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Insulator Surface Charging during Fast Pulsed Surface Flashover in Vacuum*

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INTRODUCTION

The fact that charge accumulates on the surface of an electrically stressed insulator in vacuum is well established, but the rate of charging is not. Furthermore, the role of this charge in surface flashover is controversial.

Previous investigations support the hypothesis that charging proceeds very rapidly by means of an avalanche of electrons released from the insulator surface by secondary emission and that the avalanche is responsible for establishing the discharge channel in cathode-initiated surface flashover.[1,2] Work reported here verifies that electron avalanches occur prior to breakdown, even for voltage pulses lasting only a few nanoseconds. In addition, the critical electric field angle associated with the equilibrium surface charge has been determined under fast pulsed conditions, and found to agree well with the dc measurements of Boersch, et al.[3]

EQUILIBRIUM SURFACE CHARGE

Insulator surface charging by means of secondary electron emission will be briefly reviewed, so that the experimental results which follow may be understood.

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DISCLAIMER

According to the analysis of Boersch, et al.,[3] the charge on an insulator surface under electrical stress reaches equilibrium when secondary electrons are returned to the insulator surface with an average kinetic energy equal to A_1, the lower of the two primary electron energies for which the total yield of secondaries is unity. This means that the electric field in the vacuum at the insulator surface becomes inclined at a constant critical angle with respect to the insulator surface. The tangent of this angle is given by

$$E_{\perp}/E_{\parallel} = [2\bar{A}_0/(A_1 - \bar{A}_0)]^{1/2} \quad , \tag{1}$$

where $E_{\perp}$ and $E_{\parallel}$ are the components of the electric field which are perpendicular and parallel to the insulator surface and $\bar{A}_0$ is the average emission energy of secondaries. The validity of Eq. (1) has been experimentally demonstrated.[3,4]

The relative magnitude of the equilibrium parallel field component at the vacuum interface of a rectangular insulator slab between parallel electrodes, obtained by numerical solution of Poisson's equation (see Ref. 5), for the case of a 30° critical angle, is plotted in Fig. 1. According to Eq. (1), the perpendicular field component, and therefore, the positive charge on the insulator surface, is proportional to the parallel field component. For an applied field of 5 MV/m, the total surface charge is 89 $\mu C/m^2$ on the average. Because of dielectric polarization, the charge that must be generated by electron multiplication is a factor $(\epsilon+1)/2$ larger, where ϵ is the relative dielectric constant of the insulator. The surface charge distribution described here is greater than zero everywhere except at the insulator-anode junction, in contrast to the charge distributions obtained through numerical simulation by Sudarshan, et al.[6]

EXPERIMENTAL

In this work, insulators are subjected in vacuum (10^{-3} to 10^{-4} Pa pressure) to high-voltage steps having 3 ns risetime. The methods of voltage generation and measurement and of the attachment of insulators to parallel stainless steel electrodes are the same as described previously.[2,7,8]

RESULTS AND DISCUSSION

Observation of Avalanche Current

Measurements of the current of electrons arriving at the anode electrode at the edge of a 20 mm long, rectangular insulator (Fig. 2) verify that a secondary electron emission avalanche occurs on the insulator surface prior to breakdown. Electrons passing through a 1.5 mm diameter hole in the anode electrode are collected by a Faraday cup probe. A small needle on the cathode electrode initiates a region of insulator surface charging in line with the hole in the anode electrode. Typical simultaneous voltage and Faraday cup current waveforms for alumina ceramic are displayed in Fig. 3. Results for polymethyl methacrylate (Plexiglas) are similar.

