CONDUCTION THROUGH PUNCTURES IN METAL-BACKED DIELECTRICS*

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SUMMARY

The current conducted through a dielectric, as well as the characteristics of any arcs, are significantly influenced by the presence of punctures through the dielectric. This paper presents a theoretical mechanism to explain the main features of experiments with punctured spacecraft-thermal-blanket materials. The model is based on consideration of the electric fields developed about punctures; the focusing of primary electrons toward the punctures; the generation, migration, and cascade of secondary electrons along the surface; and the radiation induced conductivity characteristics of thin dielectric films. Qualitative predictions of the model agree with experiment results.

INTRODUCTION

Observation of discharges at defects or edges of thermal blanket materials exposed to an electron beam has led the authors to study pinholes as a means of reducing problems associated with charging of spacecraft dielectrics. Current leakage through punctures in dielectrics to a charged conductor beneath has been a concern for a number of years (ref. 1-7). In 1969 an anomalously high current collection ability of pinholes in dielectrics was first reported by Sellen et al. (ref. 1), who were studying the effects of drainage current through solar cell interconnects in ionospheric (100 to 600 mile altitude) plasma. Pinholes are small, and it would be expected that the trapping of negative charge on the dielectric surface near positively charged pinholes would repel, and therefore reduce, the collection of negative charge (ref. 6).

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Figures 1 and 2 show some measurements of pinhole current collection for positively biased pinholes, as a function of the area of the dielectric surface and the applied voltage. At low voltages (the conductor beneath the pinhole set below +1000 volts) the pinhole is effectively shielded from the plasma as originally expected. However, as the voltage increases, the current collected on the conductor exceeds that predicted from simple probe theory or simple electrostatic effects (ref. 6). The higher than expected current through the pinhole was tentatively attributed to surface leakage currents near the pinhole. Equally unusual are the effects of the surface area of the specimen (a ring of dielectric concentric about a pinhole). The "effective" area of current collection can be as large as the surface of the sample itself (ref. 2).

EXPERIMENT

The situation of a positively charged pinhole in a dielectric surrounded by a neutral plasma (as generally assumed in the above references) is somewhat similar to the authors' configuration of a grounded pinhole in a dielectric being irradiated with an electron beam. Experimental results pertaining to pinholes used in this way are shown in figures 3 and 4 and table I. Details of the experiment used to obtain the results presented here are given in Reference 8. In figure 3a, the dielectric surface voltage is plotted versus the electron beam energy for planar Kapton and Kapton with pinholes. At beam energies up to 8 keV, there is no significant difference in equilibrium voltage. Above 10 keV, further charging of the punctured Kapton is prevented by arcs. Similar results below 10 keV for Teflon are shown in figure 3b. The leakage current as a function of the number of pinholes is shown in figure 4. Table I contrasts the arc energies for planar Teflon and pinholed Teflon.

In the discussion that follows, the punctured structure will be compared with an identical planar structure that has not been so altered. The influence on experimental measurements of surface potential and current collected by the metal back will be considered as a function of hole density. The probability and nature of surface discharges will be contrasted for the two structures.

THEORY

The structure considered is a hole punched through a dielectric sheet (very large compared to the pinhole) from the metal coated side. The conditions include a monoenergetic electron beam normally incident on the dielectric surface with the metal layer grounded. Interaction of the beam with the structure and development of potentials, electric fields, and currents in and around the dielectric adjacent to the hole will be discussed.

Charging of Planar Samples

An electron beam, incident on a planar dielectric, will generate electron-hole pairs and deposit negative charge up to the electron range in the material. This negative charge will electrostatically drive electrons from the metal backing to ground, leaving a positive charge at the metal-dielectric interface. The electric field generated between the negative front surface volume and the positive back layer will polarize the dielectric and direct the otherwise random motion of thermally generated mobile charge carriers in the bulk and of radiation induced charge carriers in the irradiated volume.

