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Breakdown Between Bare Electrodes with an Oil-Paper Interface

Edward F. Kelley and Robert E. Hebner, Jr.

Electrosystems Division
Center for Electronics and Electrical Engineering
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Summary

This report describes experimental measurements of the location of electrical breakdown in a composite insulating system. For these measurements, a paper sample was mounted so that it connected the two electrodes. Electrode structures ranging from plane-plane to sphere-sphere were used. The electrode-paper system was tested in oil in an attempt to determine the properties of an oil-paper interface.

The data indicated that in a carefully prepared system the breakdown will not necessarily occur at the interface. In addition, it was found that the breakdown voltages were not significantly lower for those breakdowns which occurred at the interface than for those which did not.

It was noted that if the paper interface was not dried or if many gaseous voids were left in or on the paper, the breakdown will regularly occur at the interface and at a lower voltage.

I. INTRODUCTION

The purpose of this work is to provide a more comprehensive and more fundamental understanding of prebreakdown phenomena at an oil-paper interface. Because of particular concern with power system apparatus, the investigation was limited to 60-Hz and impulse waveforms.

A significant feature of the experimental program was the use of photographic techniques to record the location of the breakdown event in a composite insulating system. Different electrode shapes were used to obtain a variety of field distributions.

The theoretical background for interfacial breakdown is reviewed in Section II of this report. Section III describes the experimental conditions used in this test and the results are presented in Section IV. Section V summarizes the conclusions which were drawn from this investigation.

II. THEORETICAL BACKGROUND

Much of the modern work on interfacial breakdown has been influenced by the results of Wechsler and Riccitiello.[1] Their work was apparently motivated by the revision of an American Society for Testing Materials standard test method for solid materials. This method, and their experiments, used tapered pins as electrodes (about 7.5 cm long, 2.5 cm centers, 2 cm/m taper). The pins were inserted through 0.3 cm thick solid samples and the test piece was immersed in an oil tank for measurements. It was found, under 60-Hz voltages, that the breakdown generally occurred in the liquid at or near the liquid-solid interface. The breakdown strength of the combination was as much as 50% lower than the breakdown strength of the oil alone.

To explain these results, they proposed that the breakdown was due to field enhancement in the fluid at the interface caused by surface irregularities on the solid. An idealized interfacial surface is shown in Fig. 1. The potential difference, V, is assumed to be given by the expression

$$V = E_s \cdot \sum_j z_{sj} + E_l \cdot \sum_j z_{lj} \quad , \tag{1}$$

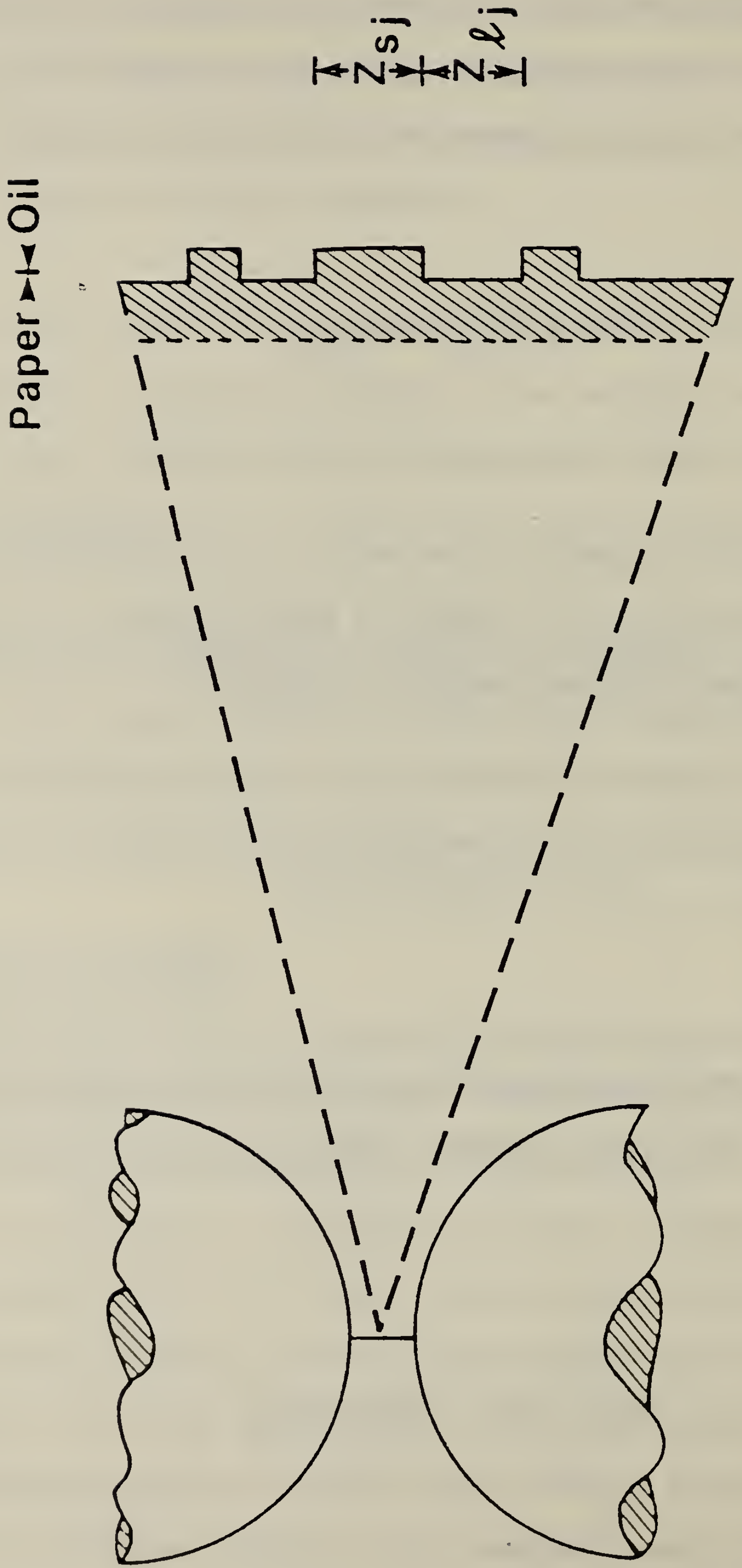
where E_s is the field strength in the solid, E_l is the electric field strength in the liquid, z_s is a length in the solid and z_l is a length in the liquid. Neglecting space charge and conduction

$$E_s = (\varepsilon_l/\varepsilon_s)E_l = \varepsilon_i E_l \quad , \tag{2}$$

where ε_l and ε_s are the permittivities of the liquid and solid, respectively. Combining Eqs. 1 and 2, the breakdown voltage, V_B, is related to the electric fields by

$$V_B = E_{lB} \cdot \Sigma z_l + E_{lB}(\varepsilon_i \cdot \Sigma z_s) \quad , \tag{3}$$

where, for convenience of notation, the summation indices are implied. If no solid were present, we note that



Paper
Oil
Z_{sj}
$Z_{\ell j}$

$$V_B' = E_{1B} \cdot d \quad , \tag{4}$$

where d is the spacing between the electrodes.

So the ratio of the breakdown strength of the composite system to breakdown strength of the fluid alone is given by

$$V_B/V_B' = (1 + \varepsilon_i) \cdot \Sigma z_s/d \quad . \tag{5}$$

An alternative explanation of interfacial breakdown has also been proposed.[2-4] This model attributes the reduction of breakdown voltage at the interface to electrohydrodynamic phenomena. The experimental results which motivated this explanation were Kerr effect measurements of the steady-state field distribution in the vicinity of a liquid-solid interface, current measurement in the vicinity of the interface, and fluid flow measurements.

Measurements of the steady-state electric field showed that the field near the interface differed by approximately 10% from the uniform field value. The authors concluded that these steady-state distributions offer little insight into the interfacial breakdown process.

The measured interfacial current density was significantly greater than the current density through the bulk of the fluid. Separate measurements were performed which suggested that the increase in current was due to electrohydrodynamic motion of the fluid. A subsequent re-examination of this work indicated that the magnitude of the interfacial current is strongly dependent on the geometry of the electrode structure.[5]

The fluid flow pattern was recorded using conventional flow visualization techniques. These measurements suggested that the fluid cavitation may contribute to a reduction of the breakdown in the vicinity of the interface.

