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Development of Power System Measurements -- Quarterly Report October 1, 1983 to December 31, 1983

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Electronics and Electrical Engineering
Electrosystems Division
Washington, DC 20234

May 1984

Prepared for:
Department of Energy
Division of Electric Energy Systems
1900 Independence Avenue, SW
Washington, DC 20585

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MEASUREMENTS -- QUARTERLY REPORT
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R. E. Hebner, Editor

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Foreword

This report summarizes the progress of three technical investigations during the first quarter of FY 84. Although reasonable efforts have been made to ensure the reliability of the data presented, it must be emphasized that this is an interim report so that further experimentation and analysis may be performed before the conclusions from any of these investigations are formally published. It is therefore possible that some of the observations presented in this report will be modified, expanded, or clarified by our subsequent research.

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DEVELOPMENT OF POWER SYSTEM MEASUREMENTS -- QUARTERLY REPORT
October 1, 1983 to December 31, 1983

R. E. Hebner, Editor

This report documents the progress of three technical investigations sponsored by the Department of Energy and performed by or under a grant from the Electrosystems Division, the National Bureau of Standards. The work described covers the period October 1, 1983 to December 31, 1983. This report emphasizes the errors associated with measurements of electric and magnetic fields, the properties of corona in compressed SF₆ gas, and the measurement of interfacial phenomena in transformer oil.

Key words: electric fields; gaseous insulation; interfaces; liquid insulation; magnetic fields; partial discharges; SF₆; solid insulation; transformer oil.

1. INTRODUCTION

Under an interagency agreement between the U.S. Department of Energy and the National Bureau of Standards, the Electrosystems Division, NBS, has been providing technical support for DOE's research on electric energy systems. This support has concentrated on the measurement of electric and magnetic fields, the measurement of interfacial phenomena, and of partial discharge phenomena. The technical progress made during the quarter October 1, 1983 to December 31, 1983 is summarized in this report.

2. ELECTRIC AND MAGNETIC FIELD MEASUREMENTS Subtask Nos. 01 and 02

The objectives of this investigation are to develop methods to evaluate and calibrate instruments which are used, or are being developed, to measure the electric field, conductivity, the space charge density, and current density in the vicinity of high-voltage dc transmission lines, and in apparatus designed to simulate the transmission line environment; to provide electrical measurement support for DOE-funded efforts to determine the effects of ac fields on biological systems, and to provide similar support for biological studies which are being funded by the State of New York.

During the current reporting period, measurements were made to determine the dimensions of a parallel plate system which would be suitable for calibrations of flat probes frequently used to measure the 60-Hz electric field strength in biological exposure systems. Additional measurements were made to test the adequacy of the NBS parallel plate system as a calibrational apparatus for aspirator-type ion counters operating in the ground plane. This report summarizes the calibration of flat probes for 60-Hz for electric field measurement. Ion counter calibration will be described in a subsequent report.

While information is available for calibration of free-body type electric field strength meters used for measurements above the ground plane [1], no guidance currently exists for flat (square or circular) probes which are used for measurements on the surface of the ground plane of a biological exposure system.

Regions of nearly uniform electric field strength of known magnitude can be produced for calibration purposes with a parallel plate system provided that the spacing of the plates, relative to the plate dimensions, is sufficiently small. The uniform field value E_0 is given by V/t where V is the applied potential difference between the plates and t is the plate spacing. The magnitudes of the normalized field E/E_0 at the plate surfaces and in the midplane of semi-infinite parallel plates can be theoretically determined [2], and are plotted as a function of normalized distance x/t from the plate edge in figure 1; numerical values are given in table 1.

The numerical values in table 1 show that the departure from field uniformity due to fringing field effects is 0.1 percent at a distance of one plate spacing from the edge. For finite square plates, the fringing field effects from four edges can be estimated by superposition when the effect from one edge is less than 0.2 percent. These results are valid in the absence of perturbations due to nearby grounded objects, interaction between the probe located on the bottom plate and the surface charge distribution on the top plate, and the influence of the high voltage leads to the plates. These possible sources of perturbation of the field were examined for the case of one plate referenced to ground potential, and this report summarizes the result of that examination. It is noted that field perturbations due to nearby ground planes and high voltage leads may be reduced when both plates are energized with a center-tapped transformer.

Influence of Nearby Ground Planes. From figure 1, it can be seen that the electric field strength at the surfaces of the parallel plates increases as the distance to the edge decreases. However, when one plate is grounded, as would be the case during calibration of a flat probe, nearby ground planes such as the floor, ceiling or walls will perturb the field between the plates. In general, the presence of ground planes leads to the reduction in field strength at the grounded plate and an increase at the surface of the energized plate. Corresponding changes occur in the field strength at intermediate points between the plates. The effect of nearby ground planes on the field strength at the surface of a grounded plate of a parallel plate system 1 m x 1 m x 0.18 m spacing was examined with a flat probe with dimensions 8.5 cm x 8.5 cm x 0.16 cm [3]. A guard band 0.5 cm wide reduced the field-sensing area to 7.5 cm x 7.5 cm. The parallel plates were made from 0.95 cm thick aluminum plate with surfaces that had been milled flat in order to better define the parallel plate spacing. The top plate was energized with an autotransformer-transformer combination. A line conditioner was also used to stabilize the line voltage.

Measurements of the 60-Hz electric field strength as a function of distance d between the field probe edge and one of the edges of the bottom plate were made in the presence of a vertical ground plane two plate spacings (0.36 m) away from the edge of the parallel plates. The inset in figure 2 shows the geometry of the parallel plates, the probe, and the vertical ground plane. The electric field strength was near 3.33 kV/m during these measurements. Figure 2 also shows the change in field strength, in percent, as the distance (d) normalized by the plate spacing (t) is varied. For example, the decrease in field strength, which is largely [4] due to the vertical ground plane near one edge of the parallel plates, is near 0.64% when d is equal to one plate spacing. In the absence of nearby perturbing ground planes, the field strength would not decrease (see fig. 1).