Details of the waveforms in Fig. 3 are consistent with electron avalanche theory. After an initial burst of current 1.5 ns wide, corresponding to a few tenths of an ampere per millimeter surface current, a smaller steady current persists until it grows exponentially immediately prior to the collapse of insulator impedance. If the avalanche propagates toward the anode at about 2×10^7 m/s,[9] one may conclude from the discussion of the equilibrium surface charge that insulator charging is equivalent to a 1 ns pulse (for a 20 mm long insulator) of a few amperes per millimeter surface current. Apparently, only a small fraction of the electrons emitted escape the avalanche and are accelerated to the anode to be detected as the initial burst of current. The remaining electrons drift slowly toward the anode in a space charge sheath above the insulator surface. The current observed here during the latent period prior to breakdown is, roughly, equal to the predicted current due to space charge drift.[7,10]

Determination of Critical Electric Field Angle

The test arrangement depicted in Fig. 4 allows insulator surface charging prior to breakdown to be observed. The insulator is a bent, 1.6 mm thick sheet of polymethyl methacrylate, which bridges a 20 mm inter-electrode gap. This particular shape gives rise to minimal distortion of the electric field angle due to dielectric polarization, for field angles in the 30° to 45° range investigated; the electric equipotentials are parallel to the electrodes as they approach the inclined surface of the insulator. A capacitive voltage divider at the anode electrode behind the inclined portion of the insulator is sensitive to electric field distortions due to insulator charging. A small needle at the surface of the insulator at the cathode end initiates charging in line with the capacitive voltage divider.

A typical waveform indicating positive charging of the insulator surface is displayed in Fig. 5. The secondary emission avalanche might reasonably be expected to propagate more slowly at field angles near the critical angle,[9] so that several ns are required in crossing the insulator surface. During this time the space charge sheath masks the positive charge on the insulator surface. After the avalanche reaches the anode, the sheath charge begins to drain away because it is not fully replenished by the needle source at the cathode. Unmasking of the positive surface charge is evidenced by the upward turn of the waveform in Fig. 5 about 6 ns before voltage collapse. Indication of positive charging disappears between 35° and 40° for smooth-surfaced samples. The critical electric field angle therefore appears to lie between 35° and 40°. Samples that have been rubbed with 400 grit silicon carbide paper to roughen the surface appear to have a critical field angle a few degrees smaller.

These critical field angles may be compared with dc measurements. Boersch, et al. measured the charge remaining on the surface of massive polymethyl methacrylate insulators after a period of high voltage stress, and found that the charge was zero when the insulator surface was inclined at 31.5°.[3] When dielectric polarization is accounted for, the electric field angle at which no charging occurred is found to be approximately 40°, which agrees well with our results.

<u>Breakdown Voltage of Negative-Angle Conical Insulators</u>

The influence of the critical electric field angle is evident in the breakdown voltage of conical, polymethyl methacrylate insulators having the smaller end at the cathode electrode. (According to a sign convention, which we ignore here for simplicity, the angle of the wall of a conical insulator is considered negative if the smaller end of the insulator is the cathode end.) A low, reproducible breakdown voltage is found for small-angle insulators.[8] The surface of such an insulator charges positively, allowing self-sustained propagation of an electron avalanche. At insulator angles larger than about 27° (< -27° according to the sign convention) the breakdown voltage departs from the small-angle value, becoming larger and variable, which suggests that positive surface charging no longer occurs.

Numerical solution of Poisson's equation indicates that the electric field angle at the surface of a 27° conical insulator with a relative dielectric constant of 3 is close to 37° over most of the surface. The field angle at which larger breakdown voltages are encountered is, therefore, in agreement with the value of the critical field angle we have determined.

Measurement of the critical electric field angle of the type described here may be a useful diagnostic of the effects of insulator surface coatings which are designed to alter secondary emission properties.

REFERENCES

1. J. P. Brainard and D. Jensen, in 1973 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena, (National Academy of Sciences, Washington, DC, 1974), p. 250; J. Appl. Phys. 45, 3260 (1974).
2. R. A. Anderson in 1973 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena, (National Academy of Sciences, Washington, DC, 1974), p. 258; Appl. Phys. Lett. 24, 54 (1974).
3. H. Boersch, H. Hamisch, and W. Ehrlich, Z. Angew. Phys. 15, 518 (1963).
4. J. P. Brainard and D. Jensen, in 1974 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena, (National Academy of Sciences, Washington, DC, 1975), p. 442.

5. J. E. Boers, in 11th Symposium on Electron, Ion, and Laser Beam Technology, (San Francisco Press, San Francisco, 1971), p. 167.