The investigations summarized above indicate that, although insight has been gained, a comprehensive, coherent model of interfacial phenomena has yet to emerge. This report describes a consistent set of measurements which demonstrate the strengths and weaknesses of the present models. In addition, the significance of selected additional measurements is discussed.

III. EXPERIMENTAL CONDITIONS

The electrode-interface geometries under consideration are shown in Fig. 2. The transformer oil used was a commercial grade and was filtered to remove particle greater than 20 μm. The paper, typical of that used in transformers, was 0.062 mm thick. Care was taken to remove as much water as possible from the paper prior to its use in the tests. The paper was clamped by the split electrodes and held parallel to the field. The four electrodes were designed to be identical in all respects except, of course, for their differing radii of curvature. The four radii of curvature were chosen to be 1.6 mm, 3.2 mm, 6.4 mm and 12.7 mm. The entire electrode structure is 25.4 mm in diameter.

Tests were performed using both impulse and 60-Hz voltage waveforms. The 60-Hz tests were performed using the circuit shown in Fig. 3. A motor-

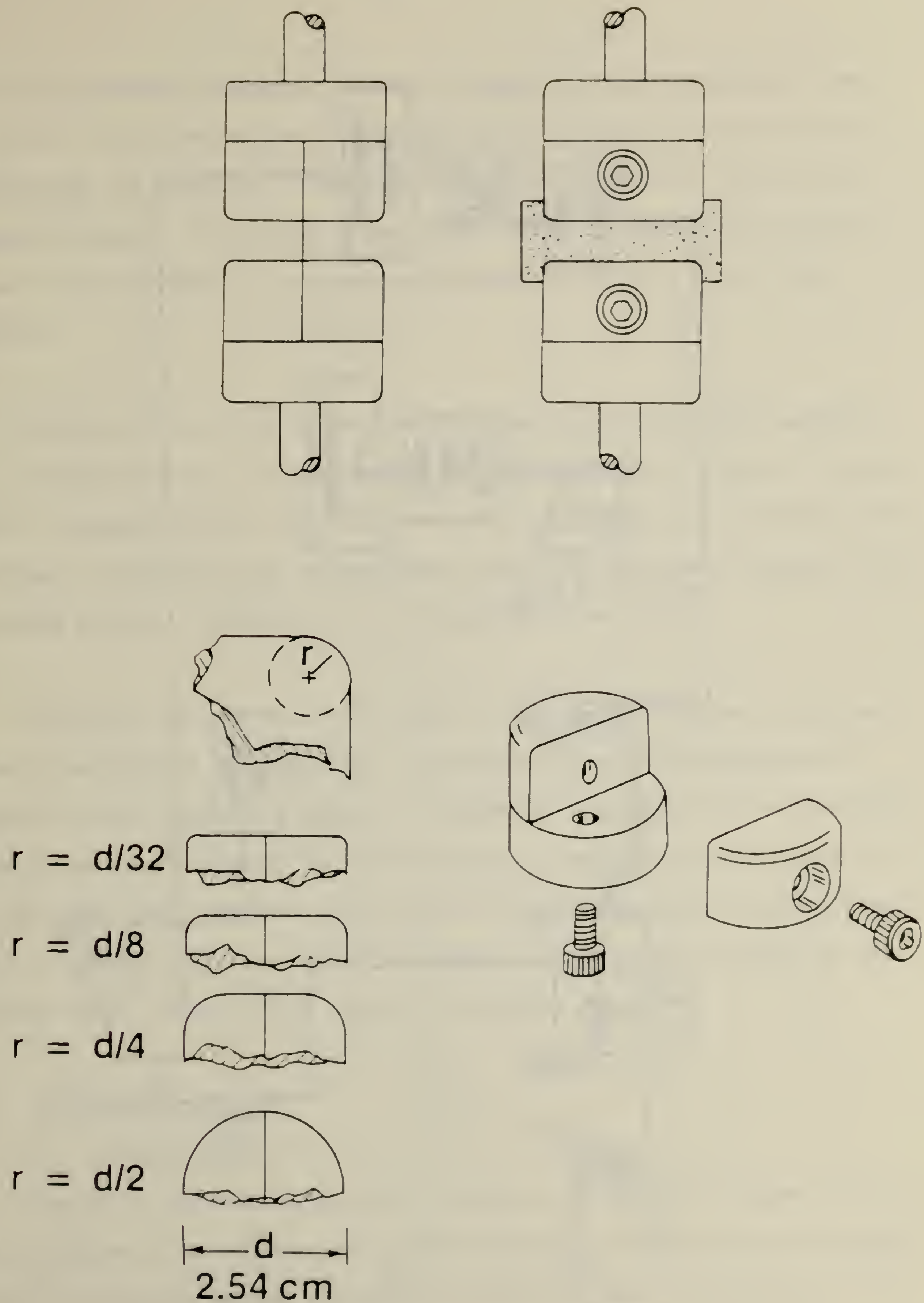


FIGURE 2. Split electrode geometry for mounting paper samples. The four different electrode sets are shown in approximate scale.

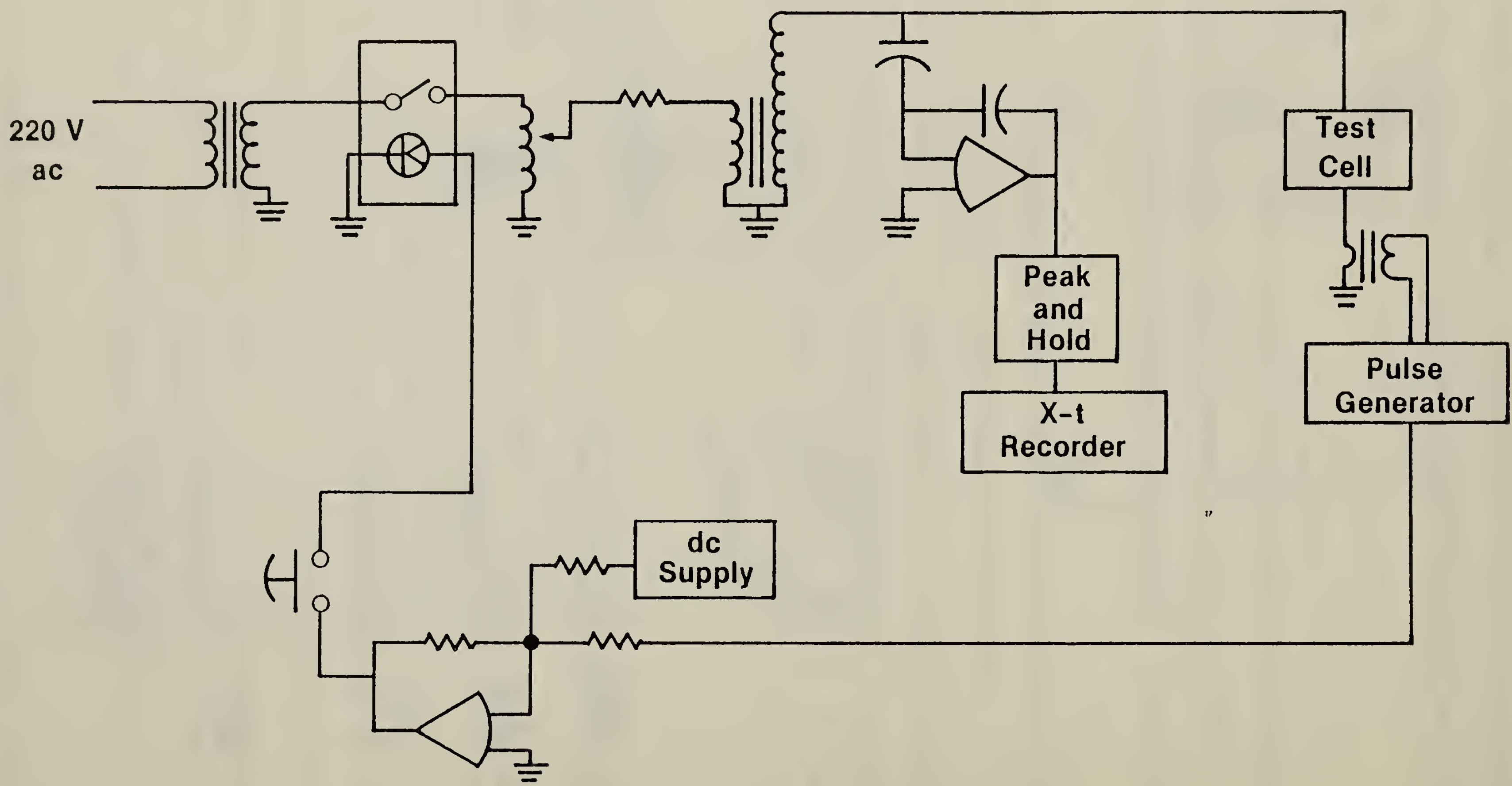


FIGURE 3. 60-Hz breakdown voltage.

