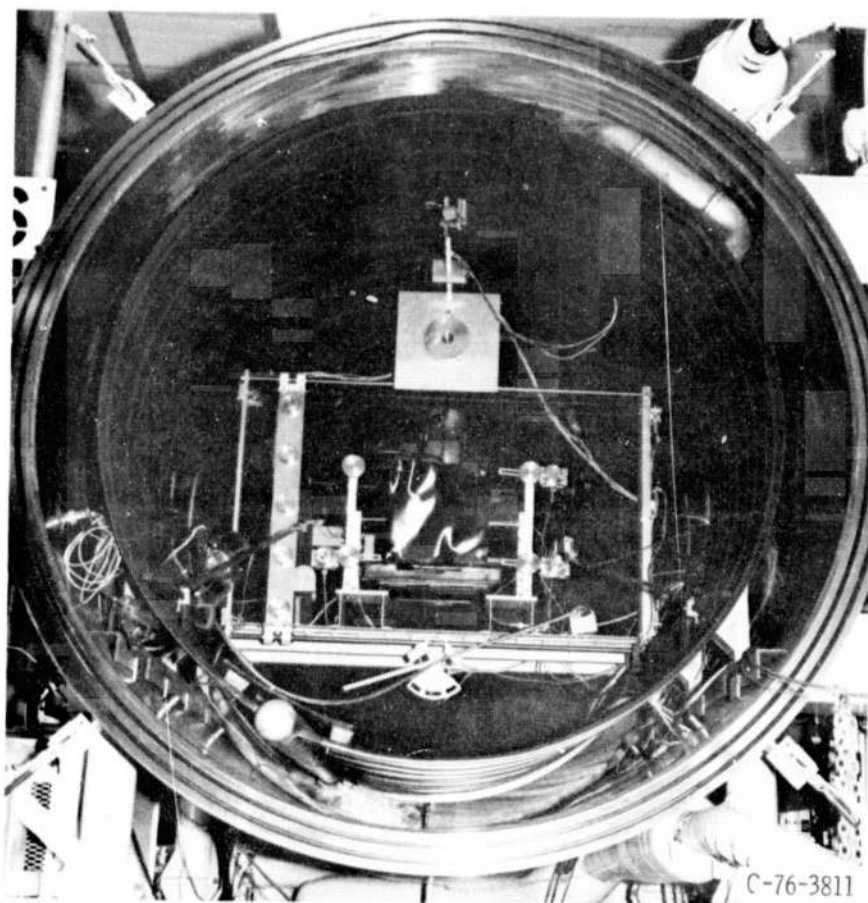aluminum substrate with conductive adhesive.

C-76-3811

Figure 3. - LeRC geomagnetic substorm simulation facility.

SILVERED TEFLON

METAL SUBSTRATE

V_B, kV

-10

-8

-5

(a) THREE-STRIP SAMPLE.