Table 1. Normalized electric field strength midway between plates and at plate surfaces

Midway Between Plates		Plate Surface	
x/t	E/E_0	x/t	E/E_0
0.0698	0.837	0.0185	2.449
0.1621	0.894	0.0829	1.414
0.2965	0.949	0.1230	1.265
0.4177	0.975	0.1624	1.183
0.6821	0.995	0.2431	1.095
0.7934	0.997	0.4376	1.025
1.0000	0.999	0.6861	1.005
		0.7954	1.002
		1.0000	1.001

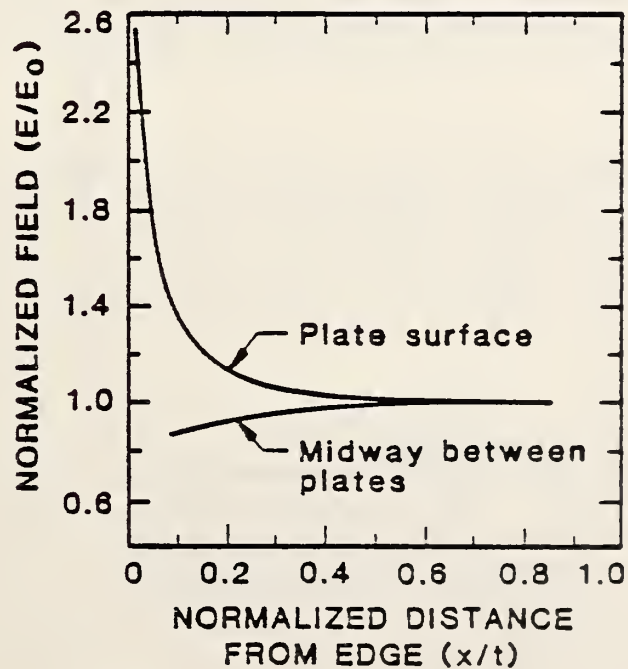
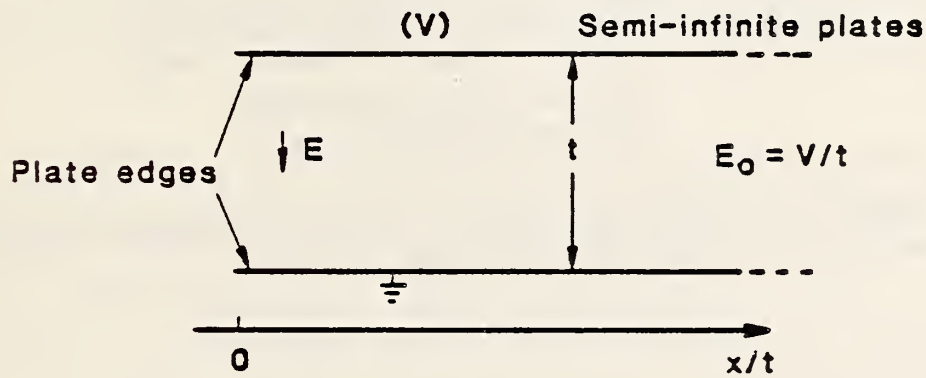


Figure 1. Normalized electric field at the surfaces of and midway between semi-infinite parallel plates.

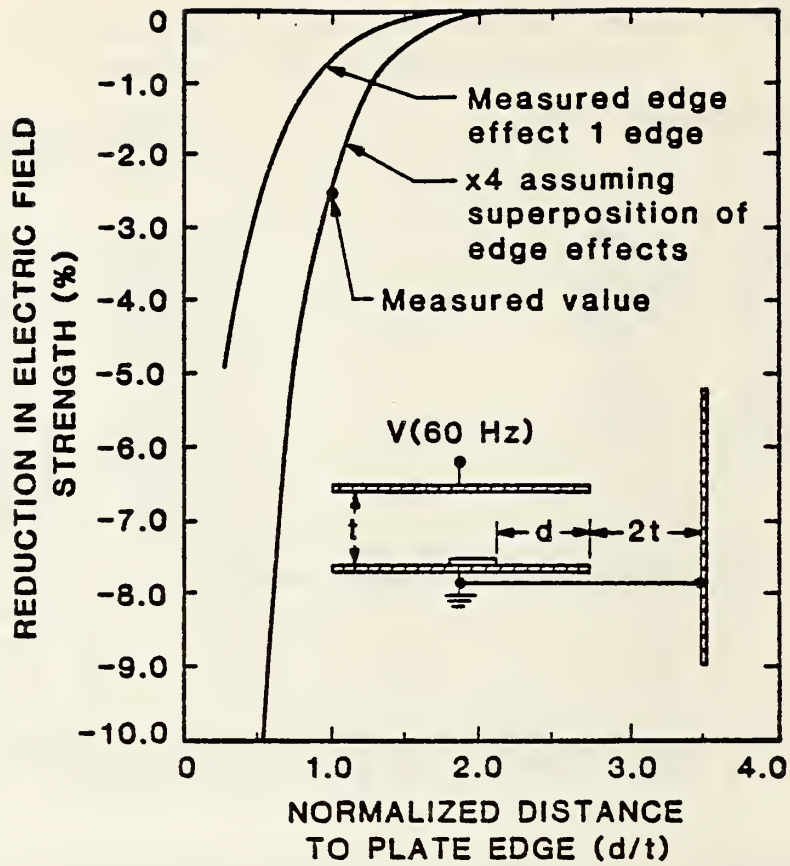


Figure 2. Reduction in field strength at surface of grounded plate due to presence of nearby ground plane.

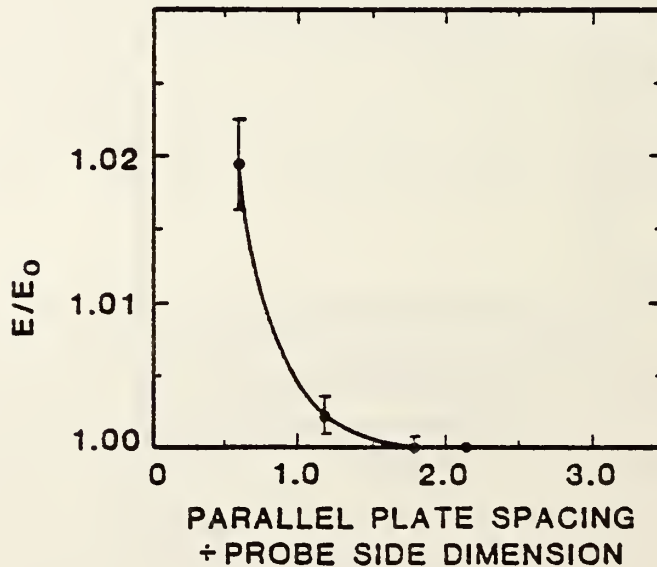


Figure 3. Perturbation of electric field strength at probe surface due to interaction between probe and surface charge distribution on energized plate.

The edge effect on field strength due to four edges of a parallel plate system in which the distance between the probe and each plate edge is the same can be estimated by the principle of superposition (the presence of vertical ground planes two plate spacings away from each side of the parallel plates is assumed). The measured reductions in field strength due to a single edge and vertical ground plane in figure 2 are multiplied by four and these results are also shown in figure 2 with the curve designated with x4.

The results assuming superposition of edge effects were checked experimentally at one point with a smaller parallel plate system 46 cm x 46 cm x 18 cm spacing and constructed with the same type of milled aluminum as used for the larger parallel plates. Each edge of the probe (8.5 cm x 8.5 cm), placed at the center of the bottom grounded plate, was approximately one plate spacing away from the nearest edge of the bottom plate. A vertical ground plane was located two plate spacings away from each edge of the parallel plates. The measured field strength was found to be 2.6% less than the uniform field value determined with the 1 m x 1 m x 0.18 m parallel plate system. This reduction is plotted in figure 2 and is in very good agreement with the predicted value assuming superposition of edge effects. The size of the data point reflects the uncertainty associated with the measured value. It is noted that the 2.6% field strength reduction was found after correction for a small perturbation due to the influence of the high voltage lead described below.