controlled variable transformer is used to power a step-up transformer rated at 100 kV. The output voltage is measured using a capacitor divider having a compressed gas capacitor as the high impedance element and an active low-impedance element. The divider output is the input to a peak-detect-and-hold circuit which provides a dc voltage proportional to the peak of the input waveform.

The output from a pulse transformer is used to trigger a pulse generator when breakdown occurs. The output from the pulse generator, in turn, is used to open the power input to the circuit at the first current zero following the breakdown. By limiting the postbreakdown current in this manner, damage to the electrode surface is reduced, but in no way eliminated.

The impulse voltage circuit is shown in Fig. 4. The impulse is obtained using a conventional Marx generator. The external load on the generator is chosen to insure that the waveshape is relatively independent of the electrode geometry or the fluid under test. The voltage is measured using a resistive divider which has a response time of about 20 ns.[6] The typical applied pulse shape is shown in Fig. 5. This pulse shape is approximately the same as that used by Taylor[7] in an earlier study of interfacial breakdown.

IV. EXPERIMENTAL RESULTS

IV-1 Introduction

Results are reported using all of the electrode geometries shown in Fig. 2. Most of the work concentrated on the two electrode structures having the larger radii of curvature, because they were the most technically significant.

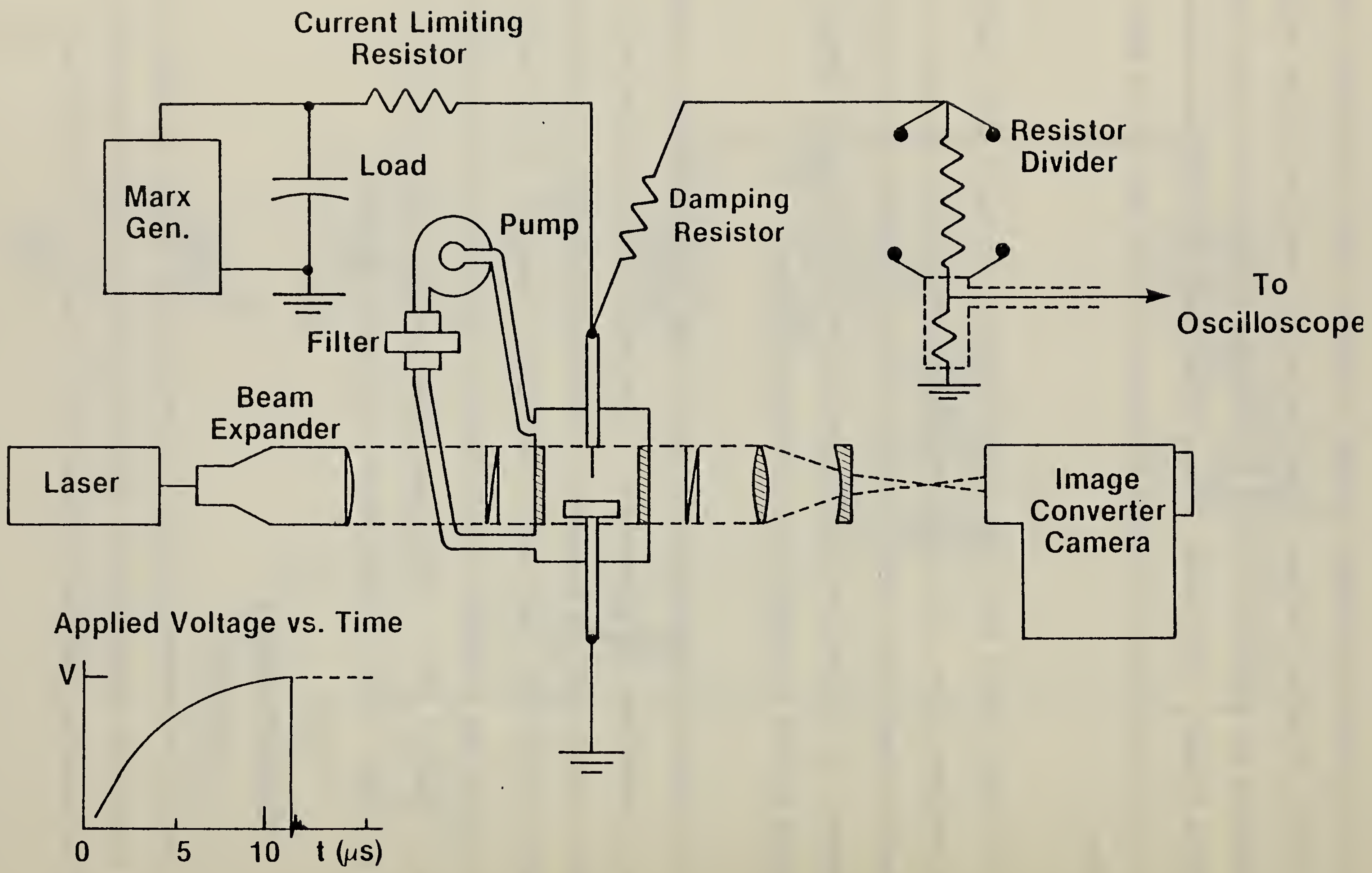


FIGURE 4. Impulse circuit.