Charging will continue until steady state is established between the incoming electron beam, secondary and backscattered electrons, and carrier migration through the bulk and surface layer of the dielectric. At steady state, since the surface potential will generally be within several kilovolts of the beam energy, the beam will not penetrate as deeply as initially. Therefore, charge redistribution within this surface layer could be considerable; however, most of the charge, prior to steady state, will migrate toward the back surface. Near steady state, the secondary emission coefficient approaches 1, and most of the newly deposited electrons migrate toward the front surface rather than toward the back. (This migration toward the front surface is a consequence of an electric field generated by the positive charge remaining on the front surface when secondary electrons are knocked off by incident electrons, and by the electrons trapped deeper in the dielectric.)

Charging of Punctured Samples

If the unbounded surface described above is punctured, then a ground point is established on the front surface and steady state conditions are modified significantly in the vicinity of the hole. Initial charging conditions are not much altered until the surface potential begins to approach a high negative steady state value. As the surface potential away from the hole becomes more negative and secondary emission increases, this region contributes less and less to the current being collected at the back surface. The surface in the immediate vicinity of the hole maintains a lower secondary emission because it is still close to ground potential. The near ground potential is maintained by surface conductivity enhanced by tertiary emission (electrons knocked from the surface by secondary electrons) and has several influences:

a. the beam incident in that area penetrates as deeply as at initiation of charging, and with the much lower secondary emission of the initial conditions;

b. the incident beam is focused toward the hole by the low potential; and

c. the strong potential gradient on the surface approaching the hole acts as an electron multiplier, thereby transporting a disproportionate number of electrons to the ground plane.

The effect in each case is an increase in the electron current collected on the back plate (figure 4); in fact, the current density collected by the hole and its immediate surface area may be 2 or 3 orders of magnitude higher than that expected from the area of the pinhole alone or than that migrating through an equivalent bulk of the dielectric.

The local potentials are useful in describing the charge and discharge phenomena in the vicinity of a hole. Figure 5 illustrates the potential well in which secondary electrons are trapped and, along with the tertiaries, collected by the ground plane in a hole. This figure also indicates that holes reduce the surface potential in only a small area about the hole; therefore, a very large hole density is required to alter the general surface potential measured only a small distance from the dielectric.

Discharges in Dielectrics

High energy electrons focused and incident on the area about the hole generate a high density of carriers at a depth greater than that in the planar areas. Since the potential is also much less negative near the hole, transverse surface fields will be much greater and the consequent surface and subsurface current densities will be higher than for nonadjacent regions. If holes in the dielectric are formed by mechanically punching through from the metal layer side, then the metal will probably emerge through the deformed dielectric in such a manner as to intersect the heavily irradiated region (figure 6). The radiation induced conductivity (RIC) would then be field enhanced to propel electrons through the dielectric toward the emergent metal. If such currents happen to find or generate a preferred path, ohmic heating (which will increase conductivity) and thermal runaway could result in an electric discharge across or under the surface near the hole.

Since the discharge mode is for trapped electrons going to ground, a negative pulse is expected. The low energy negative component of this discharge would be confined to the vicinity of the hole (and collected at the ground) except to the extent that the steady state potential is disrupted by the plasma generated by the discharge. However, some electrons would escape and constitute a positive pulse as viewed from the metal back. The positive ions created in the plasma formed by the arc in the hole will be accelerated away from the hole; most will go into space, but many will return to the negatively charged surface away from the hole. Positive ions returning to the surface will generate

secondary electrons, most of which will escape (adding to the tail of the electron pulse), but many of which will find their way to the hole region and contribute to the tertiary electron cascade across the surface toward the ground plane. The resultant current observed on the back metal contact would be a fast, ringing pulse with little energy content.