In the absence of other perturbations, the superposition results in figure 2 indicate that a calibration field that is within 0.25% of the uniform field value (V/t) can be produced if the distance between the flat probe (edges) and the edges of the bottom plate is twice the parallel-plate spacing and if there are no ground planes closer than two plate spacings away. This result also assumes that the probe has a narrow guard band (i.e., width is ~6% of side dimension). A larger guard band or ground planes further than two plate spacings should reduce the influence of the parallel plate edge effects. Finally, it is noted that the choice was made to use two plate spacings as the distance between the parallel plates and nearby ground planes (and not a larger distance) because it appears to be a condition that can be readily met in most laboratories.

Interaction of Probe With Surface Charge Distribution on Top Plate.

Because of the thickness of the flat probes, the electric field in the vicinity of the probe will be perturbed. If the upper (energized) plate of a parallel plate system which is being used for calibration of the probe is sufficiently close, the surface charge distribution on the upper plate will be rearranged by this perturbation. The resultant effect is an increase in field strength at the surface of the probe [5].

Measurements of the same nearly uniform electric field V/t were performed with a 8.5 cm x 8.5 cm x 0.3 cm thick probe in the 1 m x 1 m parallel plate system with different plate spacing to determine when the interaction between the probe and the upper plate became negligible. Figure 3 shows the field strength measurements normalized by the field strength observed when the spacing was 0.18 m (taken to be the uniform value E_0) as a function of plate spacing which is normalized by the side dimension of the probe (8.5 cm). The error bars shown in figure 3 reflect uncertainties in the measurement of the voltage (<0.05%) and the parallel plate spacing (<0.3% for 5 cm spacing and less for larger spacing). The data in figure 3 show that the interaction between the top

plate and a probe with a thickness that is 3.5% of its side dimension leads to a field enhancement at the probe surface that is less than 0.25% when the parallel plate spacing is one and one-half times the probe's side dimension. Similar measurements with a probe of half the thickness led to enhanced fields at the probe surface which were about half as large as those shown in figure 3.

Influence of High Voltage Lead on Field Between Plates. The possibility of the calibration field being affected by the presence of the high voltage lead to the upper plate of the parallel plate system was examined for a number of parallel plate spacings. The procedure used to determine an effect was to compare field strength measurements obtained with a flat probe 8.5 cm x 8.5 cm x 0.16 cm thick when one high voltage lead was connected to the upper plate with measurements obtained with two leads connected. The connections to the upper plate were made at adjacent corners and the leads were routed approximately horizontally to the transformer, maintaining approximately equal distance between the probe (at the center of the bottom plate) and leads. If there was no difference between measurements, the influence from the leads was considered negligible.

Field strength measurements obtained when the distance between the probe edges and plate edges was 1.25 times the plate spacing indicated that the high voltage lead contribution to the field, at the location of the probe, was about 0.1%. No contribution to the field could be detected (within 0.04%) when the distance between the probe and plate edges was twice the plate spacing.

In summary, a calibration electric field which is within 0.5% of the uniform field value V/t can be established for a ground referenced flat probe using a parallel plate system, provided that the spacing of the plates is at least 1.5 times the side dimension of the probe and the distance between the probe (edges) and plate edges is no less than two plate spacings. These results are valid for a square probe with 6% guard band width and a thickness that is 3.5% of the probe's side dimension. All nearby ground planes should be at least two plate spacings away from the parallel plates.

During the next quarter, the latest revision of the IEC draft standard will be completed and distributed to members of IEC TC42 Working Group 6. A technical note describing electrical parameters which must be controlled during biological experiments will undergo internal review. At least one site visit will be made to measure 60-Hz electric and magnetic fields in a biological exposure system. Additional measurements will be performed with an aspirator-type ion counter operating in the ground plane of the parallel plate system.

For further information, contact Dr. M. Misakian, (301) 921-3121.

3. TECHNICAL ASSISTANCE FOR FUTURE INSULATION SYSTEMS RESEARCH Subtask No. 03

The objective of this project is to develop diagnostic techniques to monitor, identify, and predict degradation in future compressed gas electrical insulating systems under normal operating conditions. The focus is on the fundamental information and data needed to improve test design and performance evaluation criteria. The scope of the project encompasses the following

investigations: 1) measurement and calculation of electric discharge inception in compressed electronegative gases; 2) measurement, calculation, and compilation of fundamental data on electron transport and electrical breakdown in gases; 3) measurement of absolute electric discharge-induced decomposition rates in gaseous dielectrics; and 4) examination of the influence of contaminants like water vapor on the performance of compressed gas-insulated systems. Emphasis is given in these investigations to the development and evaluation of new measurement techniques.

During the past reporting period emphasis was given to activities 1, 3, and 4. Some of the progress made in these activities is highlighted in this report.

As a part of activity 3, about 500 archival publications dating back to 1950 were examined and evaluated according to their appropriateness for inclusion in the bibliography on electrical breakdown data in gases. Some assistance in this effort was provided by members of the IEEE Insulation Society Technical Committee S-32-11 on Gaseous Dielectrics. A preliminary version of the bibliography was presented and discussed at the last meeting of this committee which took place during the 1983 Conference on Electrical Insulation and Dielectric Phenomena. At present about 470 papers have been determined to be suitable for inclusion, i.e., they contain theoretical or experimental data on electrical breakdown in gases considered to be relevant to electrical insulation technology. These papers are now being listed by computer in a cross referencing format that will facilitate the location of particular kinds of data which are available for the different types of gases or gas mixtures that have been studied. The computerized form of the bibliography has been designed so that it can be easily updated and periodically reprinted.

Concerning activity 1 above, a draft of a manuscript entitled "Production Rates for Discharge Generated SOF_2 , SO_2F_2 and SO_2 in SF_6 and $\text{SF}_6/\text{H}_2\text{O}$ Mixtures" by R. J. Van Brunt, T. C. Lazo, and W. E. Anderson has been prepared for submission to the Fourth International Symposium on Gaseous Dielectrics, Knoxville, April-May, 1984. This paper presents the results of our measurements of the absolute production rates for SOF_2 , SO_2F_2 , SO_2 , and H_2O generated by point-plane corona discharges under a wide range of conditions in SF_6 containing trace levels of water vapor.

Related to this work, our previous measurements of decomposition species production rates for negative corona discharges in SF_6 were extended to a higher pressure of 300 kPa (~3 atm) for several different discharge power levels. The results for SOF_2 , SO_2F_2 , and H_2O production were consistent with the trends that we previously reported (see previous quarterly report) for other gas pressures and discharge conditions.