SILVERED TEFLON

METAL SUBSTRATE

V_B, kV

-12

-10

-8

-5

(b) TWO-STRIP SAMPLE.
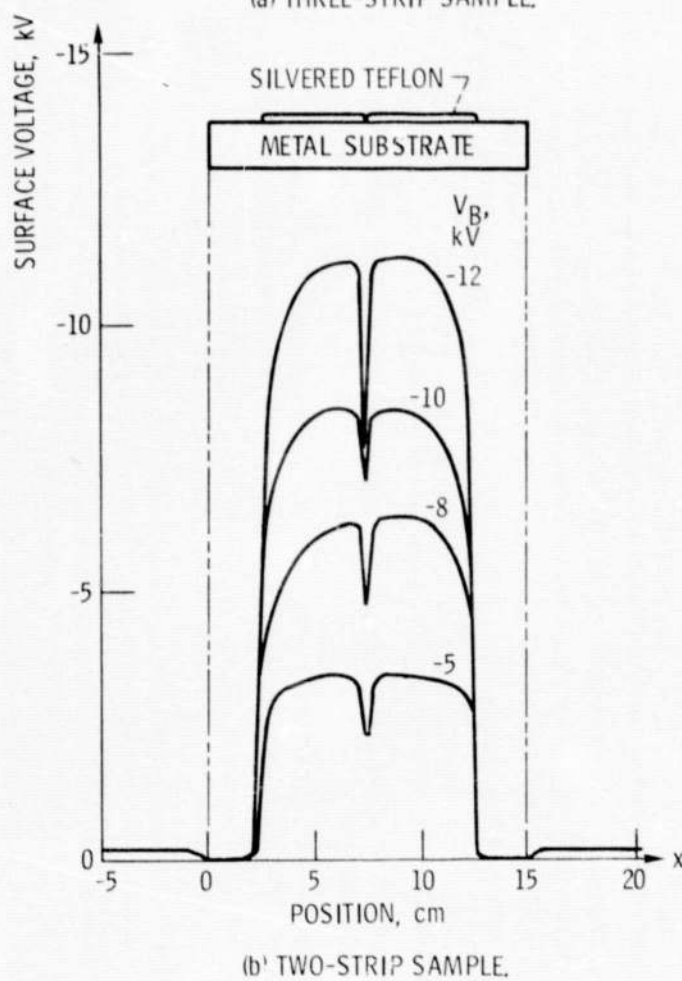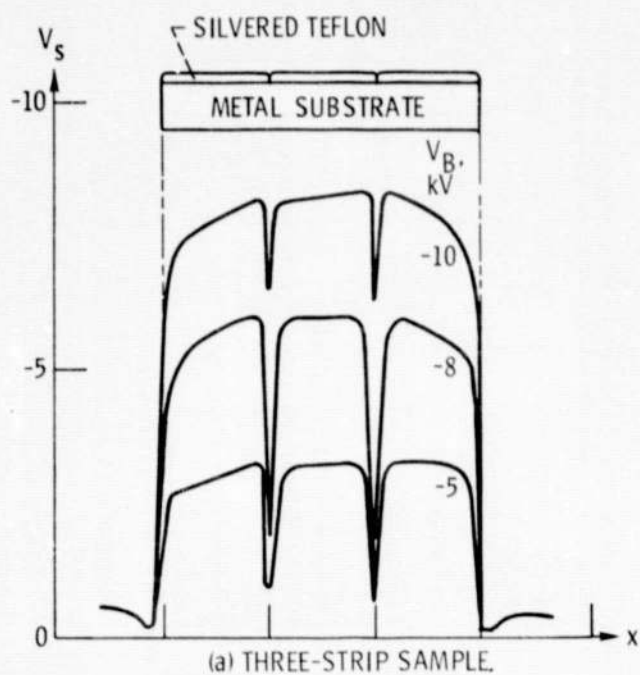
Figure 4. – Typical surface voltage profiles.
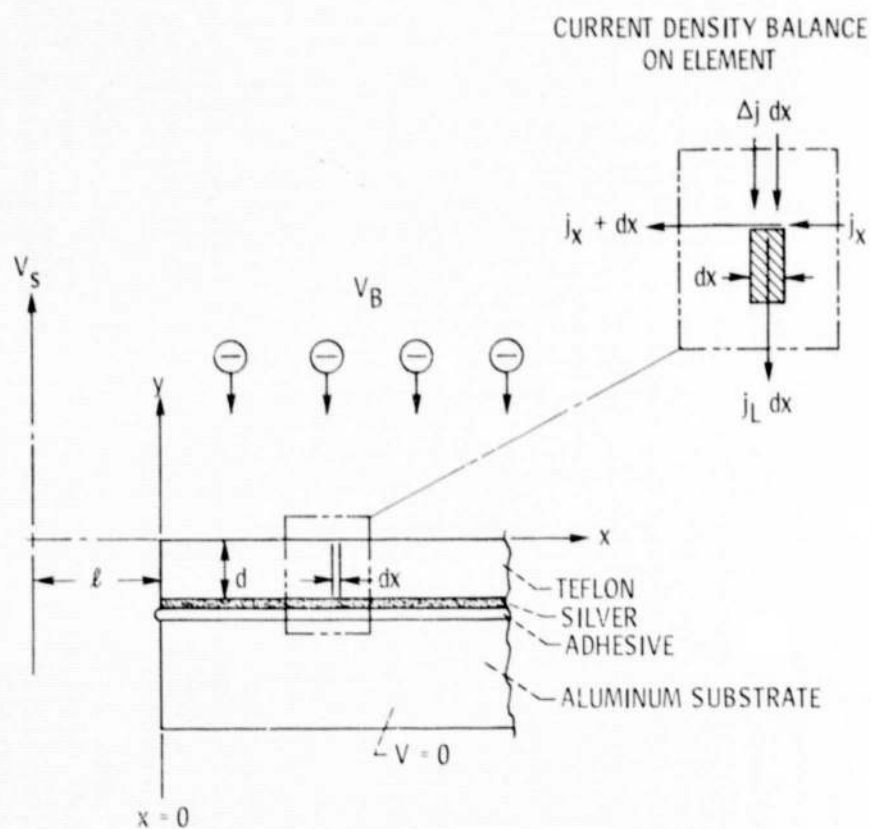
(a) THREE-STRIP SAMPLE.