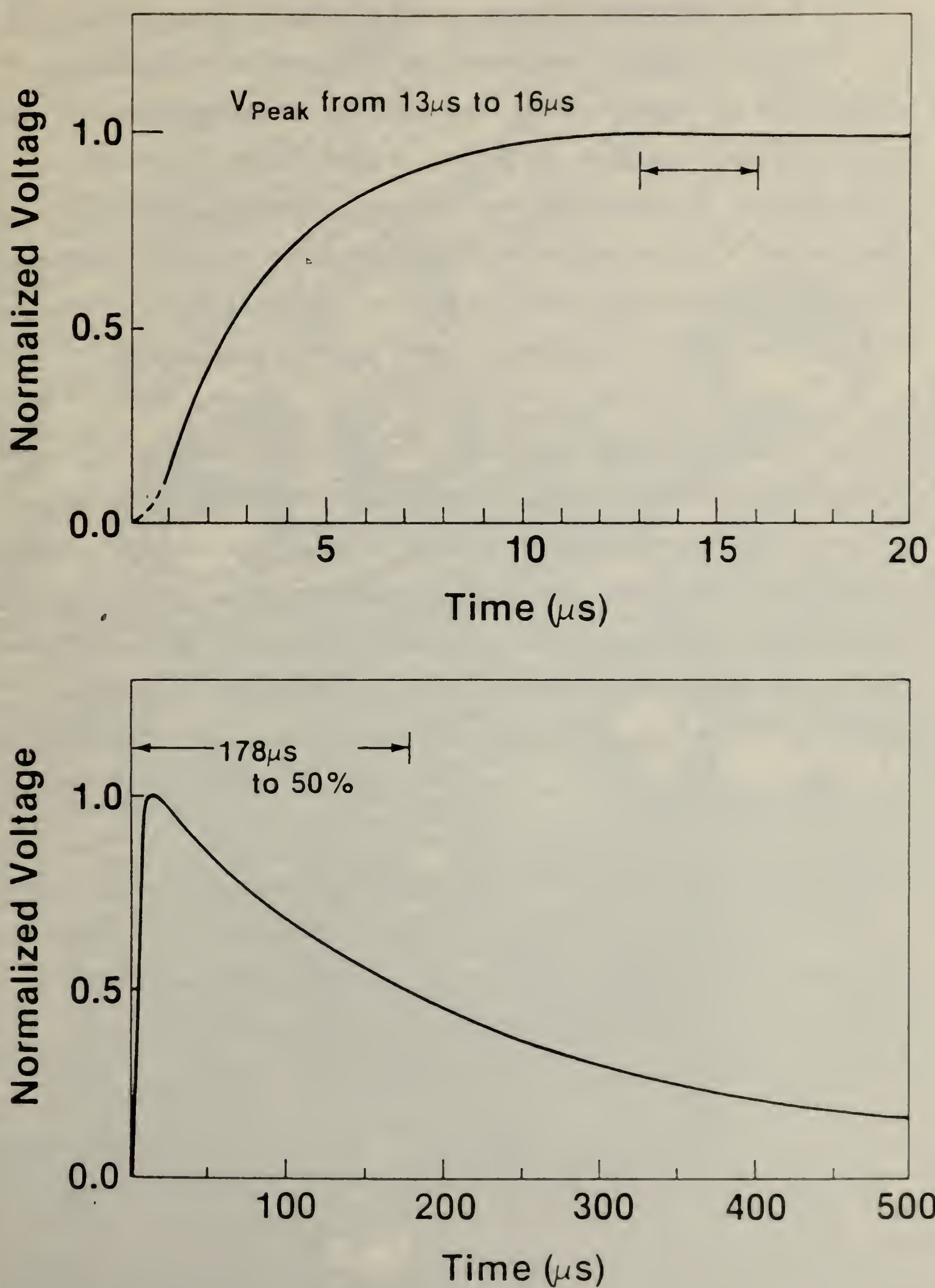


FIGURE 5. Applied pulse shape for impulse studies.

IV-2 Results Using Electrodes Having a Radius of Curvature of 1.6 mm

A preliminary set of measurements was made without an interface, to characterize the behavior of the oil alone. For twenty breakdowns the mean field strength at breakdown was 310 kV. A least-squares linear fit indicated that, on the average, the breakdown strength increased by approximately 0.4% per shot. This result repeated in a number of data runs and is qualitatively consistent with previously published data.[8] This increase in breakdown strength is presumably due to electrode conditioning.

In this specific experiment, one effect of conditioning was to roughen the electrode surface. Figure 6 is a photograph of the electrode surface after a number of breakdowns has occurred. Although the effect of the breakdown is to create pronounced asperities, the breakdown voltage increased as the number of breakdowns increased. Because the conditioning was a small effect, and because the details of the process were probably specific to this particular set of experimental conditions, no further study of the effect was attempted.

Results both with, and without, an interface indicated that the breakdown occurred preferentially near the edges of the electrodes for this radius of curvature. It was assumed that there was sufficient field enhancement in the vicinity of the electrode edges to dominate any interfacial effect. No further studies, therefore, were performed using this electrode system.

IV-3 Results Using Electrodes Having a Radius of Curvature of 3.2 mm

In contrast to the data taken with the electrodes having a smaller radius of curvature, there was no tendency for the breakdown sites to be concentrated near the electrode edges. The photograph of the electrode surface after a

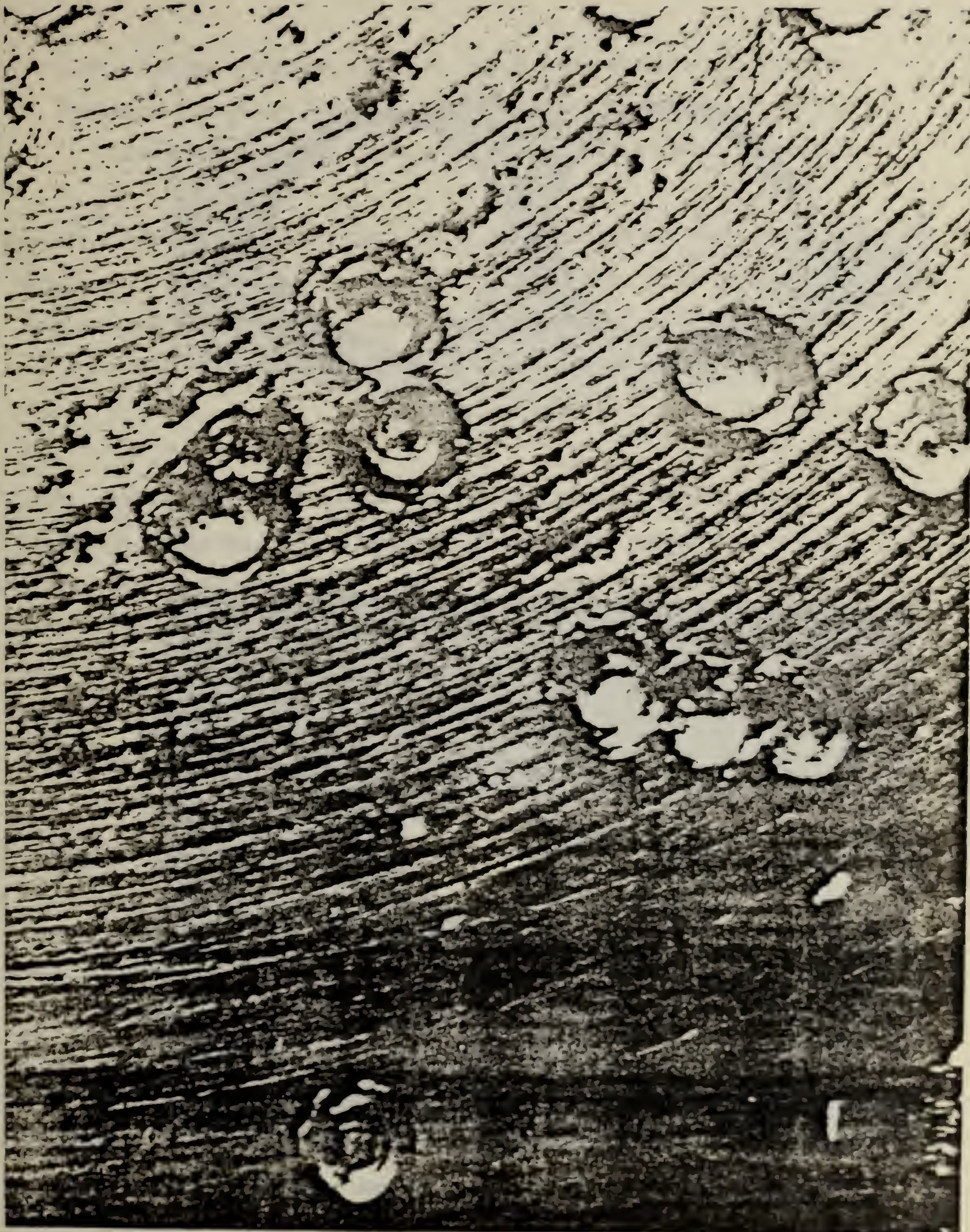


FIGURE 6. The electrode surface, after a number of breakdowns, exhibits many asperities.

series of breakdowns is shown in Fig. 7a. This photograph shows the relatively uniform distribution of discharge sites. A typical record of a breakdown location is shown in Fig. 7b. The paper sample joins the electrodes.

From these photographs it can be seen that there is no dominant preference for breakdown at the interface. To isolate interfacial effects, it was judged to be most efficient to concentrate the investigation on electrodes with even larger radii of curvature -- electrode systems in which the highest field strength is in the vicinity of the interface.

Two additional observations were made using the 3.2 mm electrodes. First, the average breakdown field strength increased by about 20% as the radius of curvature was increased from 1.6 to 3.2 mm. This observation is consistent with the assumption that the data taken using the 1.6 mm electrodes were influenced by field enhancement at the electrode edges. Second, even though the oil was circulated and filtered, the test geometry resulted in hydrodynamically "dead" spots in the vicinity of the interface. After repeated breakdowns using the same interface, particulate contamination accumulated in the interfacial region.

