AN EXPERIMENTAL INVESTIGATION OF ELECTRIC FLASHOVER ACROSS SOLID INSULATORS IN VACUUM

Final Contractors Report

NASA Grant NAG 1-332

March 1983 - February 1984

#1 Hans C. von Baeyer

Virginia Associated Research Campus
12070 Jefferson Avenue, Newport News, VA 23606

(NASA-CR-175379) AN EXPERIMENTAL INVESTIGATION OF ELECTRIC FLASHOVER ACROSS SOLID INSULATORS IN VACUUM Final Contractors Report, Mar. 1983 - Feb. 1984 (College of William and Mary, Newport News, G3/33

N84-17478

Unclas 18245

Virginia Associated Research Campus
12070 Jefferson Avenue
Newport News, VA 23606

An Experimental Investigation of Electric Flashover Across Solid Insulators in Vacuum

Final Contractor Report

NASA Grant NAG 1-332
March 1983 - February 1984

Hans C. von Baeyer, Principal Investigator
Hiromu Isa, Senior Research Physicist
Ja H. Lee, Consultant

Dr. Nelson W. Jalufka
The NASA Technical Officer
NASA Langley Research Center
Hampton, VA 23665

Table of Contents

I. Introduction

The insulation of high voltage conductors often employs solid insulators for many applications. In such applications, an unexpected electric flashover may occur along the insulator surface. Under conditions of high vacuum, the flashover voltage across the insulator is observed to be lower compared with that of the same electrode separation without an insulator. The reason for such an extreme reduction of flashover voltage is not well understood. Although several models, based on the secondary electron emission, have been proposed to explain the onset of the surface flashover, precise experimental and theorectical investigations of flashover phenomenon have not been carried out.

In this paper, we report on an investigation to determine the starting point and the developing velocity of the surface flashover. The study was carried out using an intensified image converter camera to observe the initial stage of electrical flashover along the insulator surface parallel to the electric field. We also used several different insulator materials as test pieces to determine the effect of the dielectric constant on the flashover voltage characteristics.

II. Experimental Arrangement

Fig. 1 shows a schematic diagram of the experimental arrangement. The test gap was placed in a bell jar, made of stainless steel, 17 inches in diameter and 28 inches in height. The bell jar was evacuated by an oil diffusion and mechanical pumping system. The lowest pressure of 6×10^{-5} Torr was obtained with the vacuum system. A negative high voltage pulse from a 6-stage Mini-Marx generator was applied to the test gap through a Teflon high voltage bushing mounted on a window of the bell jar to initiate a flashover. The flashover phenomena were observed by using an IMACON 600 image converter coupled with an EMI type C 141 image intesifier. The streak or framing photograph was recorded on Polaroid film. The entire camera system was placed inside of an aluminum shielding cabinet to reduce the noise pickup of the system. An oscilloscope, Tektronix type 7844, was used to observe the wave form of the high voltage pulse. The image converter was triggered by a signal from the Mini-Marx generator using a coaxial cable as a delay line for synchronization between the flashover and the image converter. Test pieces, made of Plexiglass, TiO_2 and $BaTiO_3$, were used. These materials were chosen for the large differences in their dielectric constants. The shape of the test piece was a right cylinder, 3 cm in diameter and 1 cm in length. Each test piece was cleaned in an ultrasonic cleaner with ethanol, and then rinsed with deionized water. The test piece and the electrode system is shown Fig. 2.

III. Experimental Results

(1) Flashover voltage characteristics

Fig. 3 shows an example of a series of flashover voltage measurements. After the first flashover occurs, the flashover voltage decreases rapidly as shown in the figure. The characteristic was consistently observed in our experiment. This result strongly contradicts those obtained by other researchers.[1,2] In this experiment, the contacts between the upper and lower surfaces of the test piece and electrode surfaces are very important. However, we did not control the contact precisely. For example, 2 of the 3 Plexiglass test pieces produced no flashover for applied voltages upto the maximum applied voltage of 102 kV (See Table 1.). Similar characteristics were also observed for the TiO_2 test pieces. Table 1 shows the highest, the lowest, and 50% flashover voltages measured. Where, 50% flashover voltage means the voltage at which 50% of the voltage applications produced flashover. In the case of Plexiglass test piece of No. 1, the first 30 shots were neglected from the data. As shown in the table, the flashover voltage decreases when the dielectric constant is large. However, the relation between these parameters is not inversely proportional. In the case of $BaTiO_3$, a partial dishcharge was frequently observed. It is thought that the extremely large dielectric constant produces a large electric field enhancement at the triple junction and a large field reduction at mid-gap simultaneously, causing such a partial discharge. Furthermore, for $BaTiO_3$, a large hysteresis phenomenon was observed during the measurement of flashover voltage. As a result, widely scattered flashover voltages were observed for $BaTiO_3$ as shown in Table 1.