(b) TWO-STRIP SAMPLE.
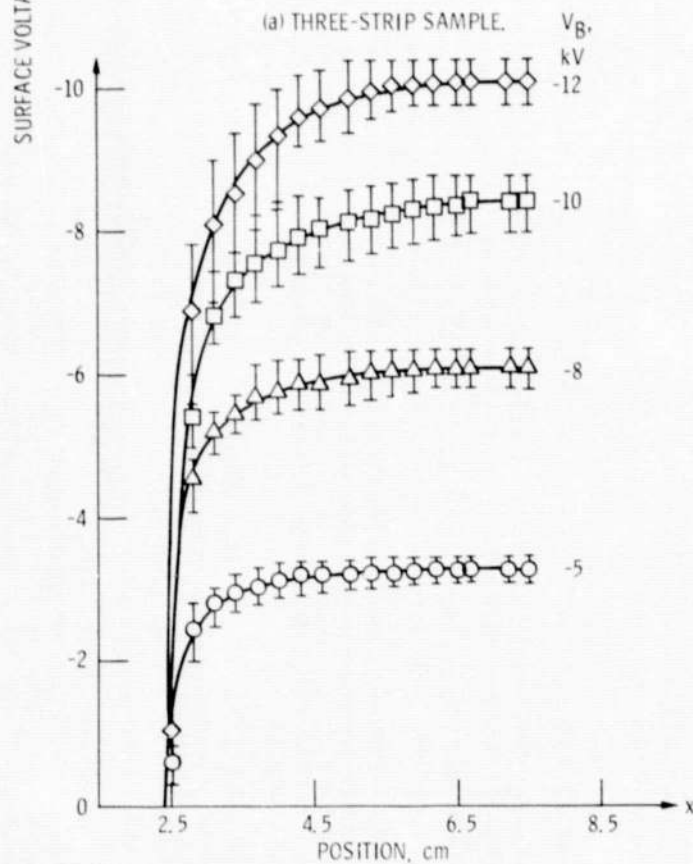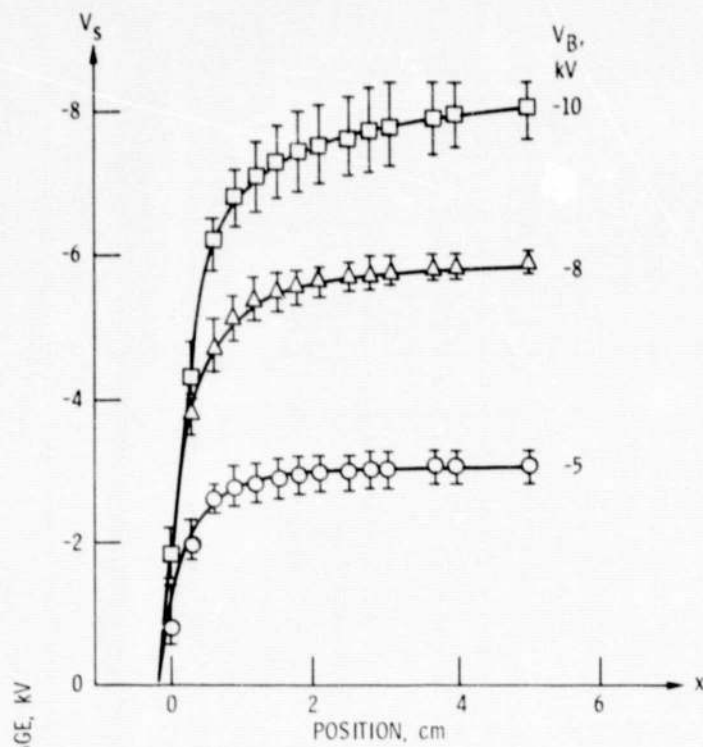