IV-4 Results Using Electrodes Having a Radius of Curvature of 6.4 mm

Data taken under impulse conditions are shown in Fig. 8. In this figure, three separate regions are indicated. These regions denote different methods of handling the interface. The interfaces for regions A and B had been vacuum baked several weeks prior to their use and were kept in a closed bottle. Because they had not been stored under vacuum and because they were handled in air, there is a good chance that they were contaminated by water before use.

(a)

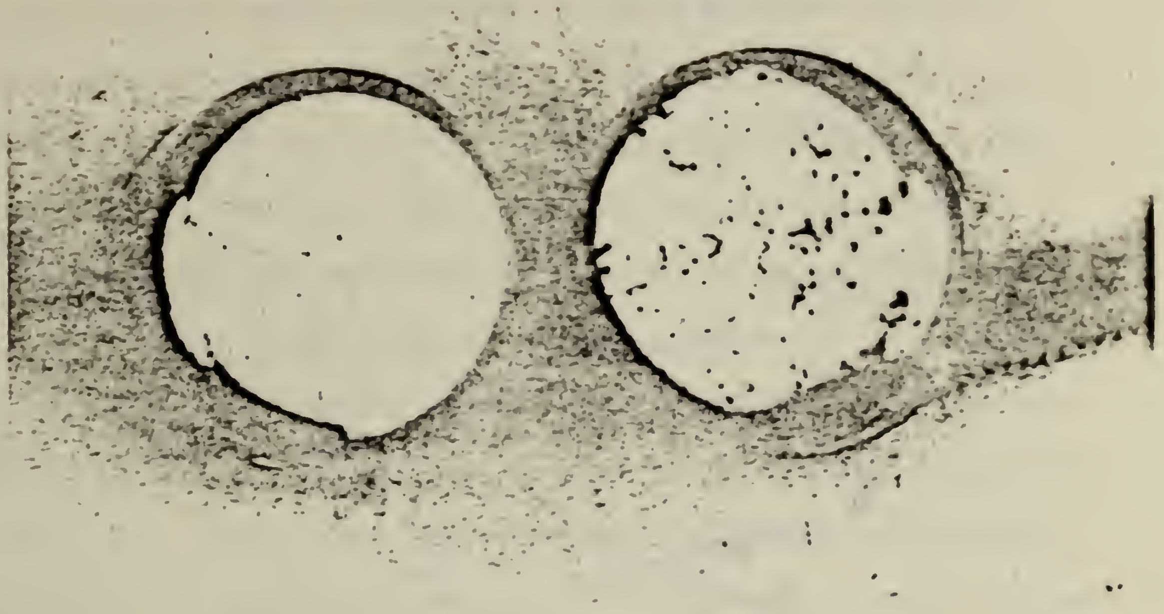


FIGURE 7a. Facing electrode surfaces after a series of breakdowns.

(b)

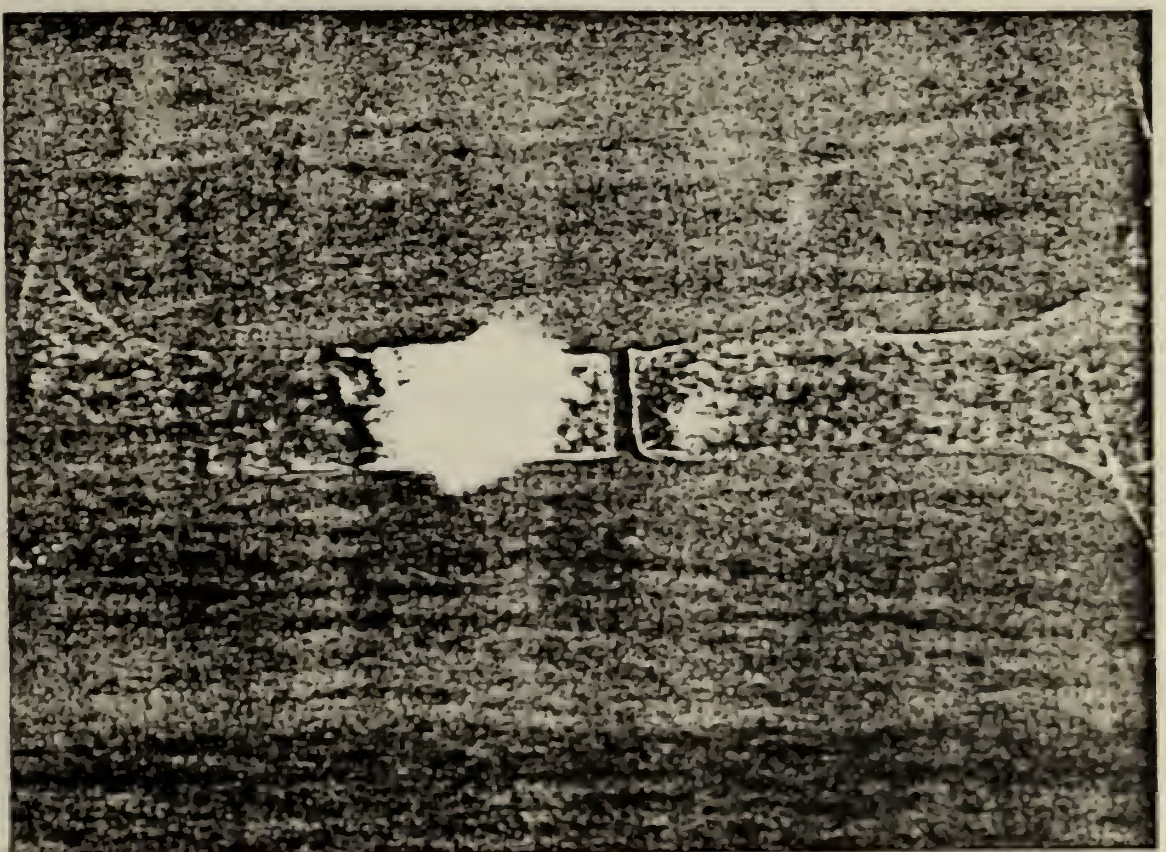


FIGURE 7b. Typical breakdown photograph. The grounded electrode is at the bottom of the photograph; the high voltage electrode is at the top. The paper sample connects the electrodes.