6. T. S. Sudarshan, J. D. Cross, and K. D. Srivastava, IEEE Trans. Elect. Insul. EI-12, 200 (1977).

7. R. A. Anderson, in 1974 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena, (National Academy of Sciences, Washington, DC 1975), p. 435.

8. R. A. Anderson, in 1975 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena, (National Academy of Sciences, Washington, DC, 1976).

9. R. A. Anderson, J. Appl. Phys., to be published.

10. K. D. Bergeron, J. Appl. Phys. 48, 3073 (1977).

FIGURE CAPTIONS

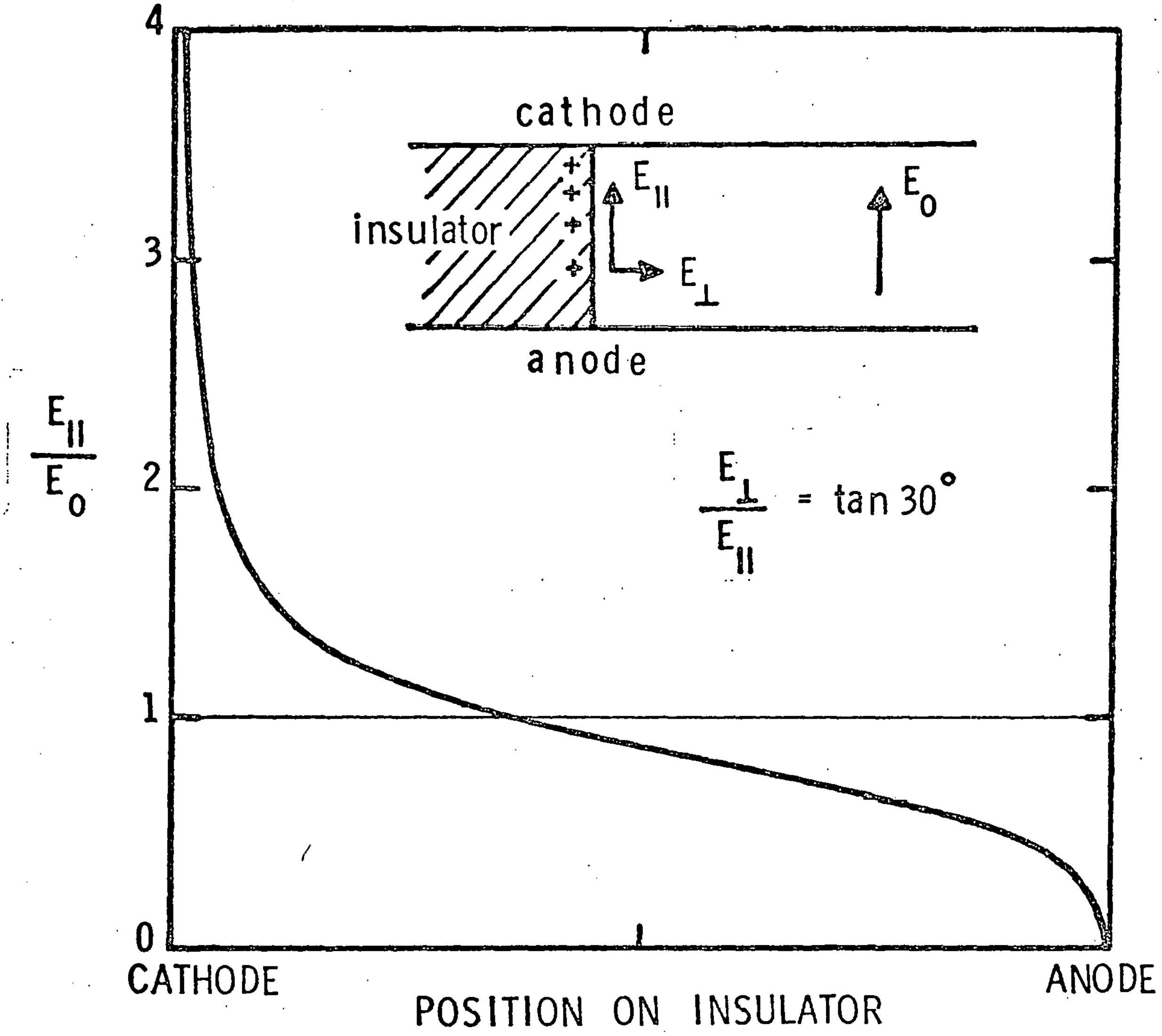
Fig. 1 - Equilibrium electric field component parallel to the surface of an insulator in vacuum, for a 30° critical angle.