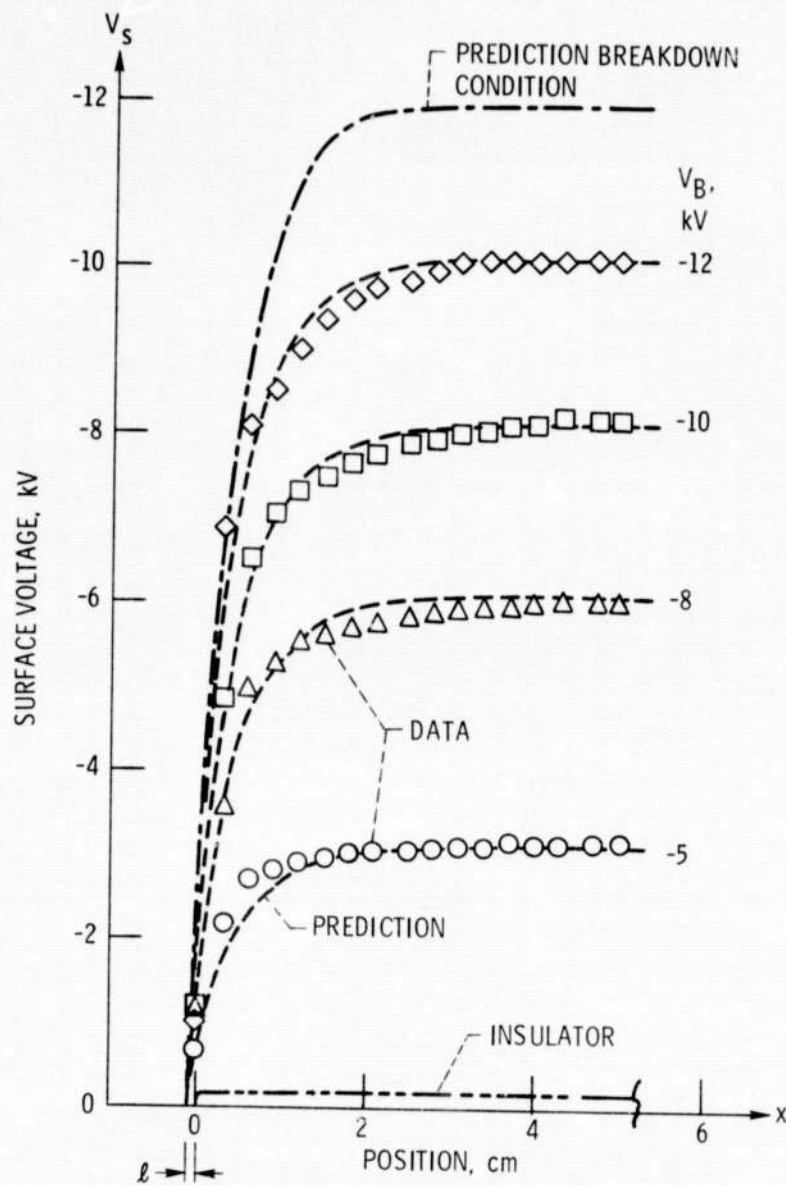Figure 5. - Edge surface voltage data.