Fig. 4 shows another example of a series of flashover voltage measurements. In this case, a straight line, parallel to the electric field, was drawn on the Plexiglass test piece using a pencil lead to stabilize the position of flashover on the test piece. This test piece also had a small scratch at the end of the cathode side superposing the pencil lead line to reduce the flashover voltage. As shown in Fig. 4, the flashover voltage increases with the repetition of flashover at first, then decreases in the same way as shown in Fig. 3. In the first phase, it can be thought that the flashover initiates at some weak points (dust particles, irregularity on the electrode surface, etc.). If the flashover occurs, these weak points disappear one by one, and the flashover voltage becomes high. In the second phase, some damage will occur at the triple junction by an extremely high temperature of flashover arc. This damage causes the reduction of the flashover voltage as shown in Fig. 3 and the second phase in Fig. 4.

(2) Streak photograph

At a point where the test piece touches the electrode, a conductor-dielectric-vacuum junction, called a "triple junction", is formed. At the point between the electrode and the test piece, the electric field becomes so high that electrons can be emitted from the cathode to the vacuum space by field emission. In a surface flashover in high vacuum, the microscopic structure of the triple junction can affect the flahsover characteristics. For example, in the case of Plexiglass test piece No. 1, the contact between the test piece and the electrode was not as good as that for No. 2 and No. 3 and consequently the flashover voltage was lower. Furthermore, as shown in Fig. 5, the bright spots appear at the end of both the anode and the cathode where a small clearance exists.

Fig. 6 is an example of a low speed (1.2 mm/ns) streak photograph taken under the same conditions as Fig. 5. From this photograph, it can be seen that the brightness along the flashover channel changes periodically. The periodic length in the figure is approximately 0.5 mm. Fig. 7 shows an example of a streak photograph taken at a higher speed (2.8 mm/ns) and a higher sensitivity than Fig. 6. In this photograph, it can be seen that two dark spaces appear at the initial stage of flashover at points 3 mm and 5 mm from the cathode. Those dark spaces really are not dark but are less bright than the adjacent part, and they become bright a few nanoseconds later. The position of these dark spots varies from shot to shot. Fig. 8 shows examples of streak photographs at various applied voltages, where the streak speed (15 mm/ns) is much faster than that of Fig. 6 and 7. From those photographs, it can be observed that two bright portions, which probably correspond to two cathode spots shown in Fig. 5, appear at the cathode and move toward mid-gap at a speed of approximately 3×10^6 m/s. These bright portions travel only 2 mm in the gap space. From Fig. 8, the speed and distance traveled of these bright portions are almost independent from the applied voltage. Except for these bright portions, the entire flashover channel is formed within 0.2 ns. This time it is almost the same as that in which a free electron travels from the cathode to the anode under the force of the applied electric field. We took many streak photographs at various pressures (4×10^{-5} ~ 4×10^{-3} Torr), but no large difference could be observed in these data.

IV Discussion

Various models have been proposed by many researchers to explain the mechanism of surface flashover in vacuum(3 ~ 5). All the models have considered the existence of electron emission from the triple junction. In our experiment, the flashover usually occured at a fixed position. And after several thousand shots the cylindrical surface of the Plexiglass text piece became very smooth compared with the original surface. It can be assumed that electrons came out from the triple junction and hit the entire surface.

The cathode and anode spots shown in Fig. 5 were formed because of a rather large clearance at the contact between the test piece and the electrode. This clearance was made by the flashover itself, i.e., the heat produced by the flashover melted and evaporated a small amount of the test piece material. To eliminate the formation of such cathode and anode spots, we replaced the test piece with a new one, the surface of which had a thin straight scratch to make the flashover path straight and parallel to the electric field. Table 2 shows the flashover voltage of the scratched test piece together with that of No. 1 Plexiglass test piece. Fig. 9 shows a still photograph and a streak photograph taken with this new test piece. These photographs show that no cathode and anode spots were formed when the contact between the test piece and the electrode is good. In this case, the flashover initiates at a point of 2.5 mm from the cathode and spreads toward both the cathode and the anode with a speed of approximately 10^7 m/s as shown if Fig. 9 (c). Futhermore, a fine periodic structure can be observed. If we assume that this periodic length corresponds to the step length of electron-hopping on the insulator surface, we obtain the value of 2×10^7 m/s for the average electron velocity under the condition of our experiment. This value is in good agreement with the expansion velocity of the bright portion in Fig. 9.