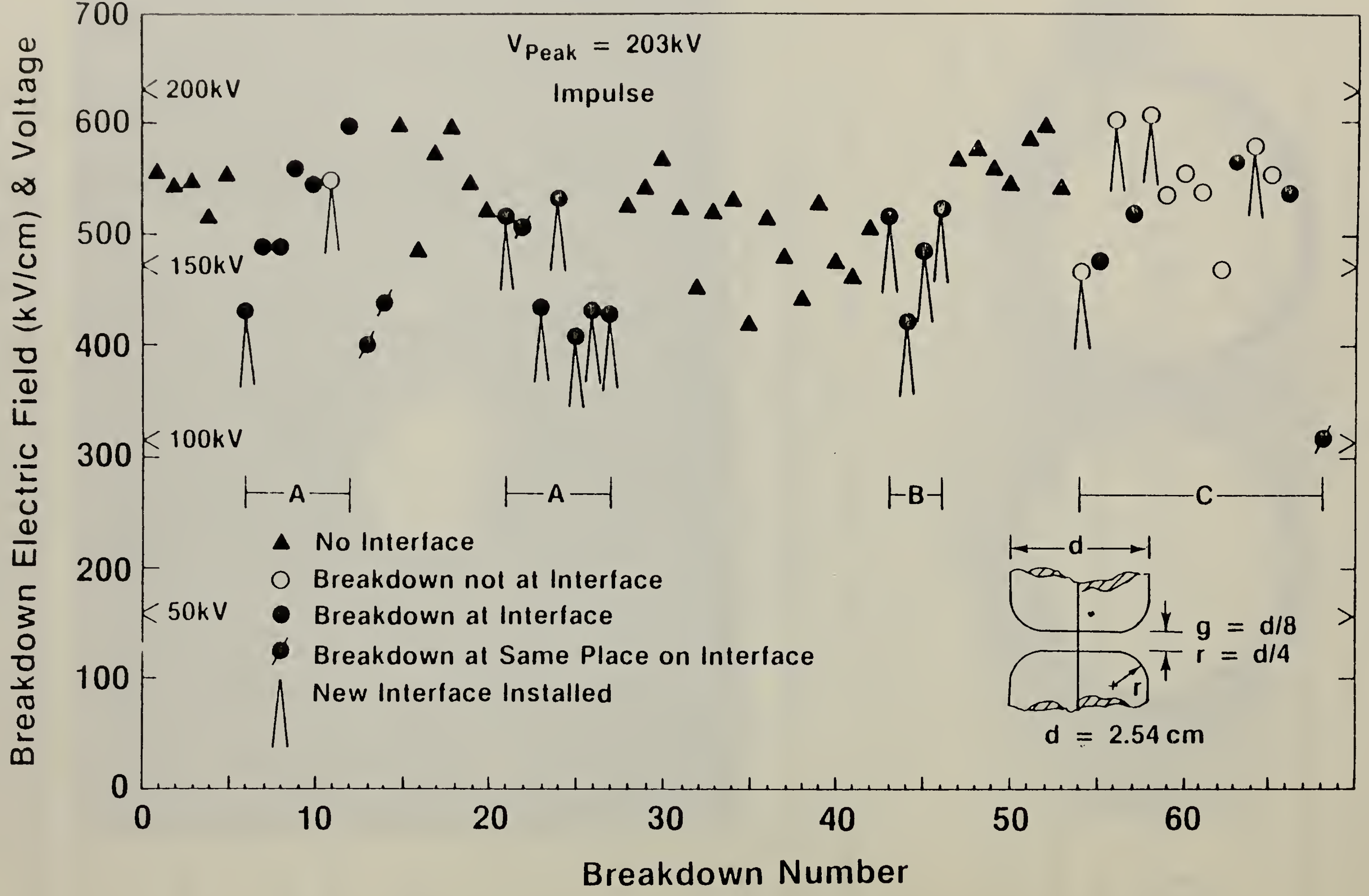


FIGURE 8. Breakdowns with and without an interface in a uniform field. Three regions are noted to indicate that the paper samples are not handled in the same manner. See text for details. These data are summarized in Table 1.

The papers used in region C were vacuum baked and were kept under vacuum to assure all water removal; they contacted air only as they were loaded into the cell. The method of loading the cell with liquid was also different in each region. In region A the liquid was pumped into the cell at atmospheric pressure. In region B the cell was evacuated and the liquid was pumped in under vacuum. Under these conditions, the outgassing of the oil produced many small bubbles which were difficult to remove from the interface. In region C the paper was coated with oil before being mounted in the cell. The paper was outgassed in the cell. The cell was then repressurized with dry nitrogen and the oil was pumped in at atmospheric pressure. The last process, when combined with careful drying of the paper, produced interfaces which were resistant to breakdown. These procedures were intended to simulate the methods used in the manufacture of power system apparatus.

A summary of the data presented in Fig. 8 is shown in Table 1. It should be emphasized that in this work, the differences among the average values is of the same order as the spread in readings under any one condition. It is difficult, therefore, to use these data to support the hypothesis that there is a significant difference between the breakdown strengths with and without an interface. This is particularly true if the data obtained using contaminated paper samples are eliminated. Although these data apparently contradict those presented by Wechsler and Riccitiello[1] they are consistent with the more recent experimental work by Taylor.[7] Taylor's data are summarized in Table 2. In an attempt to summarize the influence of the interface, Taylor calculated the "spacer efficiency" which was defined as the ratio of the breakdown strength of the solid/liquid combination to the breakdown strength of the liquid alone.

TABLE 1: SUMMARY OF DATA IN UNIFORM FIELD BREAKDOWN

EXPERIMENTAL CONDITIONS	BREAKDOWN FIELD (kV/cm)	BREAKDOWN VOLTAGE (kV)	EFFICIENCY
No interface, oil alone	529 ± 47	168 ± 15	--
Interface in place but breakdown not at interface	554 ± 50	176 ± 16	--
Breakdown at interface (all data)	482 ± 63	152 ± 20	0.91 ± 0.16
Breakdown at interface (exclude repeat breakdowns at same location)	494 ± 54	157 ± 17	0.93 ± 0.14
Breakdown at interface (exclude both repeated breakdowns and possible contaminated samples)	526 ± 38	167 ± 12	0.99 ± 0.11

Notes:
1. Uncertainties listed are one standard deviation.
2. The efficiency is the ratio of the breakdown voltage at the interface to the breakdown voltage with no interface in the system.

TABLE 2: SUMMARY OF INTERFACIAL BREAKDOWN RESULTS REPORTED BY TAYLOR

EXPERIMENTAL CONDITIONS	FIELD STRENGTH (kV/cm)	EFFICIENCY
No interface, oil alone	480 ± 39	--
Oil-polycarbonate interface	454 ± 44	0.95 ± 0.13
Oil-pressboard interface	401 ± 57	0.84 ± 0.16
Oil-polyphenylene oxide interface	463 ± 33	0.96 ± 0.11

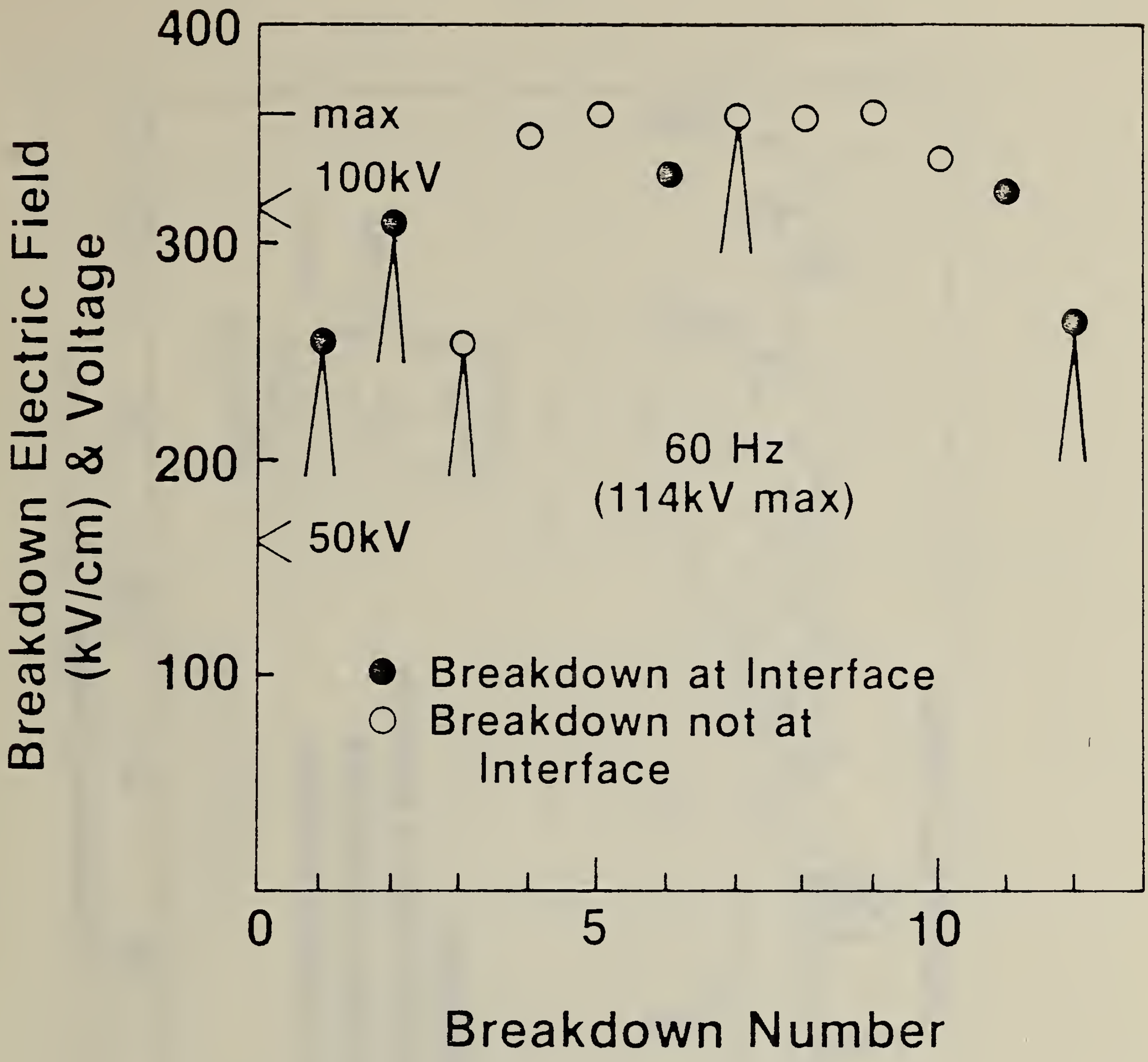
Notes:
1. The uncertainties listed are one standard deviation.
2. The efficiency is the ratio of breakdown field strength at the interface to the breakdown field strength with no interface in the system.