Two types of discharge are possible in planar dielectrics. The first is a discharge from the stored-charge regions beneath the surface to the metal backing. The energy liberated in the discharge will vaporize material, which often blasts through the front surface as well as the back. If this discharge does not erupt through the front surface, the negative pulse seen in the ground line will be very small since charge redistribution is not great. If, however, the discharge does erupt through the front surface, then a large electron concentration will be accelerated away from the surface and create a strong positive pulse in the ground line. Positive ions (from the plasma caused by the discharge) falling back on the negatively charged surface will generate a large number of secondary electrons which, when also accelerated away, could increase both the intensity and duration of the positive pulse. The presence of a hole in the dielectric will reduce the probability of a discharge to the metal layer in a planar region since a discharge is more likely to occur at the hole. As described above, a discharge near a hole produces a ground pulse which is not very large. Once occurring, it reduces the negative surface potential to some extent over most of the dielectric, as a result of positive ion return and tertiary emission.

The second type of discharge possible in planar dielectrics is a surface discharge resulting from an edge, an anomaly, a bilayer (ref. 9), or some other mechanism. If this discharge creates a plasma on the surface, which is then charge separated by the surface fields, a large pulse will result from the initial flux of electrons (separated from the plasma) driven off and followed by the secondary electrons generated by the returning ions. Again, on a pinhole sample this type of discharge can occur away from a hole, but is less likely to do so because of the lower arcing threshold near a hole.

A major point to be emphasized is that a discharge at or near a pinhole is significantly altered by the presence of this "ground" and its associated electric fields. A large percentage of electrons (particularly the slow ones), that would otherwise escape from the surface and contribute to the positive ground pulse, are collected by the pinhole, and only neutralize their image charge. The current pulses induced by discharges near a hole are therefore much smaller and faster than would be expected from a planar surface. Hence, use of pinholes in dielectrics can lower the impact of surface discharges on a spacecraft by reducing the energy of a discharge (table I), and by reducing the magnitude of the displacement current.

The current collected by the metal back can be dominated by the regions associated with the holes (as described above) and therefore this "back" current should be proportional to the number of holes in the sample. Edge leakage could interfere with this proportionality until the hole currents dominate edge leakage or unless the edges are shielded or "guarded" with a high voltage ring to prevent current flow around the edge to ground. When the pinholes exceed some concentration, the back current will begin to saturate as individual "drainage" patterns begin to overlap.

CONCLUSIONS

A model describing the charging and discharging of punctured dielectrics exposed to an electron beam has been proposed to explain the experimentally observed reduction in surface potentials and in discharge energies as compared to nonpunctured dielectrics. This model leads to the following predictions for metal coated dielectrics with holes punched through from the metal back:

a. High surface potentials (up to the breakdown level) will still occur over most of the dielectric. A surface potential probe should show dips when it traverses holes only if its sensor is close enough to the surface. Only when the hole density becomes very high will the measured surface potential show significant decrease.

b. Current collected from the back metal layer will be proportional to the hole density over a large range if edge effects are removed and the hole area is not much less than about 0.1 percent of the measured area.

c. Discharges are more likely to initiate at the hole regions, and thereby reduce the probability of discharges occurring elsewhere. The observed discharge image on the "back" current monitor will be faster and much smaller for a discharge near a hole than for a discharge on an unmodified planar sample.

This analysis pertains to a laboratory environment, and must be altered for a dielectric in a "hot" space plasma, where the isotropic energy spectrum will smear out the charge deposition in the surface layer and greatly enhance the space charge beyond the surface. However, the mechanisms for initating discharges and reducing their impact by the presence of punctures should remain valid and therefore important as a means of charge control in dielectrics.