Figure 6. - Edge voltage model.

Figure 7. - Comparison of edge voltages with simple model predictions.
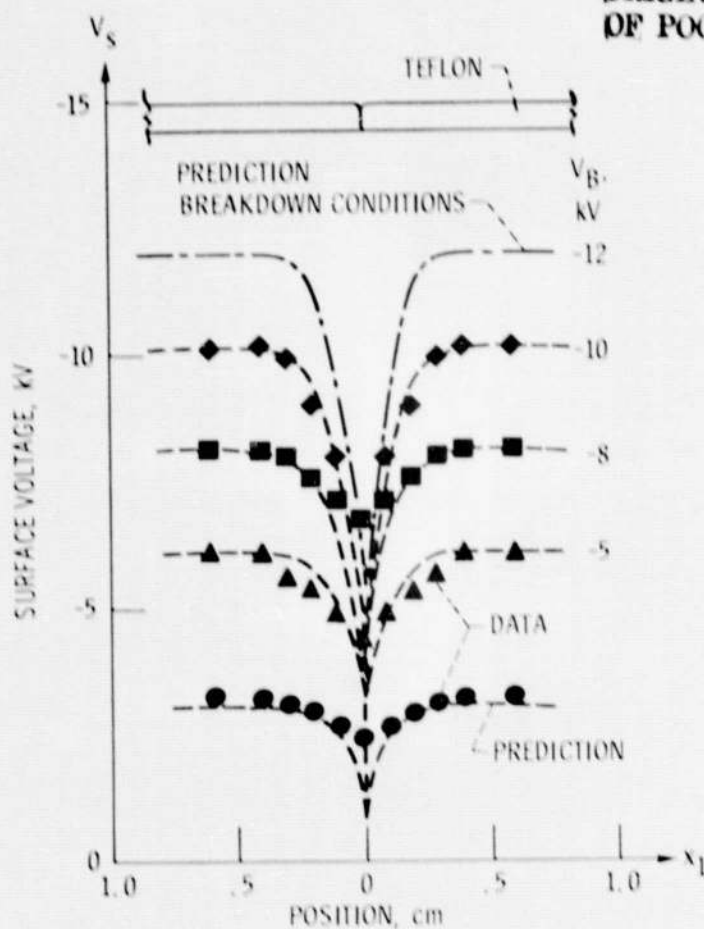
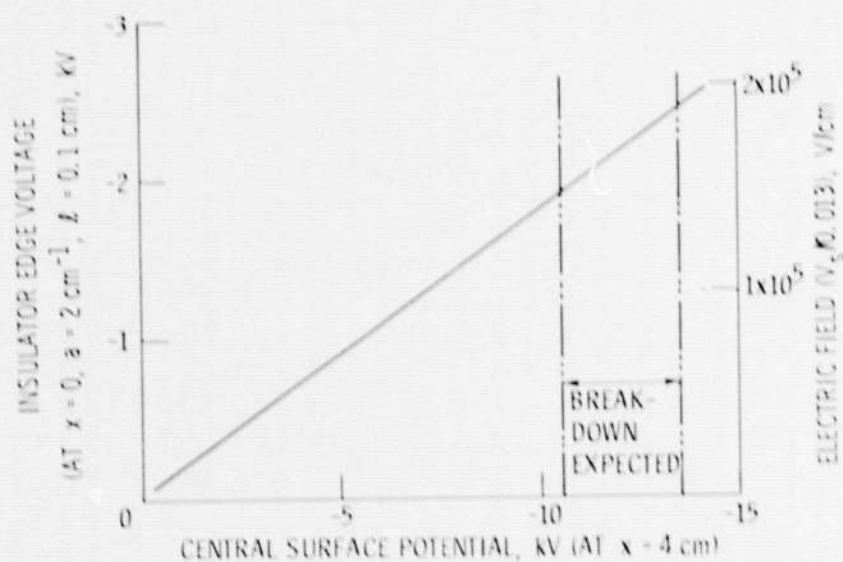Figure 8. - Surface voltage at seams.

Figure 9. - Computed edge voltage and electric fields (0.013 cm silvered Teflon samples).