The fine peiodical structure along the flashover channel observed in our streak photographs is a direct result of the periodical irregularity formed on the test piece surface. In fact, we can observe such an irregularity along the flashover path on the test piece surface after the experiment. The periodical length for test piece No. 6 is approximately 0.5 mm, which is the same as those obtained in Fig. 6 and 9 (b). From these data, we can conclude that these periodical irregularity were formed by periodical electron bombardment on the insulator surface as proposed by Boersch et al.[6]

Fig. 10 shows an example of still photographs of the surface flashover in atmospheric air and in vacuum for the same test piece. The brightness of the flashover in atmospheric air is at least four times higher than that in vacuum. The diameter of the flashover channel in air is also larger than that in vacuum as shown in these photographs. Futhermore, in the case of vacuum flashover, a luminous plasma extends from both the cathode and the anode triple junctions to the vacuum space more than 5 cm from the test piece surface. These phenomena mean that there exist some mechanisms to confine the flashover channel in a narrow region. The Coulomb force between the electrons and the surface charge produced at the test piece surface by the secondary electron emission can be one of such mechanisms. The self-pinch effect of the flashover channel can probably be the other mechanism. In our experiment, we mainly applied the voltage of 81 kV. We also used a 6 KΩ resistor as a current limiter, so the peak current flown through the flashover channel was approximately 14 A. If we assume the diameter of flashover channel is 2 mm, and the current flows in the channel entirely, the force acting on the electron at the boundary of the channel is 9×10^{-13} N, were we assumed that the electron velocity is 2×10^{7} m/s. The distance at which the repulsive force between two electrons corresponds to 9×10^{-13} N is 1.5×10^{-7} m. These data mean that an electro-magnetic force produced by the flashover current is strong enough to confine the vacuum flashover current in a narrow channel as observed.

V Summary

In this research, we observed the characteriscics of the onset of surface flashover in a vacuum for three kinds of test pieces. We also observed the development of surface flashover with good time and space resolution by using an image converter camera. The results obtained may be summarized as follows:

(1) In many cases, the flashover voltage sharply decreases after the first flashover.

(2) The flashover voltage varies as a function of contact between the test piece and the electrode.

(3) The flashover voltage decreases when the dielectric constant of the test piece is increased.

(4) The shot-to-shot flashover voltage varies widely when the dielectric constant is large.

(5) The brightness of the flashover channel varies periodically along the channel. The periodic length is approximately 0.5 mm for our experiment.

(6) The cathode spot appears when a large clearance exists between the test piece and the cathode. On the streak photographs, the bright part initiates at the cathode and moves toward mid-gap at a speed of 10^7 m/s.

(7) The speed of the bright front is almost independent of pressure and applied voltage.

(8) If the clearance between the test piece and the electrode is small, the cathode spot does not appear.

(9) The flashover was drastically reduced and the flashover path restricted by scratching the surface of the test piece.

(10) The flashover initiates at a point about 3 mm from the cathode, and expands toward both the cathode and the anode with a speed of approximately 1.2×10^7 m/s.

(11) The calculated velocity of electron hopping on the surface is in good agreement with the expansion velocity of the bright portion.

(12) The surface flashover channel in a vacuum consists of a narrow channel on the surface and a widely diffused plasma in the vacuum space.

VI References

(1) J. P. Shannon, S. F. Philp, and J. G. Trump: J. Vac. Sci. Technol. vol. 2, 234 (1965).

(2) Y. Ohki, and K. Yahagi: J. Appl. Phys. vol. 46, 3695 (1975).

(3) T. S. Sudarshan, J. D. Cross, and K. D. Srivastava: IEEE Trans. Electr. Insul. vol. EI-12, No. 3, 200 (1977).

(4) K. D. Bergeron: J. Appl. Phys. vol. 48, 3073 (1977).

(5) R. A. Anderson, and J. P. Brainard: J. Appl. Phys. vol. 51, 1414 (1980).

(6) V. H. Boersch, H. Hamisch, and W. Ehrlich: Z. fur angewandte Phys, vol. 15, 518 (1963).

VII Inventory of residual equipment and property

No residual equipment or property has been acquired with grant funds having acquisition cost of over $1,000 for the entire grant period.