The gas chromatograph-mass spectrometer data for degradation of SF_6 in negative point-plane discharges at several gas pressures were analyzed to obtain information on the relative production of thionyl tetrafluoride (SOF_4). The ratios of the peak heights of the SOF_4 and SOF_2 features in the single-ion chromatograms for a mass-to-charge ratio (m/e) of 86, and the ratios of SOF_4 at $m/e = 86$ to SF_6 at $m/e = 19$ are shown in figures 4 and 5. These ratios indicate the concentrations of SOF_4 relative to SOF_2 and SF_6 respectively as a function of net charge transported across the gap. The slopes of the $[\text{SOF}_4]_{86}/[\text{SF}_6]_{19}$ curves are directly proportional to the production rates for SOF_4 in moles-per-coulomb. The vertical arrows indicate times when the discharge was

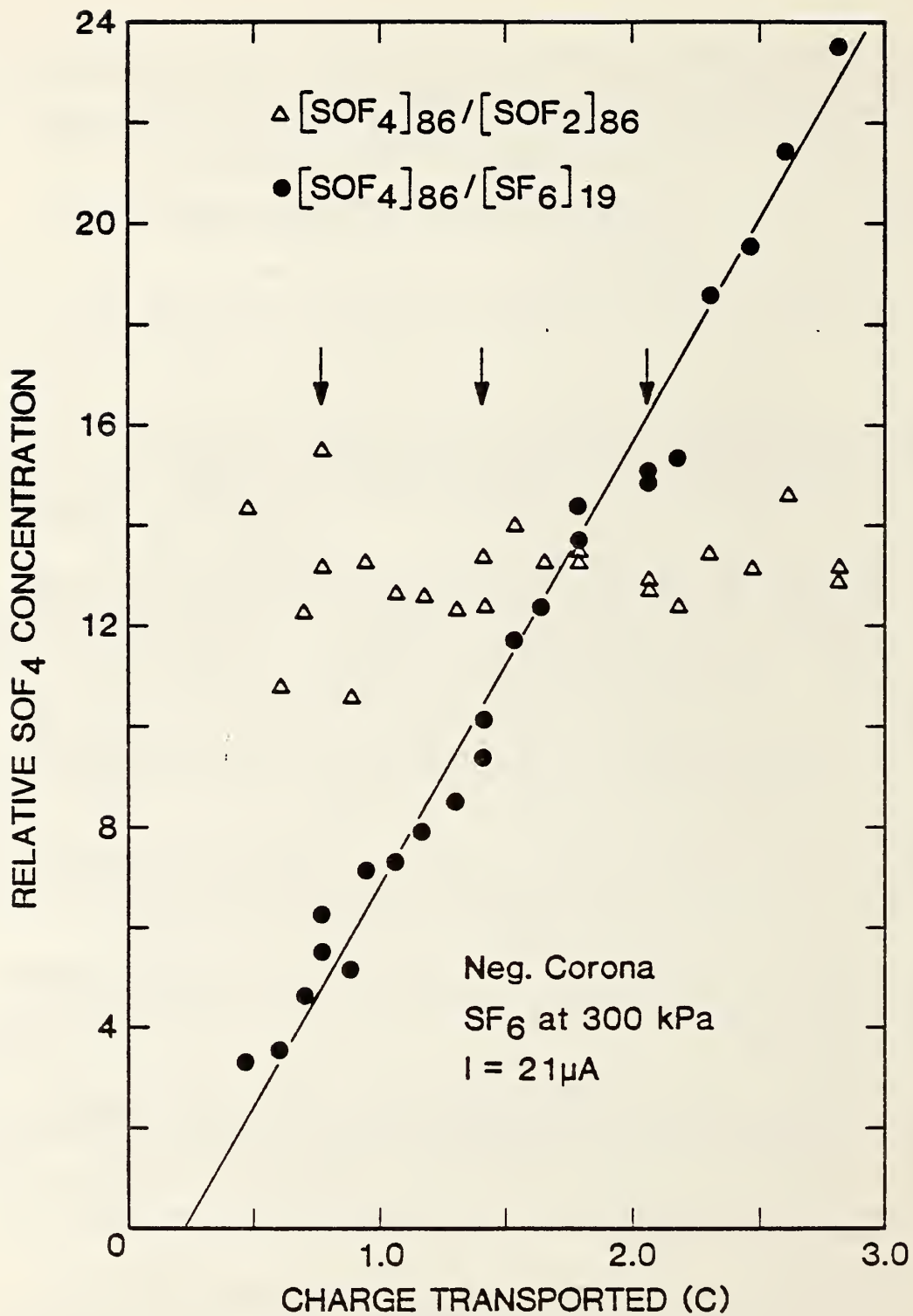


Figure 4. Relative concentrations of SOF_4 versus net charge transported across the gap for a negative corona discharge in SF_6 at a pressure of 300 kPa for a current of 16 μA . Shown are the concentrations of SOF_4 measured at $m/e = 86$ relative to both the concentration of SF_6 at $m/e = 19$ and SOF_2 at $m/e = 86$. The vertical arrows indicate times when the discharge was turned off for more than 16 hours.

