NBSIR 84-2898

Development of Power System Measurements -- Quarterly Report January 1, 1984 to March 31, 1984

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Electronics and Electrical Engineering
Electrosystems Division
Gaithersburg, MD 20899

July 1984

Prepared for:
Department of Energy
Division of Electric Energy Systems
) Independence Avenue, SW
ington, DC 20585

NBSIR 84-2898

DEVELOPMENT OF POWER SYSTEM MEASUREMENTS -- QUARTERLY REPORT JANUARY 1, 1984 TO MARCH 31, 1984

R. E. Hebner, Editor

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Electronics and Electrical Engineering
Electrosystems Division
Gaithersburg, MD 20899

July 1984

Prepared for:
Department of Energy
Division of Electric Energy Systems
1000 Independence Avenue, SW
Washington, DC 20585

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

Foreword

This report summarizes the progress on three technical investigations during the second 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.

TABLE OF CONTENTS

LIST OF FIGURES

Page

DEVELOPMENT OF POWER SYSTEM MEASUREMENTS -- QUARTERLY REPORT
January 1, 1984 to March 31, 1984

R. E. Hebner, Editor

This report documents the progress on three technical investigations sponsored by the Department of Energy and performed by the Electrosystems Division, the National Bureau of Standards. The work described covers the period from January 1, 1984 to March 31, 1984. The report emphasizes the performance of ion counters like those used to measure the ions near dc transmission lines, the production rates of oxyfluorides in SF_6 corona discharges, and the measurement of space charge associated with a pressboard interface in transformer oil.

Key words: cables; composite insulation; electric fields; high voltage; incipient fault; insulation; liquid breakdown; SF_6; space charge; 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 been concentrated in the following areas -- the measurement of electric fields, the measurement of partial discharge phenomena, and the measurement of interfacial electrostatic field distributions and of space charge density. The technical progress made during the quarter January 1, 1984 to March 31, 1984 is summarized in this report.

2. ELECTRIC FIELD MEASUREMENTS
Subtasks 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, 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 funded by the State of New York.

During the current reporting period, measurements were made of the air flow outside an ion counter inlet for different opening geometries and volumetric flow rates. This information will be used to assess the usefulness of the NBS parallel plate system in investigating the effects of external electric fields on ion counter operation and as a facility to calibrate ion counters. The results are summarized in this report. In addition, measurements were performed related to the fringing field effects of finite parallel plates near vertical ground planes. These measurements are relevant for calibrating flat electric field probes in a parallel plate apparatus. The results of the measurements have been combined with previously reported measurements into a draft manuscript which was sent to the journal, Bioelectromagnetics, to be considered for publication.

2.1 Operation of Aspirator-Type Ion Counters in Ground Plane

Previous results have been reported which show that operation of ion counters in regions of high external field result in measurements which depend on various operating parameters such as ion counter potential, air speed at the counter inlet and inlet geometry [1,2]. It appears that the source of these results is the influence of both the electric field and the air flow in determining the trajectories of the ions near the inlet of the ion counter. Air speeds at the inlet are of the order of 1 m/s, which for reference corresponds to a wind speed of about 2 mph. In an unperturbed electric field of 10 kV/m, an ion will move with a drift speed of 1-2 m/s. If the ion counter is located above the ground plane and is grounded, the actual field at the inlet of the ion counter could be several times the unperturbed field, depending on the geometry and orientation of the counter. These problems are much less important in the situation normally encountered in atmospheric physics, where the electric field in fair weather is less than 1 kV/m. It also appears that it is best to operate an ion counter so that the inlet is located in the ground plane, although this introduces a number of operational problems of non-electrical origin.

Investigations have been initated to determine the feasibility of using the NBS parallel plate system [3,4] to: (a) study in a quantitative way the effects of external electric fields on ion counter operation, and (b) calibrate ion counters against ion densities determined from the relation $J = \rho KE$, where J, ρ, and E can be determined; here J is the current density, ρ is the charge density, and K is the average mobility. Because the ion counter is an aspiration device, there is an air flow outside the instrument. This air flow perturbs the region near the inlet and adds an additional term to the equations describing ion transport near the counter [4]. The extent to which this air flow perturbs the normal operation of the parallel plate system must be determined. A second perturbation is considered in figure 1, which indicates schematically the installation of the ion counter. The inlet is in the ground plane of the parallel plate system, and must be open to allow air flow. This opening significantly modifies the electric field near the ion counter inlet [4].