VIII Inventions

NONE

IX Publications

NONE

X List of Figures

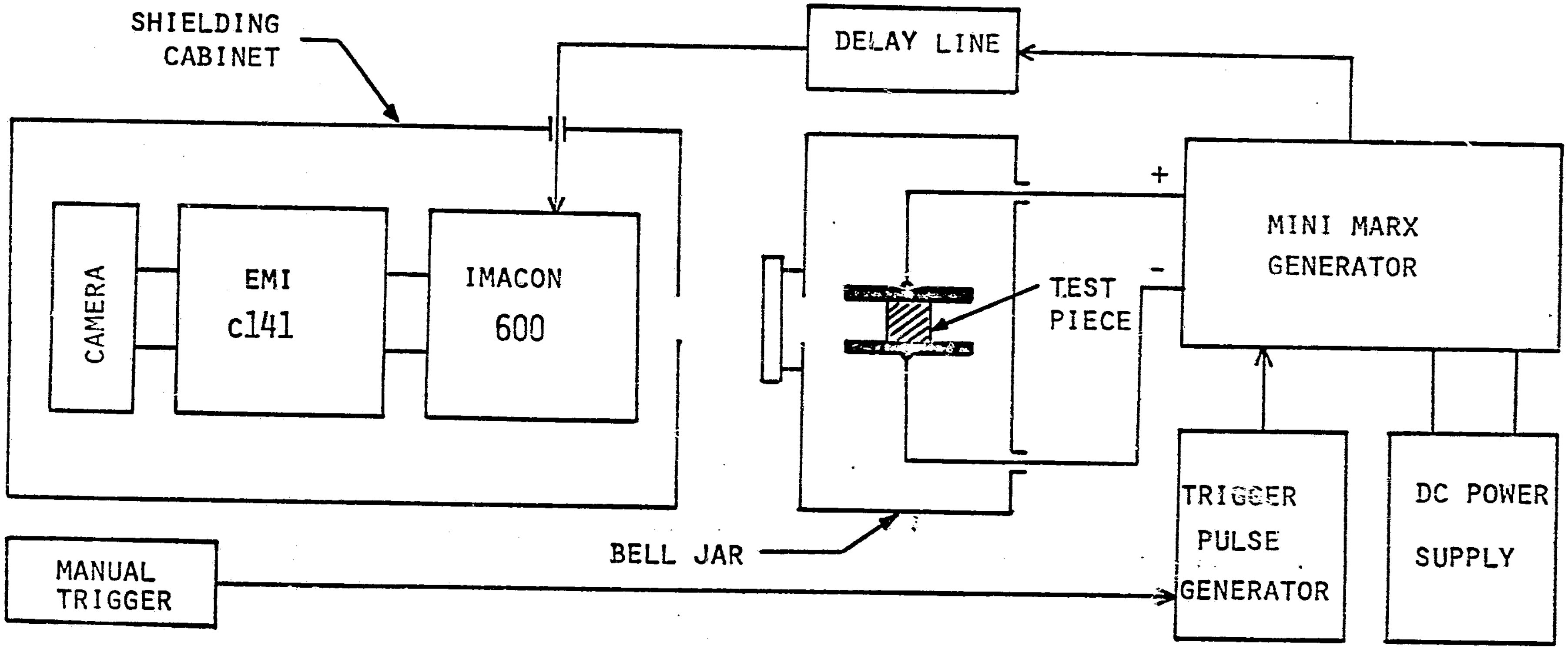


Fig. 1. Schematic diagram of experimental arrangement.