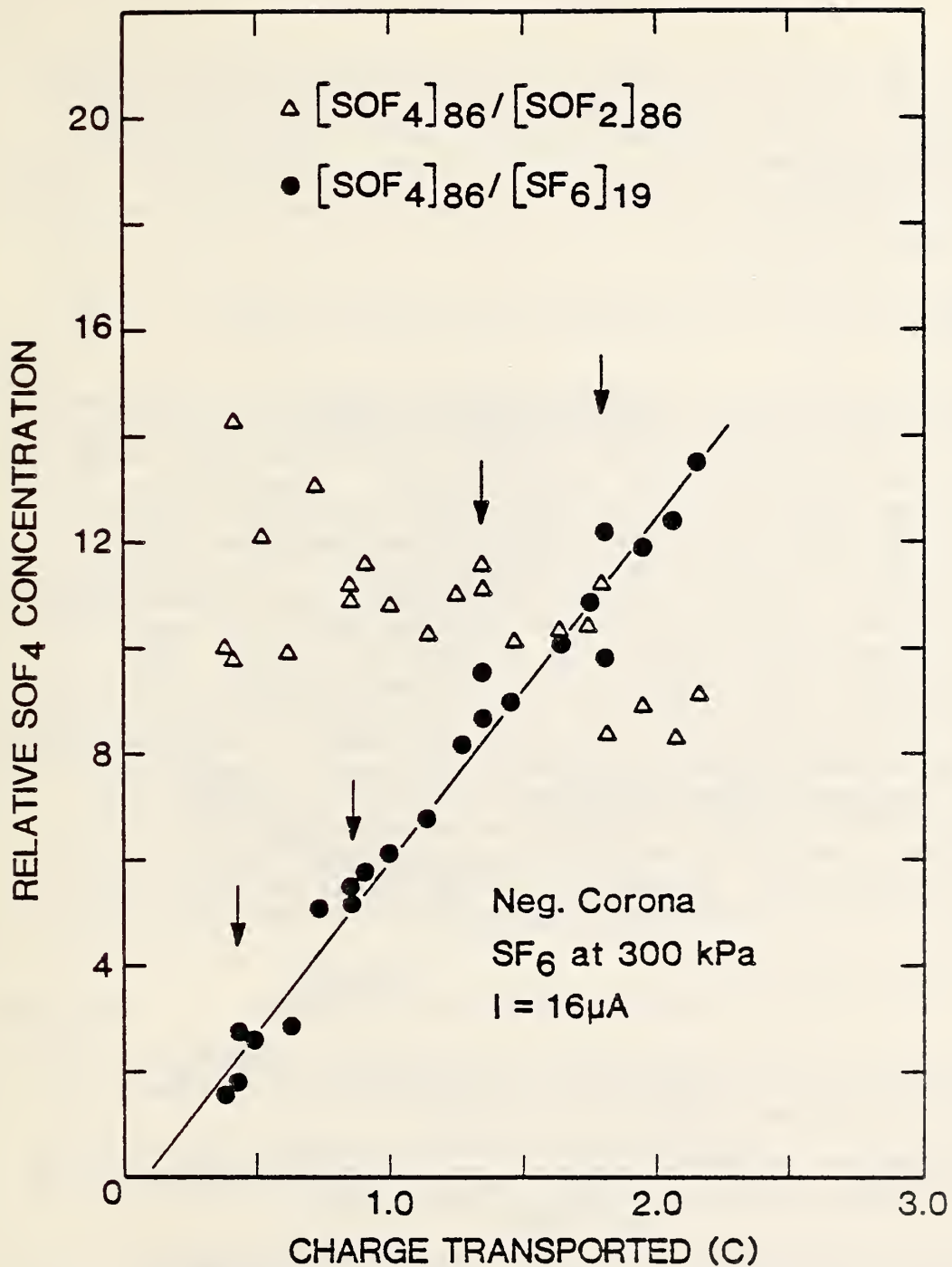
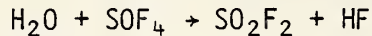


Figure 5. Relative concentrations of SOF_4 versus net charge transported across the gap for a negative corona discharge in SF_5 at a pressure of 300 kPa for a current of $21 \mu\text{A}$. Shown are the concentrations of SOF_4 measured at $m/e = 86$ relative to both the concentration of SF_5 at $m/e = 19$ and SOF_2 at $m/e = 86$. The vertical arrows indicate times when the discharge was turned off for more than 16 hours.

extinguished for periods of 16 h or more. The concentrations of SOF are seen to change very little during these times whereas the H₂O concentrations were observed to increase (see our previous quarterly report). This observation indicates that the gas phase hydrolysis of SOF₄ is very slow, and thus it can be concluded that the reaction



is not the major source of SO₂F₂ production as has previously been suggested [6-8].

Related to activity 4, a new method of preparing samples of pressurized SF₆ containing known trace quantities of water vapor in a discharge was tested. By this method 1 - 10 μl of liquid H₂O were injected into the cell under vacuum followed by introduction of SF₆ to the desired pressure. Changes in the absolute water vapor content immediately after this preparation were monitored with the GC/MS which was initially calibrated by direct comparison with the readings from a thin-film aluminum oxide hygrometer probe. The results of the measurements as shown in figure 6 indicate that the water vapor content reached equilibrium in the cell within 20-30 minutes following the initial preparation, and thereafter varied by less than ±10% for the next 2 to 6 hours. The hygrometer probe however gave erroneously high readings during this time (see fig. 6), and appeared to require more than 8 hours to reach equilibrium with the gas and thereby attain agreement with the GC/MS measurements. The hygrometer probe is thus not capable of providing reliable measurements of water vapor content during short term sample preparation. The method investigated here appears to be much more efficient, reliable, and versatile than the hot wire technique previously used [9] to prepare H₂O contaminated SF₆ samples. It is expected that this method will be employed in future investigations of the effect of trace levels of H₂O on electron avalanche and streamer development in SF₆ discharges.

Planned activities for the next quarter include the following:

- 1) A manuscript describing our results on production of oxyfluorides in SF₆ corona discharges will be submitted to the Proceedings of the Fourth International Symposium on Gaseous Dielectrics;
- 2) A bibliography on electrical breakdown data in insulating gases will be completed and prepared for publication as an NBS report;
- 3) The effects of controlled low levels of oxygen contamination on oxyfluoride production rates in SF₆ discharges will be measured at selected gas pressures; and
- 4) Standard samples of SOF₄ gas will be prepared and the gas chromatograph-mass spectrometer system will be calibrated for quantitative measurements on this species. All previously acquired data on SOF₄ production in SF₆ discharges will also be reanalyzed to obtain absolute production rates for this species.

For further information contact Dr. R. J. Van Brunt, (301) 921-3121.