Equation 5, which is based on the model of Wechsler and Riccitiello[1], relates the efficiency to the properties of the liquid and the solid. In Tables 1 and 2, the efficiencies are calculated along with their uncertainties. The uncertainty is taken as the square root of the sum of the squares of the two quantities which are divided to calculate the efficiency.

Using the same electrode system, data were also taken using 60-Hz voltage waveforms, Fig. 9. The 60-Hz voltage supplied to the interfacial system increases approximately linearly with time at a rate of 3.6 kV/s up to a maximum of about 116 kV. On several occasions the system withstood the full voltage for a few seconds before the breakdown occurred. In addition, because of a problem with the vacuum system, it is possible that a few of the interfaces were contaminated by water. As was the case with impulse voltages, however, the data indicate no obvious enhancement of the breakdown probability in the vicinity of the interface. Moreover, except for the first two and the last data points, for which water contamination is suspected, repeated breakdowns were required before the breakdown occurred in the vicinity of the interface.

IV-5 <u>Results Using Electrodes Having a Radius of Curvature of 12.7 mm</u>

In an attempt to drive the breakdown to the interface, a split sphere-sphere electrode geometry was employed. In such a system the maximum field strength occurs at the interface. Because of practical difficulties in assembling the electrode structure with the paper sample in place, a misalignment of the electrode halves was frequently observed. This misalignment was generally less than 2% of the gap spacing. It was assumed that this misalignment would increase the probability of breakdown at the interface because of field enhancement. The data, however, indicate the results were largely insensitive to this parameter. The data are shown in Fig. 10 and are summarized in Table 3.



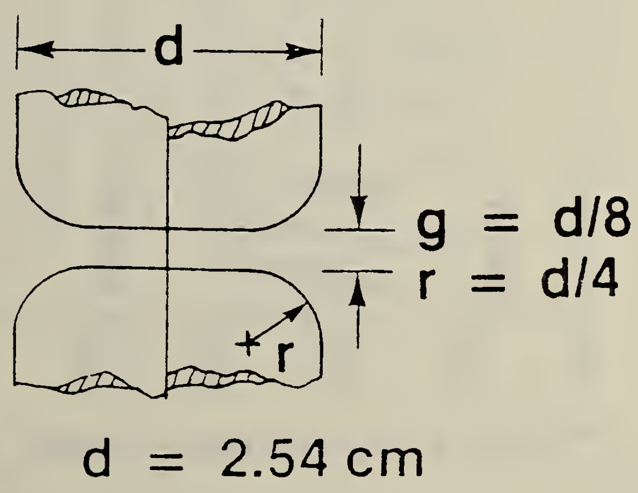


FIGURE 9. Breakdowns at, and away from, the interface for 60 Hz stress with uniform field.

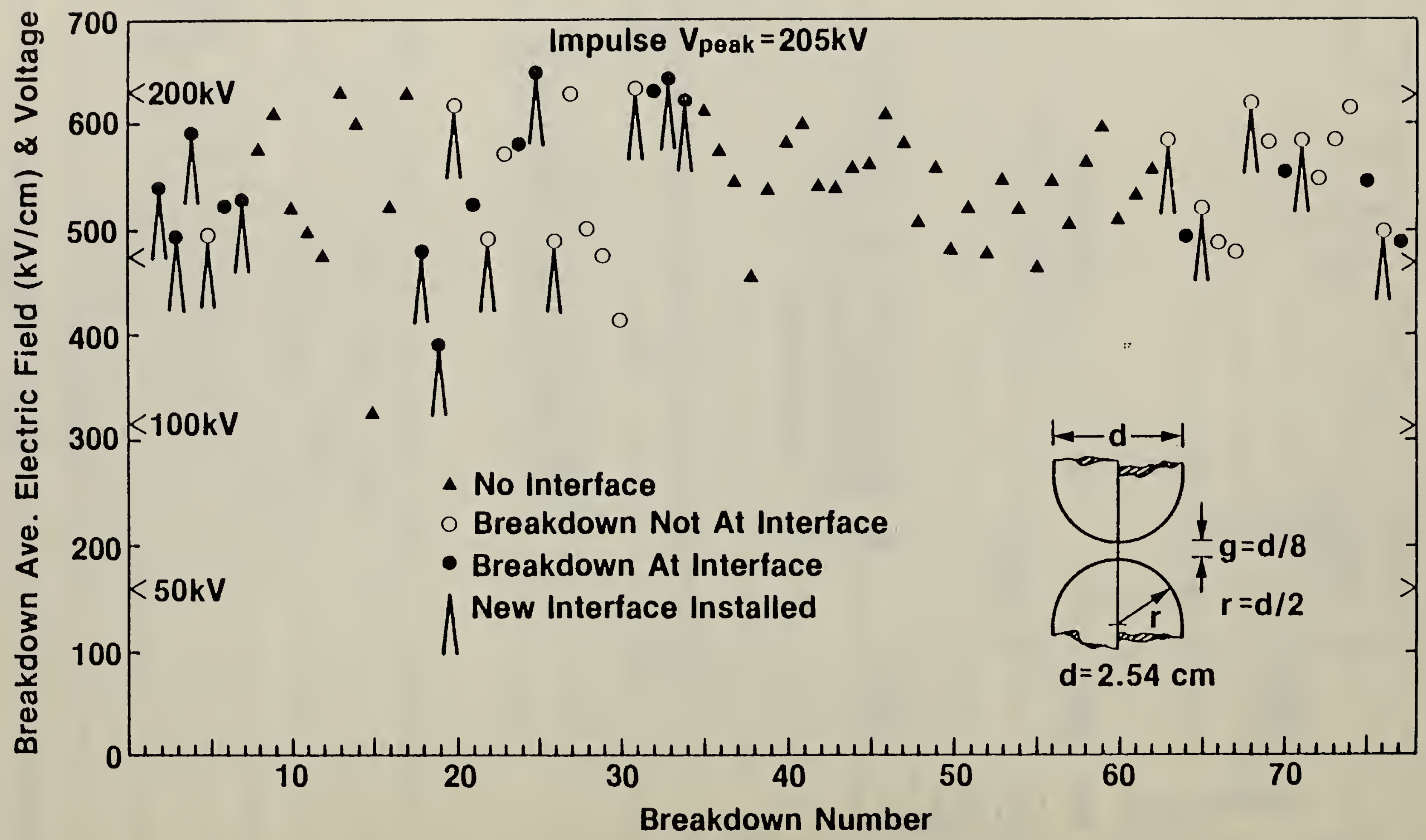


FIGURE 10. Breakdowns with and without interfaces for sphere-sphere electrode geometry using carefully prepared, dry interfaces. Peak voltage value is 205 kV. These data are summarized in Table 3.

TABLE 3: SUMMARY OF IMPULSE BREAKDOWN DATA FOR SPHERE-SPHERE ELECTRODES

EXPERIMENTAL CONDITIONS	BREAKDOWN VOLTAGE kV	EFFICIENCY
No interface, oil alone	173 ± 19	--
Interface in place but breakdown not at interface	172 ± 20	--
Breakdown at interface (all data)	170 ± 26	0.98 ± 0.19
Breakdown at interface (virgin system)	173 ± 27	1.00 ± 0.19

Notes: 1. Uncertainties listed are one standard deviation.