ORIGINAL PAGE IS
OF POOR QUALITY

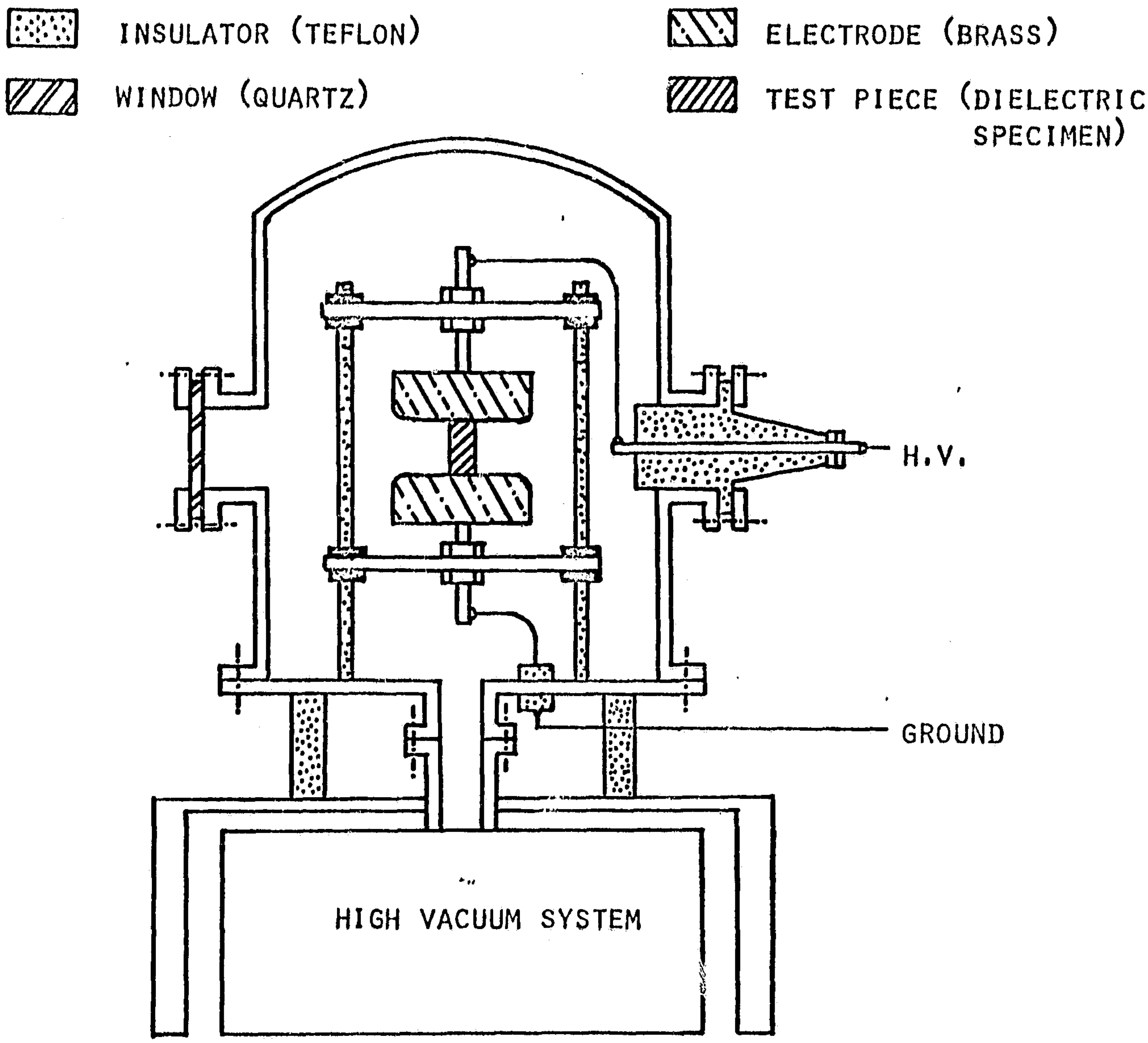


Fig. 2. Test piece and electrode system.

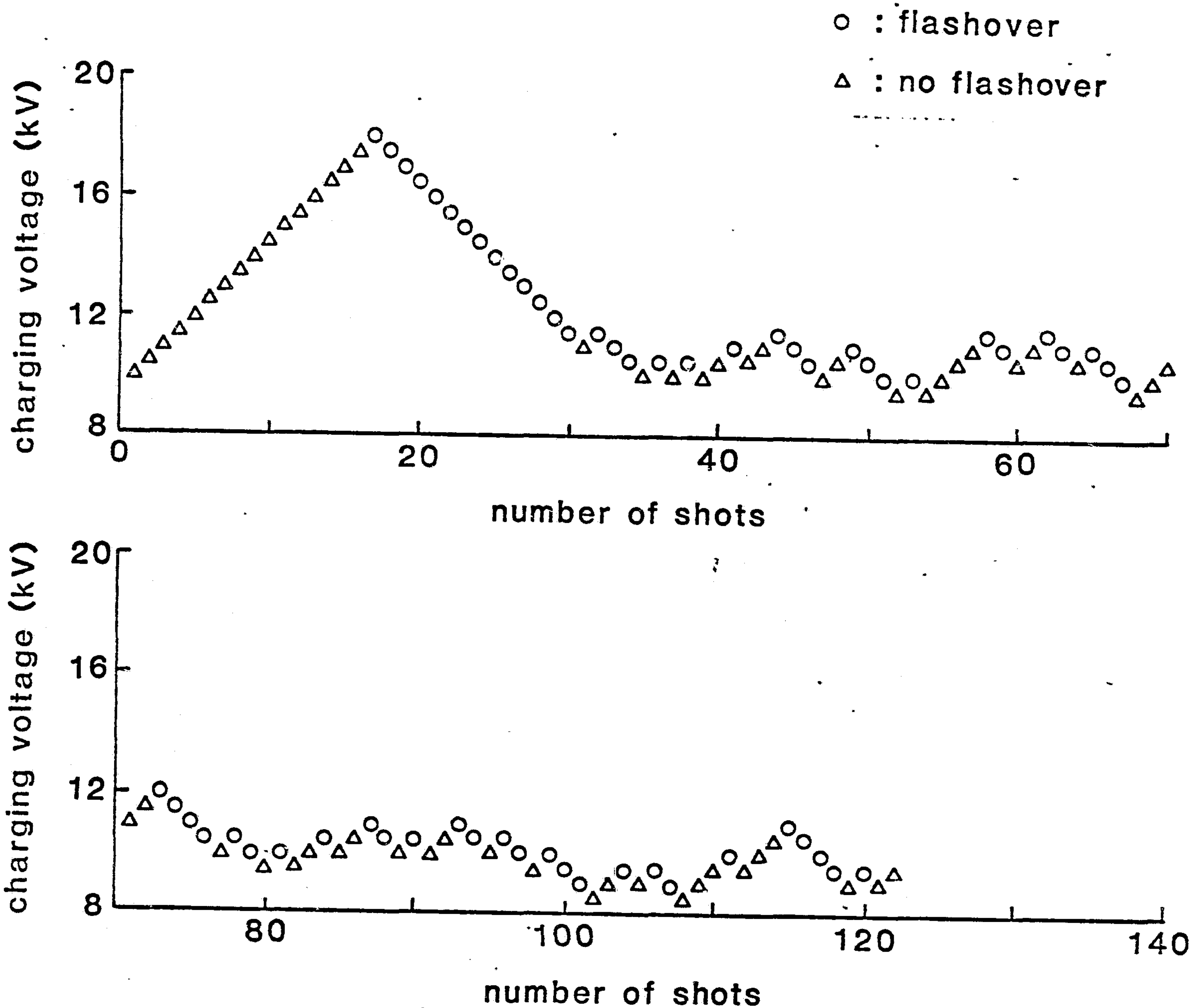


Fig. 3. Typical example of flashover voltage measurement for Plexiglass test piece.