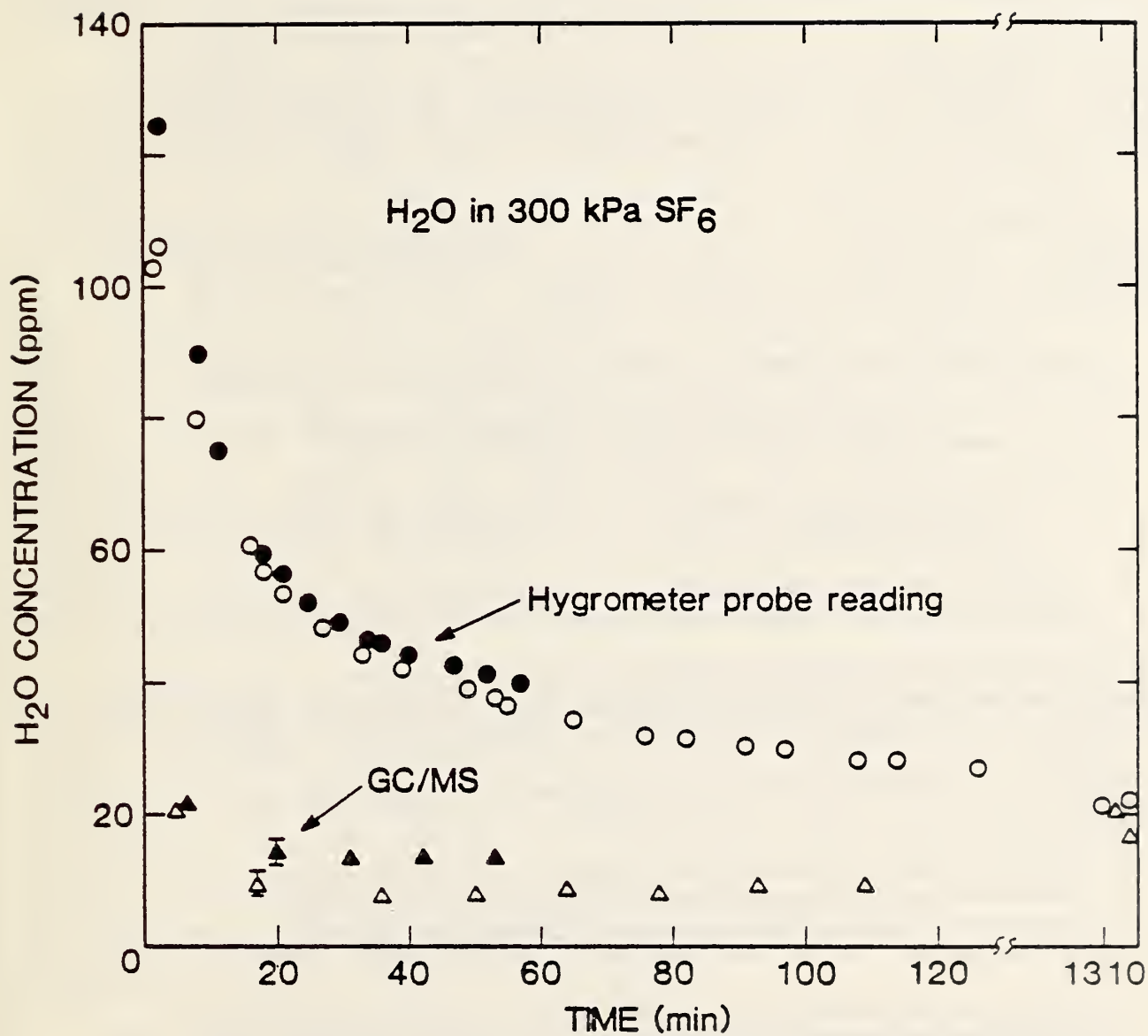


Figure 6. Concentration of water vapor in 300 kPa SF₆ versus time after sample preparation for two different samples indicated by (o, Δ) and (●, ▲) respectively. Shown is a comparison between the GC/MS measurement and the hygrometer probe reading.

4. OPTICAL MEASUREMENTS FOR INTERFACIAL CONDUCTION AND BREAKDOWN
IN INSULATING SYSTEMS
Subtask No. 04

The objectives of this investigation are to develop apparatus and appropriate procedures for the optical measurements of interfacial electric field and space-charge density in materials for electric power equipment and systems, to understand the interfacial pre-breakdown and breakdown processes in specific insulating systems, and to demonstrate the applicability of the developed instrumentation and the procedures in the development and design of future systems.

The underlying goal of this research is to understand the factors which contribute to the failure of liquid-solid high-voltage systems -- in particular transformer oil and paper or pressboard systems. There are two areas of interest:

1. Fundamental properties of a liquid-solid system which include:

The electric field distribution between conductors and in the vicinity of an interface, and

The prebreakdown processes in pure liquids and in the vicinity of an interface.

2. The influence of contaminants, particles, voids, and chemical additives upon the electrical strength of the liquid-solid system.

Since it is impossible to prepare a perfectly clean system, it is not really possible to draw a hard dividing line between these two areas of interest, but experiments can be designed to concentrate on specific areas of interest.

To support this investigation, two experimental systems have been developed:

1. Optical Field Measurement (OFM) systems [10] to determine the electric field in transformer-oil systems with and without interfaces, and with and without the addition of specific contaminants.

2. Electrical Breakdown Visualization (EBV) system [11] to provide high-speed photography of the time-evolution of the entire breakdown process, both pre- and post-breakdown.

Previous quarterly reports have documented the effects of space charge in transformer oil alone and with a pressboard interface parallel to the field direction using the OFM system. The more significant results have been the measurement of the temperature dependence of space charge in transformer oil and the demonstration that macroscopic field distortions arising from surface charging of the interface parallel to the field do not occur to within the accuracies of the experiment. These results serve to clarify the role of space charge and surface charge in the failure of practical insulation systems.

With the EBV system, liquids have been investigated and a general picture of the electrical breakdown process has been obtained. Notable results have been the documentation of multiple modes of streamer propagation and the documentation of the effects of the addition of electron-trapping chemical impurities on streamer structure. These results were obtained with liquids using both the point-plane and quasi-uniform electrode geometries.

Concerning electrical breakdown in the vicinity of a paper interface parallel to the electric field and between plane electrodes, it has been established that electrical breakdown does not necessarily occur at the interface in the oil-paper system, and the presence of the paper does not necessarily lower the breakdown voltage. Such results were achieved using carefully prepared paper samples and careful liquid-handling procedures, and the data were taken at room temperature.

The present investigation is attempting to determine if the same phenomena which occurred during the room temperature investigation are observed at operating temperatures of practical high-voltage apparatus. In order to carry out this investigation, it was necessary to construct a cell which would permit one to insert new interfacial material between the electrodes without opening or touching the cell. At room temperature it is a simple matter to open the cell and insert a new interface, but at temperatures of 125°C and higher one cannot handle the cell. The main effort this quarter was to construct and operate a cell which would permit the changing of an interface from outside the cell (and outside the heated tank which contained the cell under silicone oil for electrical insulation and to maintain a uniform temperature). This report describes the test cell and summarizes preliminary results obtained using it.

The cell body is made of polytetrafluoroethylene (PTFE) which provides electrical insulation, is stable at temperatures above 150°C, and has sufficient flexibility to withstand the shockwaves associated with repeated breakdowns. Large windows permit visual observations of the cell's interior, the breakdown location, and the condition of the interface. Because PTFE becomes soft at the intended operating temperatures, the windows and other flat surfaces are sealed with silicone rings with circular cross section rather than harder rings which could dent the hot PTFE. The flanges which hold the windows and other flat PTFE plates against the cell are secured with nylon screws. PTFE screws were tried but would break after extended periods of time. Because the nylon screws are not under much stress, their tendency to become brittle over long times at high temperatures under oil should not be a problem.

PTFE pipe-to-tubing fittings are sealed with PTFE tape in the body of the cell, and are used for electrical and mechanical access to the interior of the cell. Metal fittings cannot be used because of the difference in the thermal expansion between the metal and the PTFE. Leaks will invariably develop unless the fittings are made of PTFE. The tubing end of the fittings are sealed with a silicone ferrule which provides sufficient flexibility to seal metal tubes and shafts throughout the range of temperatures used, yet allow mechanical rotation of a shaft without leaking. Mechanical coupling from outside the cell to the exterior of the enclosing heating tank is provided by a nylon or acetal-plastic chain-sprocket system with a metallic shaft with u-joints or metallic flexible shaft.

The structure which holds the electrodes is a frame made from a machinable, glass-ceramic which has an expansion coefficient comparable to that of metal

(glass-ceramic: 1.2×10^{-5} /°C stainless steel: 2×10^{-5} /°C). With an electrode gap of about 2.8 mm, because of the respective dimensions of the component materials, a change of 100°C produces less than a 0.3% change in the gap spacing. The uniform field in the gap is produced by stainless steel rod ends with rounded edges providing a cylindrically symmetric plane-plane electrode geometry with a diameter of 2.5 cm. The electrode system is split in half along its axis of symmetry. The halves are separated to accept a new paper sample, then clamped together under spring pressure during voltage application. See figure 7 for details of the electrode-paper system.