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Table I. ENERGY REMOVED DURING DISCHARGES IN TEFLON AS A FUNCTION OF PINHOLE DENSITY

Sample	Beam Energy (keV)	Arc Energy (mJ)	Surface Voltage (kV)
Plain	20	150	>8.0
Pinholes at 3/8-in. Spacing	10	80	8.5
Pinholes at 1/8-in. Spacing	10	20	4.5

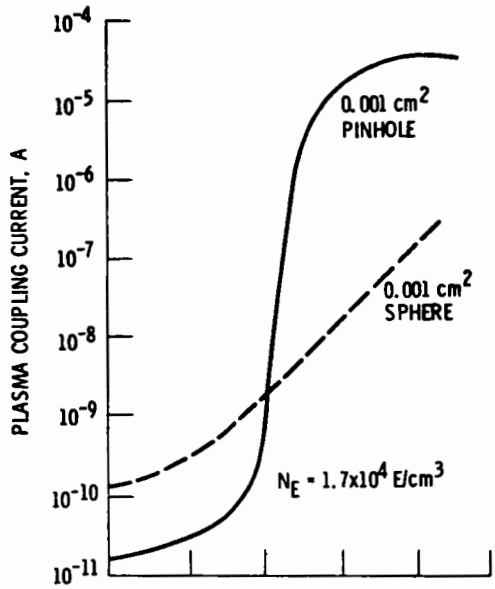


Figure 1. Pinhole Collection Current as a Function of Positive Applied Voltage. Experimental data for a pinhole (solid curve) are compared to simple probe theory for a sphere (dashed curve) (ref. 1)

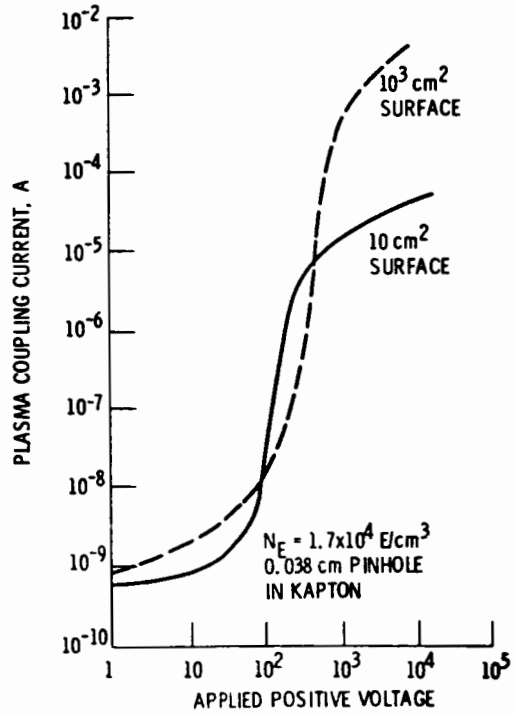
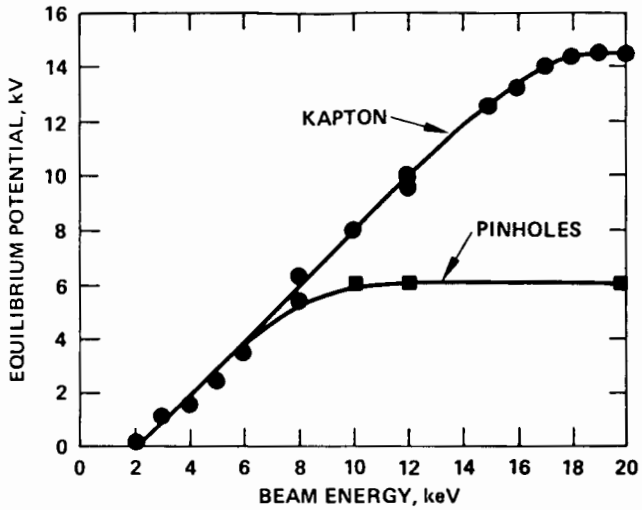
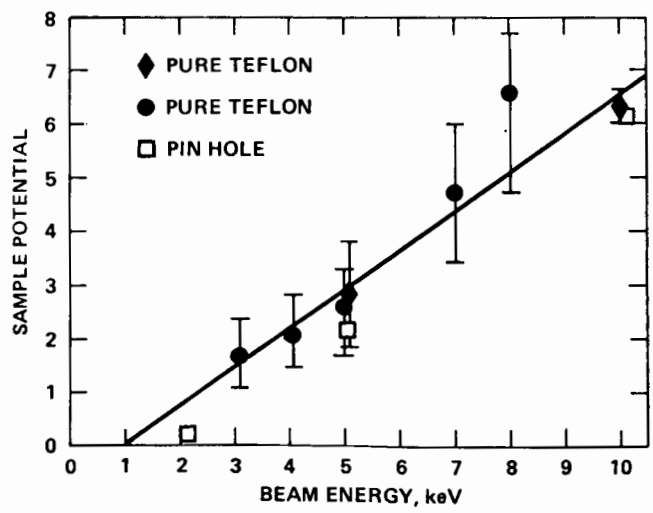