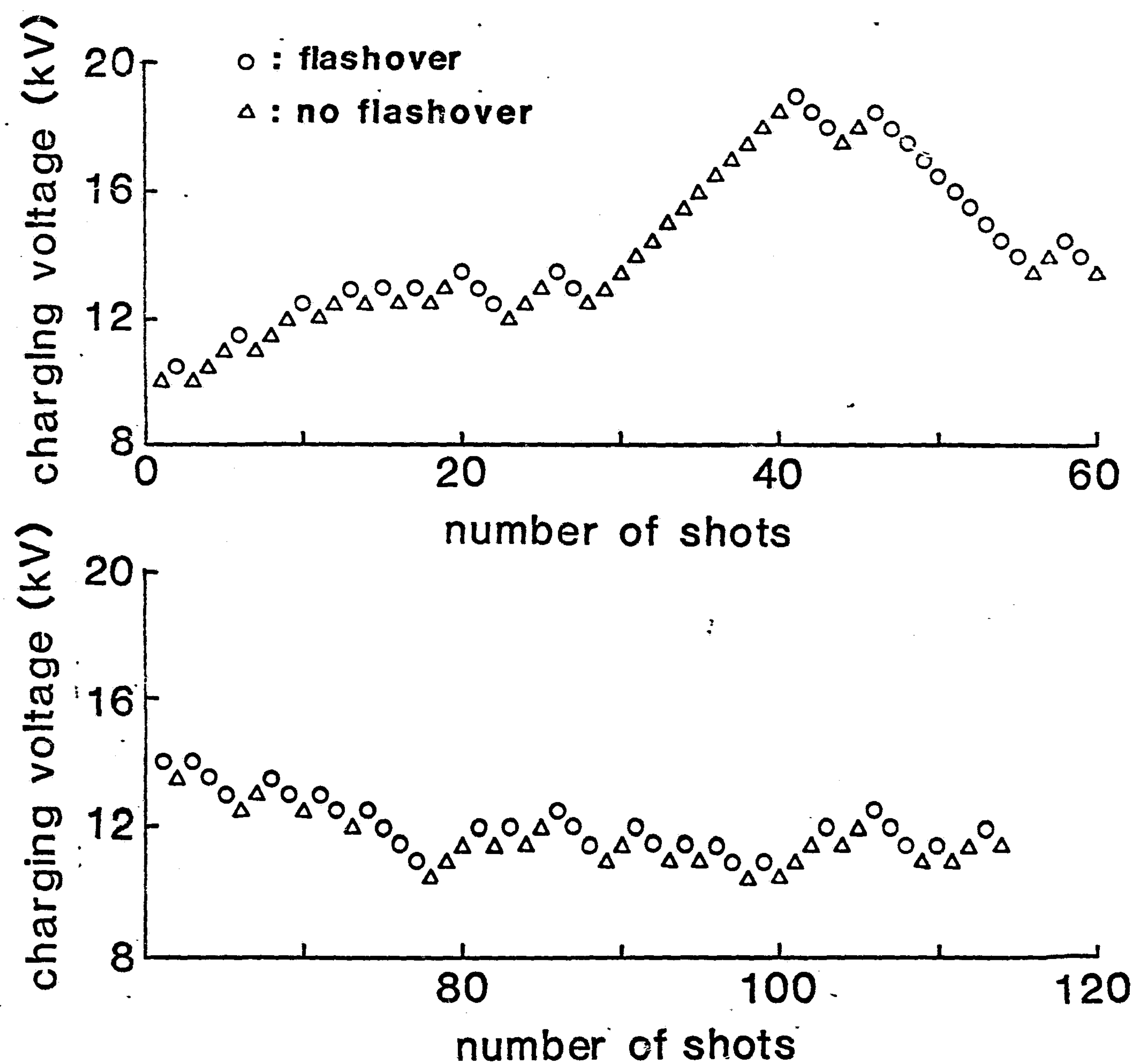


Fig. 4. Flashover voltage measurement for Plexiglass test piece which has a pencil mark on the surface.

ORIGINAL PAGE IS
OF POOR QUALITY

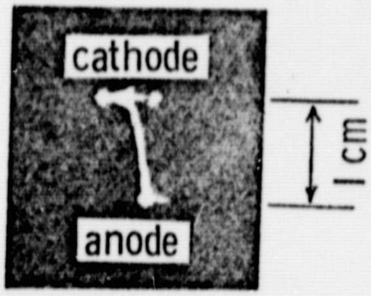


Fig. 5. Still photograph of surface flashover for Plexiglass test piece. V_a(applied voltage) =81 kV, P=9×10^{-5} Torr.