2. The efficiency is the ratio of the breakdown voltage at the interface to the breakdown voltage with no interface in the system.

There is also selective data analysis in Table 3. Those values for breakdown at the interface in which the breakdown occurred the first time that voltage was applied were averaged separately. The motivation for this was concern that breakdowns away from the interface would deposit particulate debris on or near the interface. As can be seen in Table 3, the breakdown voltage was slightly higher for interfacial breakdowns on virgin systems than for non-virgin systems. The difference, however, was too small to be considered significant with the limited amount of data that were taken. The 60-Hz breakdown data are summarized in Fig. 11. The first breakdown (without an interface) was anomalously low. It was assumed that this breakdown was due to some uncontrolled contaminant and so this data point is not included in the data summary given in Table 4.

V. CONCLUSIONS

It is widely assumed that in many situations the interface between the solid and the liquid insulation is the point in a complex system at which breakdown would occur. The data reported here do not support that conventional wisdom. From these data, which were taken using a carefully-prepared, paper-oil interface structure,it was concluded that the breakdown will not necessarily occur at the interface. Similarly the breakdown voltage for breakdown at the interface is not necessarily lower than the voltage at which breakdowns occur away from the interface.

The work indicated, however, that it seemed a relatively simple matter to force the breakdown to the interface and at the same time reduce the breakdown voltage. It is likely that interfacial breakdown will occur if the paper is not carefully dried or if many gaseous voids are left in or on the paper.

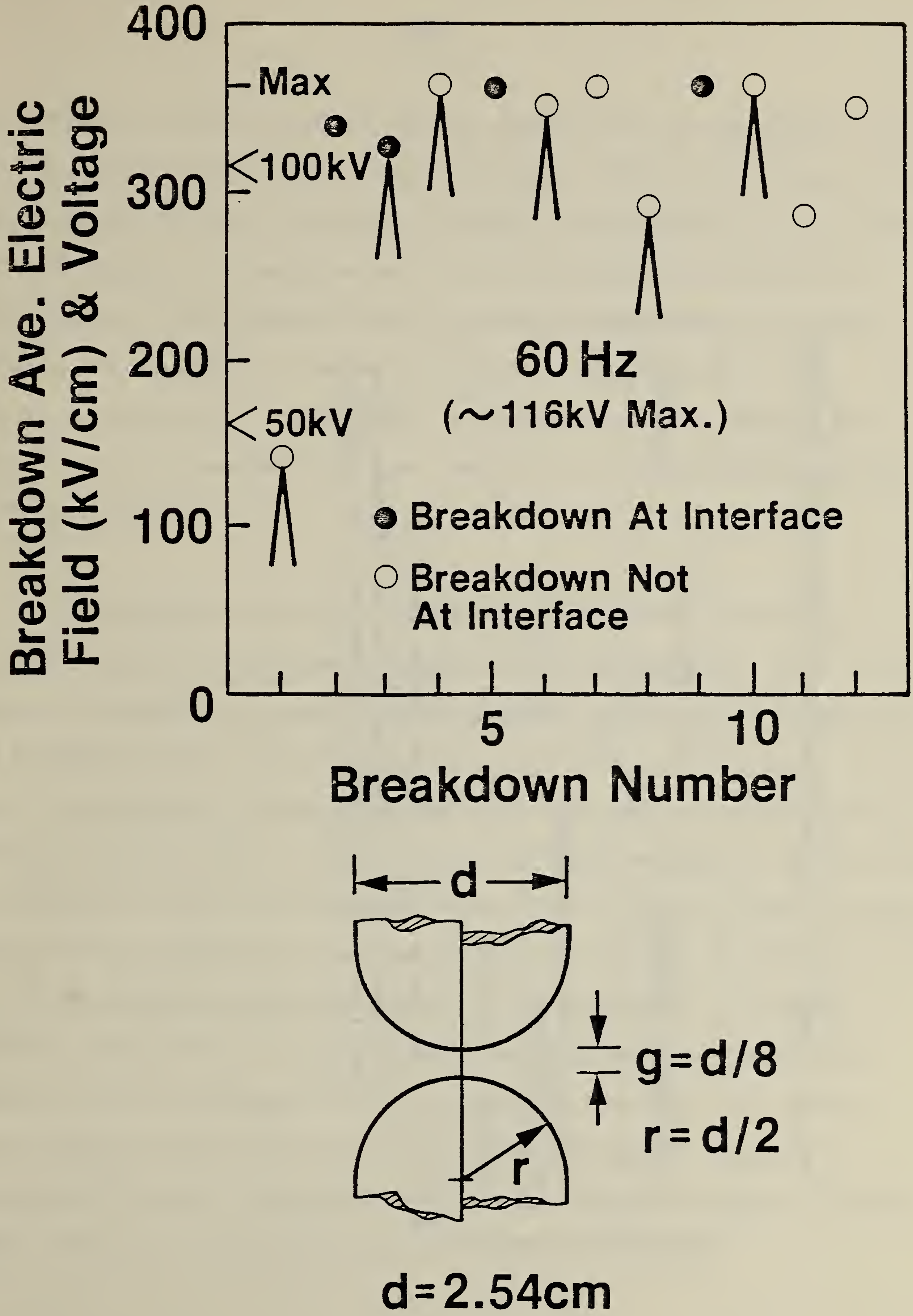


FIGURE 11. Breakdown at, and away from the interface for 60 Hz stress with sphere-sphere electrode geometry. The first point recorded reflects an unusually low breakdown voltage and is ignored in comparisons made in Table 4.

TABLE 4: SUMMARY OF 60-Hz BREAKDOWN DATA FOR SPHERE-SPHERE ELECTRODES

EXPERIMENTAL CONDITIONS	BREAKDOWN VOLTAGE kV	EFFICIENCY
Interface in place but breakdown not at interface	108 ± 11	--
Breakdown at interface	111 ± 6	1.03 ± 0.12

Notes: 1. Uncertainties listed are one standard deviation.

2. Efficiency is the ratio of the voltage for breakdown at the interface to the voltage for breakdown not at the interface.

The influence of moisture and influence of gaseous voids are recognized[9] in the process of manufacture of high voltage apparatus. Procedures have been developed, and are being followed, to minimize the impact of these factors on the finished piece of apparatus. If moisture and air are the dominant restrictions to the increase of the breakdown strength of practical apparatus, then future research and development is needed in this area. The detection of the air and water content of the materials in the devices must be improved and materials must be developed with lower sensitivity to the deleterious effects of these quantities.

It is likely that additional factors must be considered. Experience has demonstrated that breakdown voltages are distributed statistically. It is, therefore, reasonable to assume that the breakdown voltage at the interface and the breakdown voltage in the fluid are each statistically distributed. In fact, Taylor's data support the hypothesis that these two voltages are described by different distributions. If that is true, a critical parameter is the normalization of the distributions of the breakdown probabilities in the two cases. Although such a scaling parameter has also been suggested by the data of Nelson, et al.,[9] it must be emphasized that the existence of such a parameter has not been verified experimentally. Carefully controlled experiments are required to determine both the breakdown voltage and breakdown location as the ratio of the interfacial surface area (or volume) to the stressed oil volume is systematically varied. These tests will provide information required to design model tests which simulate the behavior of practical apparatus.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report describes experimental measurements of the location of electrical breakdown in a composite insulating system. For these measurements a paper sample was mounted so that it connected the two electrodes. Electrode structures ranging from plane-plane to sphere-sphere were used. The electrode-paper system was tested in oil in an attempt to determine the properties of an oil-paper interface.

The data indicated that in a carefully prepared system the breakdown will not necessarily occur at the interface. In addition, it was found that the breakdown voltages were not significantly lower for those breakdowns which occurred at the interface than for those which did not.

It was noted that if the paper interface was not dried or if many gaseous voids were left in or on the paper, the breakdown will regularly occur at the interface and at a lower voltage.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Breakdown; electrical breakdown; impulse testing; interfacial breakdown, oil-paper interfaces; transformer oil

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