Fig. 2 - Arrangement for observing electron avalanche current.

Fig. 3 - Simultaneous voltage and avalanche current waveforms recorded for the arrangement in Fig. 2.

Fig. 4 - Insulator geometry for observing insulator surface charging.

Fig. 5 - Voltage waveform recorded as in Fig. 4, indicating positive charging of the insulator surface.


4
3
2
1
0
$\frac{E_{\parallel}}{E_0}$
cathode
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$E_{\parallel}$
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CATHODE
ANODE
POSITION ON INSULATOR

ROUGH SKETCH OF FIGURES

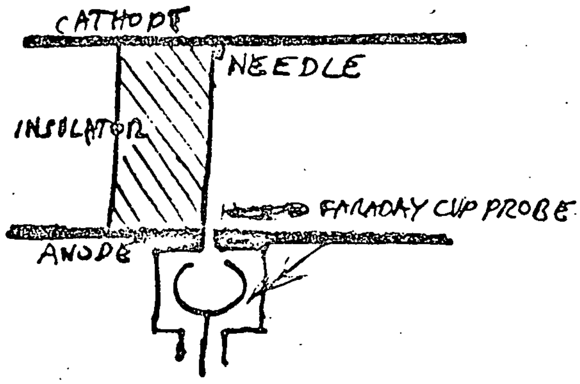

Fig. 2

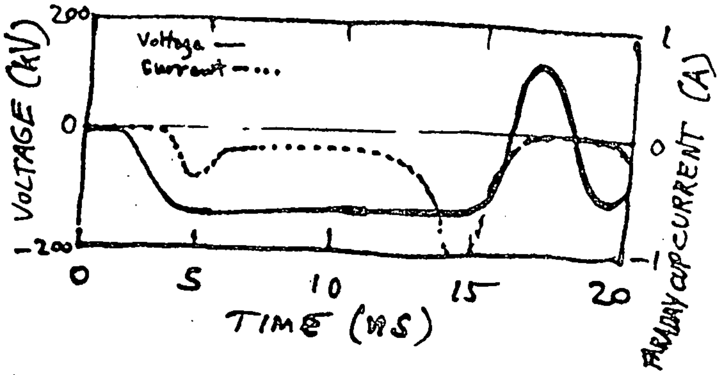

Fig. 3

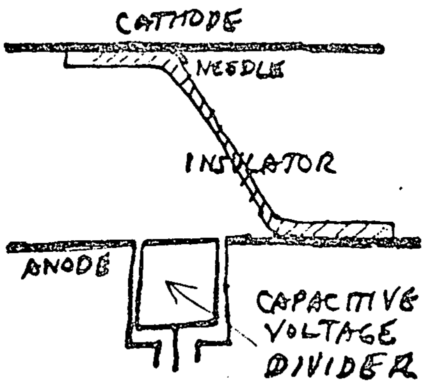

Fig. 4

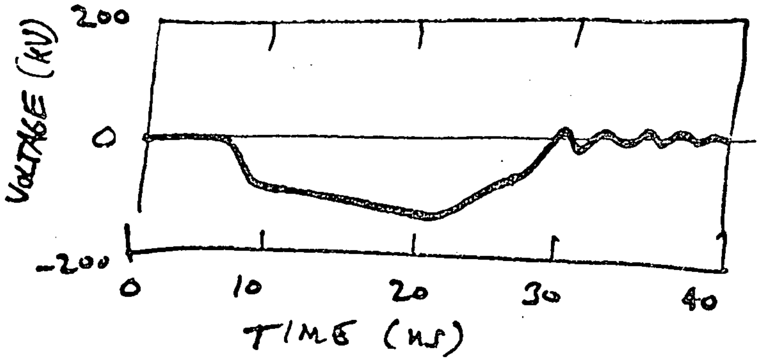

Fig. 5