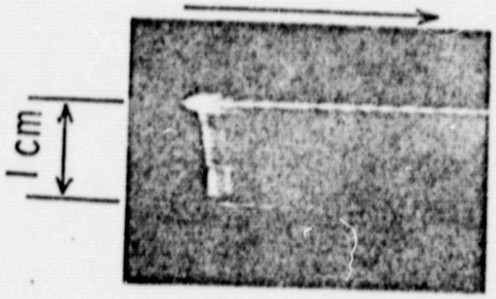


Fig. 6. Low speed streak photograph of 1 cm spark for Plexiglass. V_a=81 kV, P=4×10^{-5} Torr, streak speed=1.2 mm/ ns.

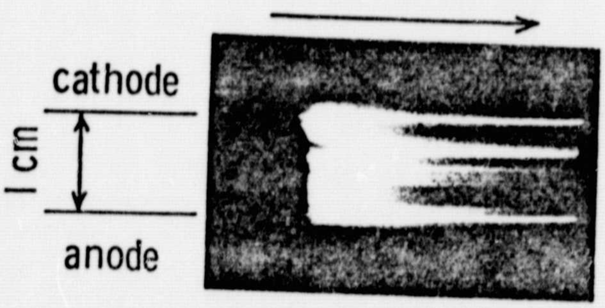
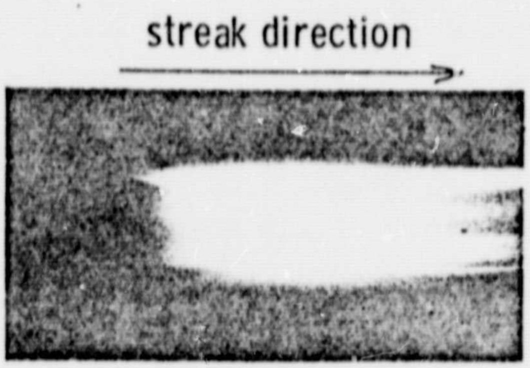
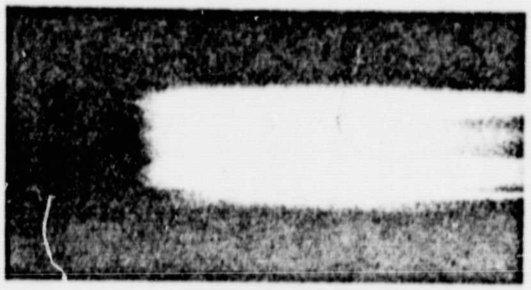


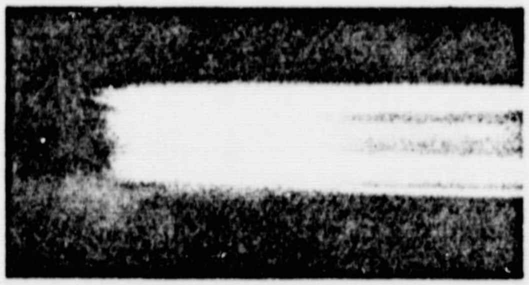
Fig. 7. Streak photograph of 1 cm spark for Plexiglass at higher streak speed than Fig. 6. V_a=81 kV, P≒10^{-4} Torr, streak speed=2.8mm/ ns.



(a) V_a=98 kV

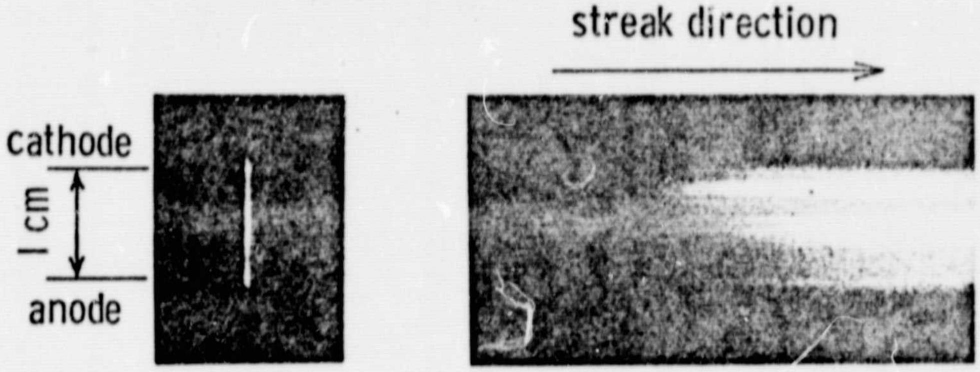


(b) V_a=81 kV



(c) V_a=65 kV

Fig. 8. High speed streak photogrph of l cm spark for Plexiglass at various applied voltage. $P=4\times10^{-5}$ Torr, streak speed= 15 mm/ ns.