Figure 2. Pinhole Current as a Function of Applied Voltage for Two Dielectric Surface Areas (ref. 1)



A



B

Figure 3. Dielectric Surface Voltage versus Beam Energy for Planar and Punctured Samples of Kapton (A) and Teflon (B)

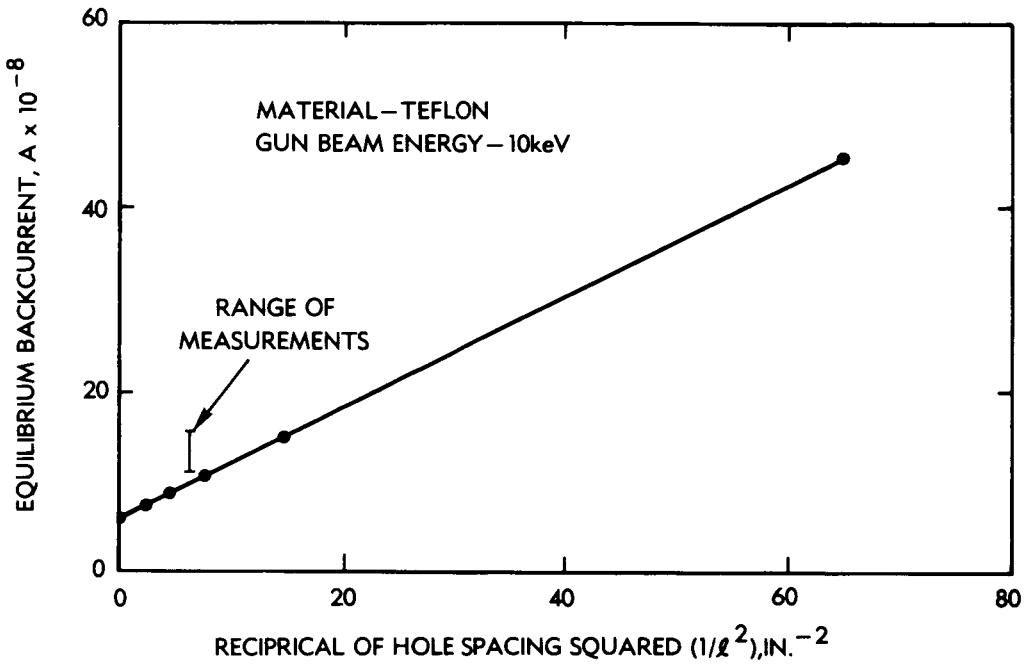


Figure 4. Leakage Current Versus the Reciprocal Pinhole Spacing Squared for a Teflon Sample in a 10-keV Beam