The electrodes are separated using a cam which is controlled by a stainless-steel shaft from outside the cell; see figure 8. The cam moves a hinged plate, the cam-plate, to which are attached two spring-loaded glass-ceramic pieces which attach to the electrode halves. These movable electrode halves are aligned by two rods in each of their bases which allow separation of the electrode halves but will not allow any misalignment of the electrodes when they are clamped back together. When the cam is turned, the cam-plate separates the electrodes sliding the halves along the alignment rods. The stationary halves of the electrode system are attached to the glass-ceramic frame.

The paper is supplied in long strips 1.3 cm wide wound on a spool within the cell. At approximately one meter intervals, a rectangular hole is cut in the paper strip so that breakdown voltages can be determined without an interface present. Every 3.8 cm a small notch is cut out of the side of the paper strip to provide indexing marks so that one can be sure to advance the paper far enough to provide a new interface between the electrodes. When the electrodes are separated, rotation of the take-up spool advances the paper strip providing a new interface. The take-up spool is controlled via a stainless-steel shaft from outside the cell. At each temperature, several values of the breakdown voltage (V_B) will be determined without an interface, then a minimum of twenty interfaces can be used to determine the breakdown voltage with the interfacial paper present, and then at the next rectangular cut-out several more values of V_B may be recorded without an interface present. In this way, the data for as many as ten different temperatures may be obtained before the cell has to be opened and a new spool of paper installed.

The paper strip was prepared with rectangular cut-outs and notches and then vacuum baked at 125°C for over 48 hours. As the oven cooled, degassed and dehydrated transformer oil was added under vacuum completely submerging the paper sample under the oil. The paper remained in the oil under vacuum until loaded into the cell -- a minimum of 48 hours later.

The cell system worked properly at room temperature, but at 125°C minor problems were encountered which prevented continuous use of the paper-advancing mechanism. Simple modifications are in progress which will correct the deficiencies. The cell should be fully operational next quarter. Despite the inconvenience, some data were obtained at elevated temperatures.

The most notable feature of these preliminary results is that the breakdown does not necessarily occur at the interface even at high temperatures. The applied voltage is 60-Hz ac, and the results are summarized in table 2. During the experiments, liquid was circulated through the cell and then through a particle filter to remove particulate breakdown by-products.

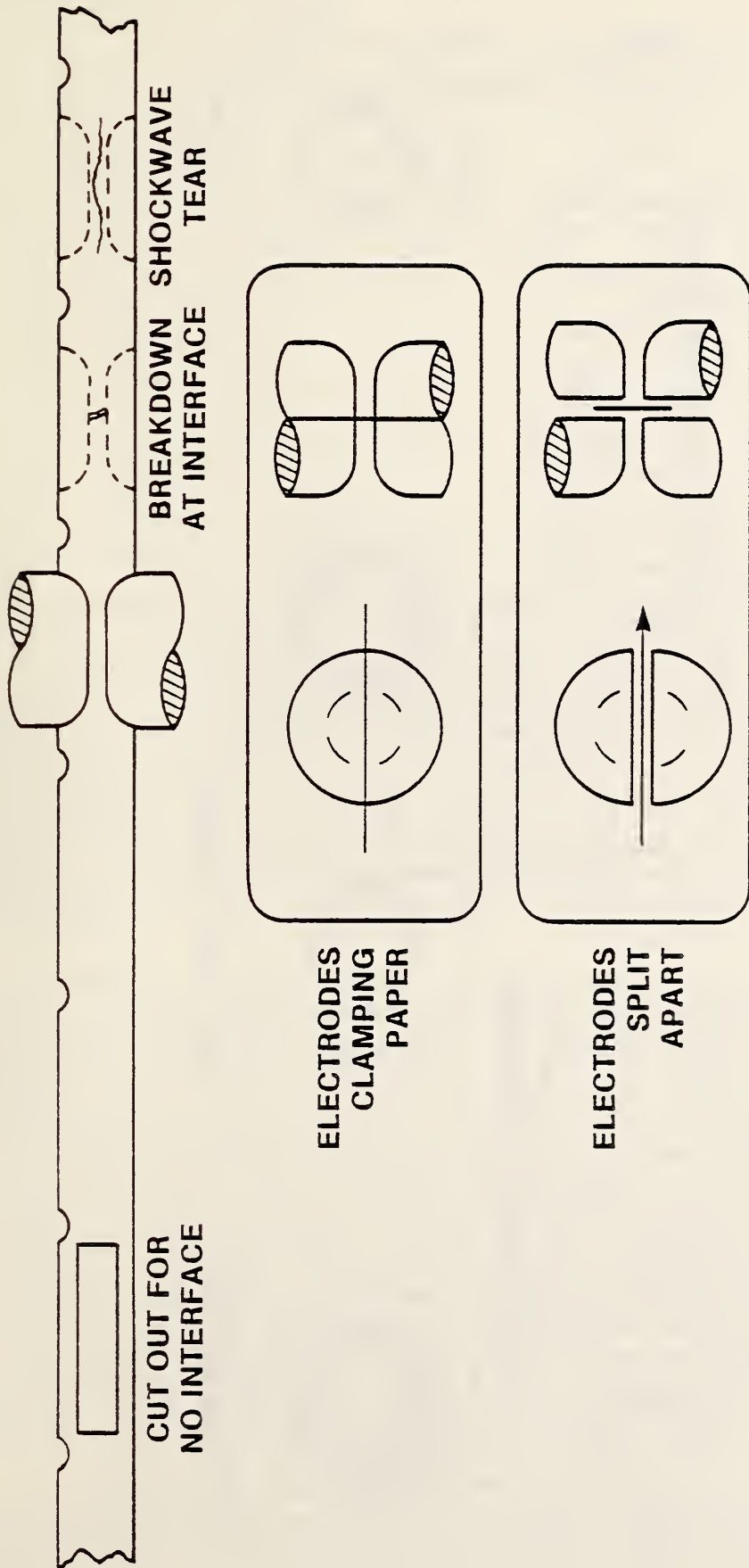


Figure 7. Split electrode system employed to clamp paper in a uniform field. Only the split electrodes are shown. The support structure and controlling mechanism are not shown. The paper is supplied in a long strip which has been notched for indexing. A rectangular cutout is provided at set lengths to permit determining the breakdown voltage without an interface present. The strip to the right of the electrode shows the results of a shockwave tearing of the interfacial material versus the appearance of a breakdown which occurred along the interface. See the text for discussion.