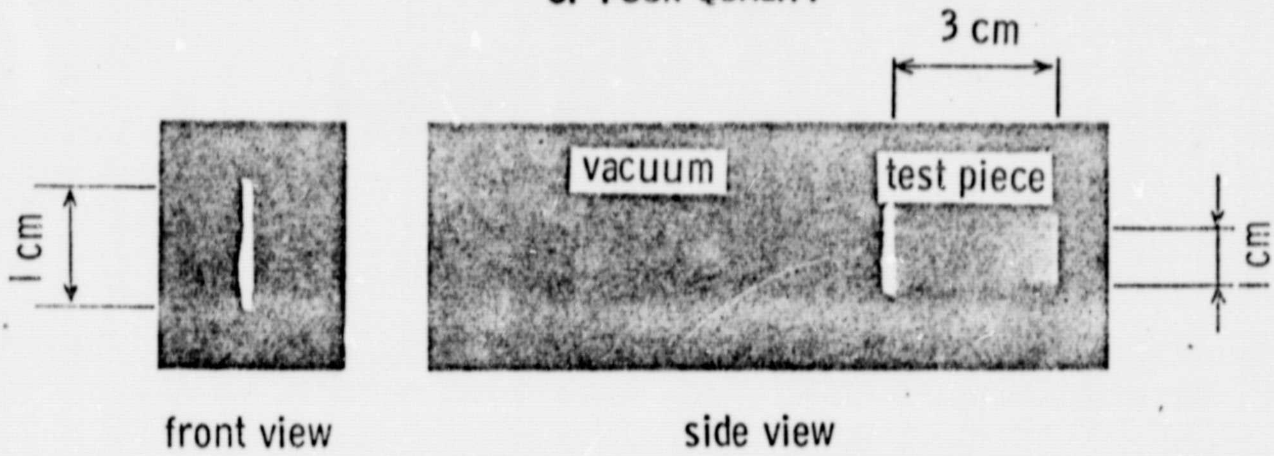


(a)
Still photogrph

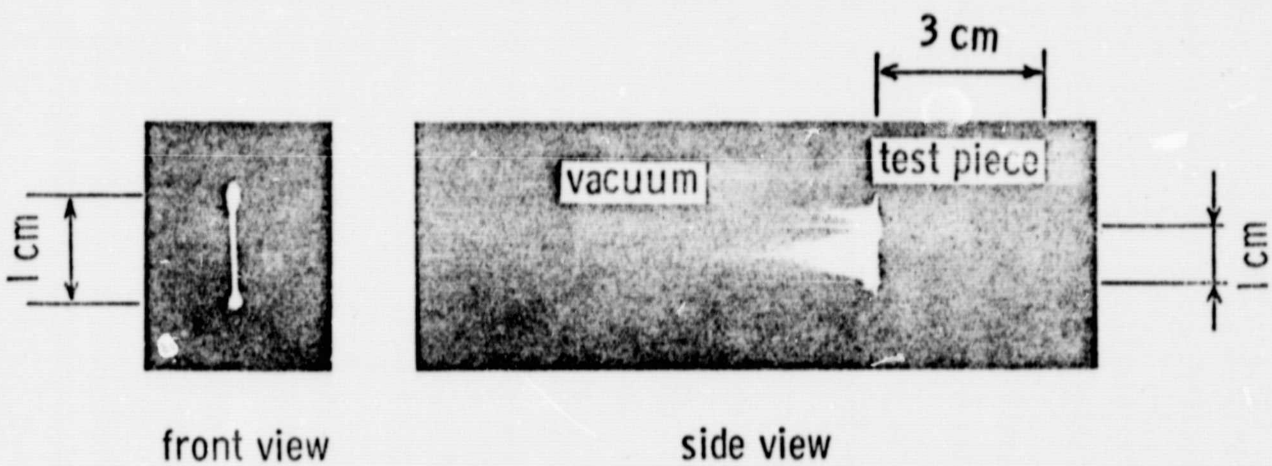
(b)
Streak photogrph

(c)
Sketch of streak photograph

Fig. 9. Still and ultra-high speed streak photogrphs of I cm spark for scratched Plexiglass test piece. $V_\alpha = 70$ kV, $P = 2\times10^{-4}$ Torr, streak speed = 27 mm/ ns.



(a) Flashover in 1 Atm. air. V_a = 56 kV.



(b) Flashover in vacuum. V_a = 70 kV.

Fig. 10. Comparison of still photographs of surface flashover in atmospheric air and in vacuum.

XI List of Tables

Table 1. Maximum, Minimum, and 50% flashover voltage observed for various test pieces. (unit: kV).

material No. of piece		plexiglass (ε ≈ 3.5)	TiO_2 (ε ≈ 80)	$BaTiO_3$ (ε ≈ 3000)
	Max	53.5	44.2	-----
1	V50	47.6	38.0	-----
	Min	39.6	34.9	2.7
	Max	> 102	11.6	14.2
2	V50	> 102	9.6	8.5
	Min	> 102	8.0	1.8
	Max	> 102	13.3	14.2
3	V50	> 102	10.3	9.6
	Min	> 102	8.9	6.2

Table 2. Comparison of flashover voltages between normal test piece and scratched test piece

	plexiglass (normal)	plexiglass (scratched)
first flashover	81.5 kV	65.2 kV
V50	47.6 kV	23.3 kV