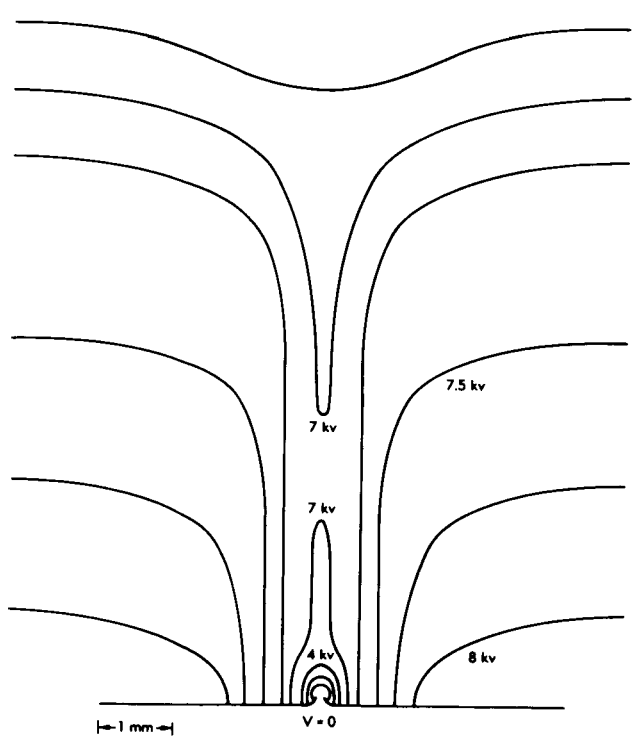


Figure 5. Equipotential Surfaces above a Pinhole through a Metal Backed Dielectric

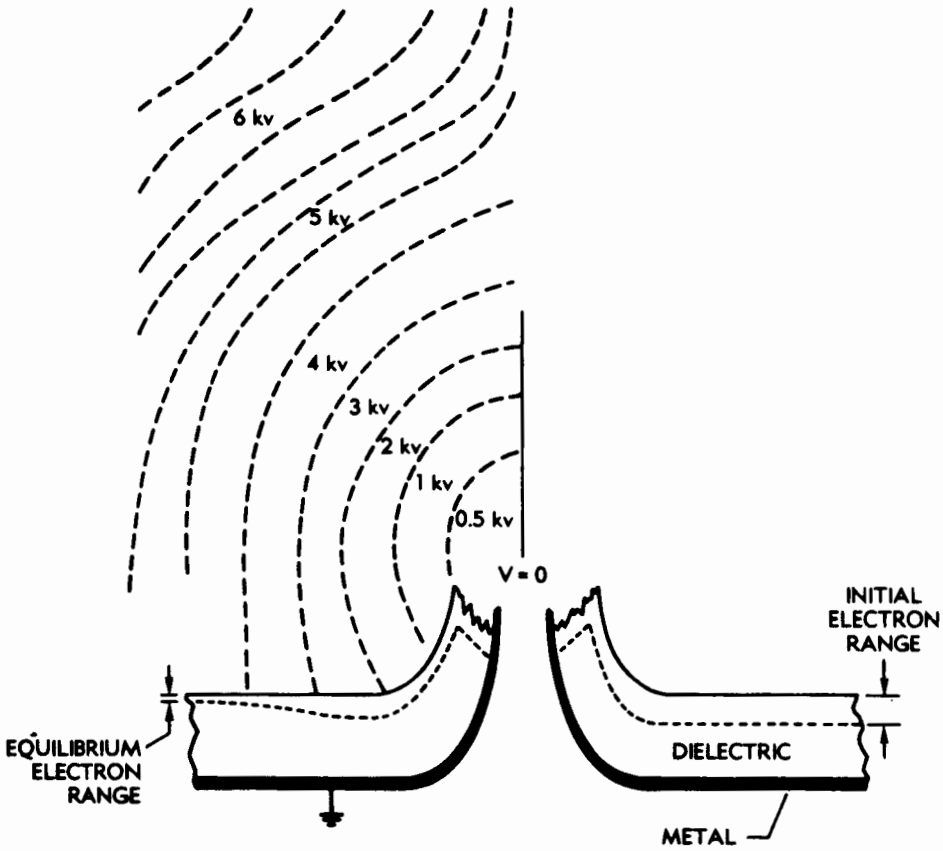


Figure 6. Idealized Structure of a Pinhole Showing the Range of Electrons Prior to Charging and at Equilibrium (left side)