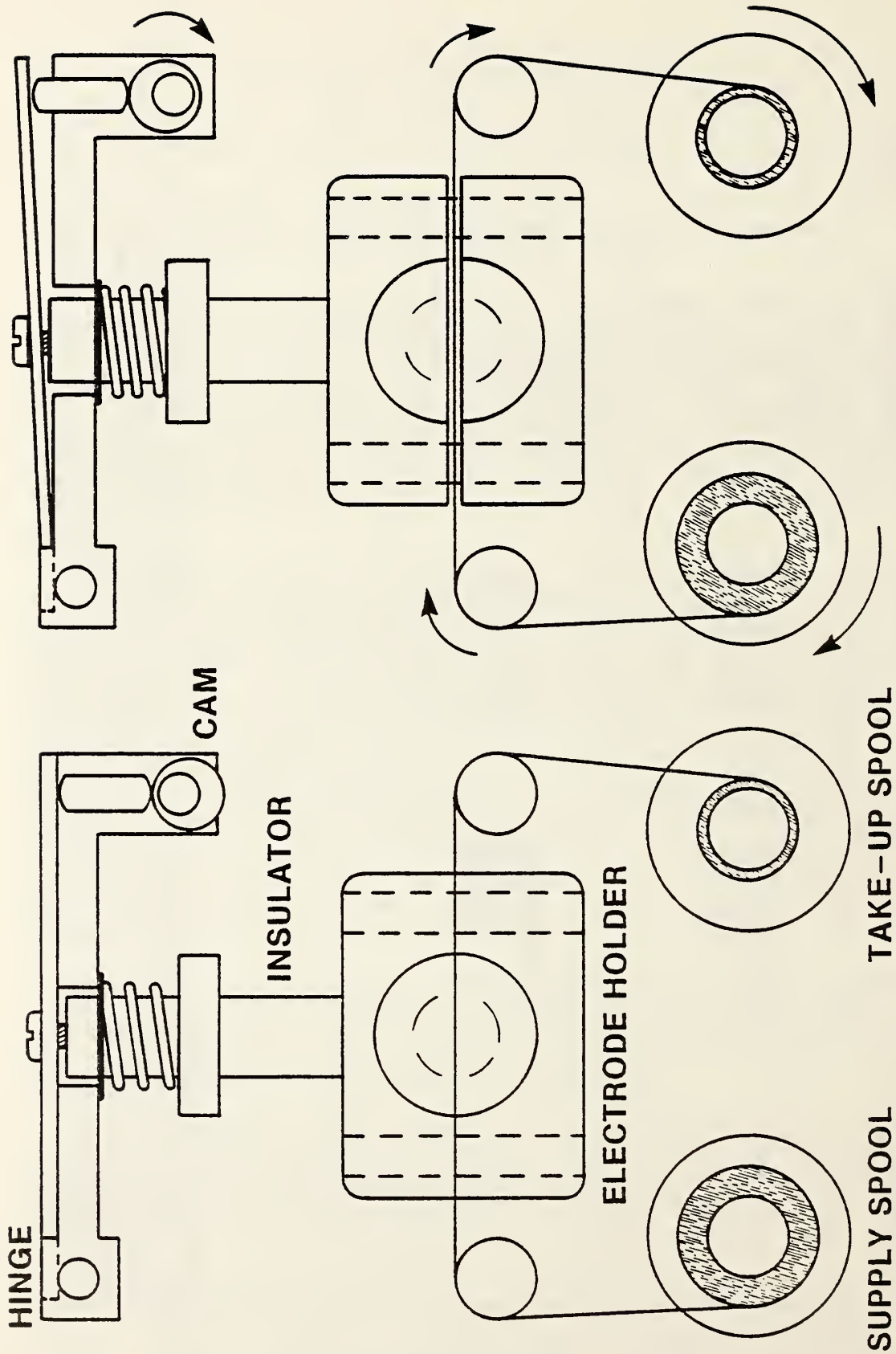


Figure 8. Arrangement for separating the electrode system to allow the introduction of a new interface.

Table 2. Summary of preliminary results

Temperature (°C)	No. of Samples or Breakdowns	(a) V_B (kV)	Condition/Result of Tests
23	11	96(4)	Breakdown <u>NOT</u> at interface
23	5	78(14)	Breakdown at interface
23	11	90(10)	<u>NO</u> interface present
115	14	78(14)	<u>NO</u> interface present
125	5	81(8)	Breakdown <u>NOT</u> at interface
125	1	51	Breakdown at interface

(a) Average voltage with standard deviation in parentheses.

Aside from the fact that the interface would not necessarily break down, there are several other observations to be made from these data. When an interface was present and the breakdown occurred at the interface, the interfacial breakdown voltage was usually lower than when the breakdown occurred away from the interface or when an interface was not present. When the breakdown did not occur at the interface, the breakdown voltage with the interface present was not significantly different from that with no interface present. It must be stressed that these are preliminary data which demonstrate the success of the cell design; more data are needed before firm conclusions can be drawn.

Whenever the interface is involved in the breakdown process, that fact is obvious from visual observations after the breakdown unless the interfacial material is completely torn away by the post-breakdown shockwave -- a rare occurrence. Often the interface is torn by the post breakdown shockwave; however, such a tear is clearly distinguishable from a breakdown which touches the interface. Where the breakdown channel -- the high-temperature post-breakdown plasma channel -- touches the paper interface, the interface is burned away. After the breakdown has occurred, the path of the breakdown channel along the interfacial paper is visible as a narrow paperless path which has relatively sharp edges and is quite well defined. Occasionally, when the interface is involved in the breakdown, the breakdown does not confine itself entirely to the interface. Either the prebreakdown streamer starts at the interface and moves away from it, or it starts away from the interface and moves to touch it. In either case, a complete breakdown channel of burned-away paper is not seen to connect the plates. Even when the paper is only partially burned away or if the breakdown channel touches the paper at any point, it is considered to be a breakdown at the interface in table 2.

In view of the method of handling and preparing of both the oil and the paper, the fact that the interface will not necessarily break down is not too surprising. If the water were successfully removed from the paper and there were no voids in the paper because of using degassed oil, then low-field

initiation sites arising from such contaminants would not be present even at elevated temperatures. Field enhancement from surface charging of the interface is not expected in view of the field measurements made last quarter where the field along an interface in hot transformer oil was nearly the same as the field in the bulk liquid between parallel plates. Thus, unless the solid material provides contaminants in the form of voids, conducting particles, or voids from vaporization of water or other low-boiling-point liquid, then it is hypothesized that the breakdown will not necessarily occur at the interface. Further effort is needed to determine if this hypothesis is correct. The effort next quarter will concentrate in the following areas:

1. Determination of the temperature dependence of the breakdown voltage of transformer oil with and without a paper interface parallel to the field direction. Repeat these measurements for paper which has not been dehydrated but is merely surrounded by degassed oil so that all voids will be removed from the paper. It is anticipated that as the temperature approaches the boiling point of water, the breakdown will tend to favor the interface more than when the paper is dehydrated.
2. Preparation of a monograph on the effects of particles on the prebreakdown streamers in liquids.

For further information contact Dr. Edward F. Kelley, (301) 921-3121.

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