To estimate the extent to which the air flow into the ion counter perturbs the electrical conditions existing in the parallel plate system, a set of measurements have been made for different openings into and volumetric flow rates through the ion counter. The approximate sizes of the openings used are 14 x 11 cm, 8 x 9 cm, and 5 x 5 cm. A wide range of air speeds and flow conditions can be obtained with existing equipment. The measurement arrangement is shown schematically in figure 2. Scans were made across the opening at five different locations and for elevations above the plane of the opening of 1.5 cm, 3.5 cm, and 5.5 cm. An example of scans taken at a distance of 3.5 cm above the plane and for two different flow rates is given in figure 3. During these measurements, the axis of the probe was oriented parallel to the plane containing the inlet of the ion counter. Discrete data points are an average taken at fixed locations as indicated and the speed values shown are obtained from a calibration chart for the probe used in these measurements. The continuous records have not been corrected for the nonlinear calibration of the probe in this low speed region. The air speeds indicated are not the actual speeds, since the flow is three-dimensional and the hot film probe responds only to velocity components perpendicular to the probe. Knowledge of the full air velocity field would not be of use at this point. The fluctuations in the continuous record are due in part to the motion of the probe during the scan.

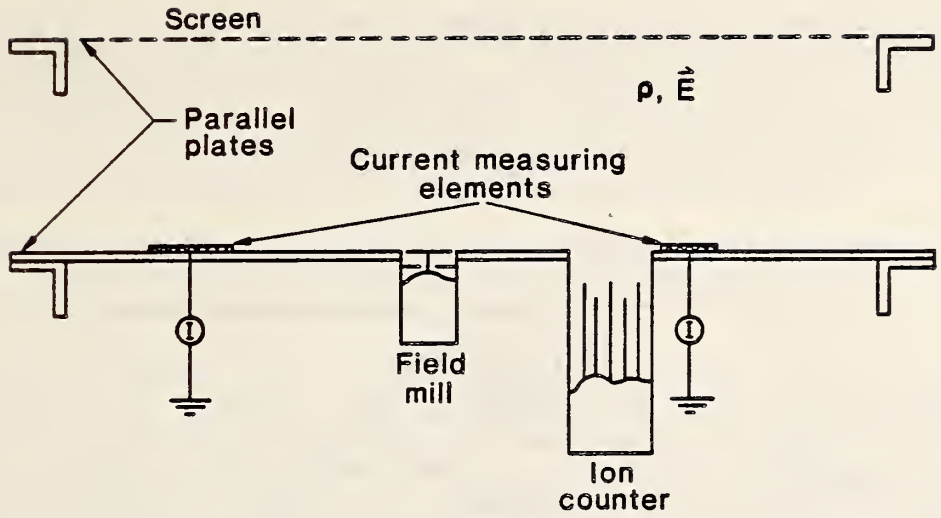

Figure 1. Ion counter location in parallel plate system. System details have been eliminated for clarity and drawing is not to scale.

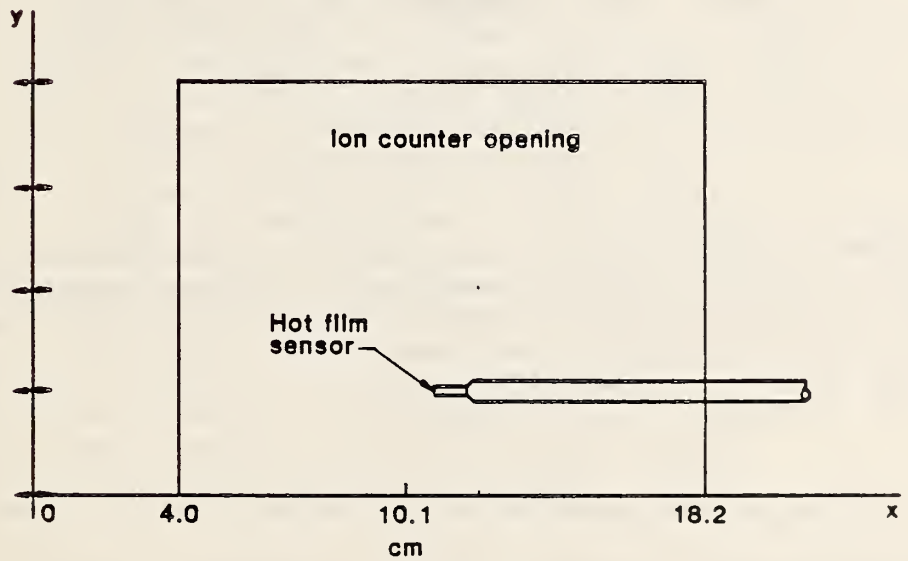

Figure 2. Top view of geometry used for air speed measurements. Scans along the x direction were taken at the 5 y positions indicated. Discrete measurements were taken at selected locations. The probe was positioned at heights of 1.5, 3.5, and 5.5 cm above the inlet.

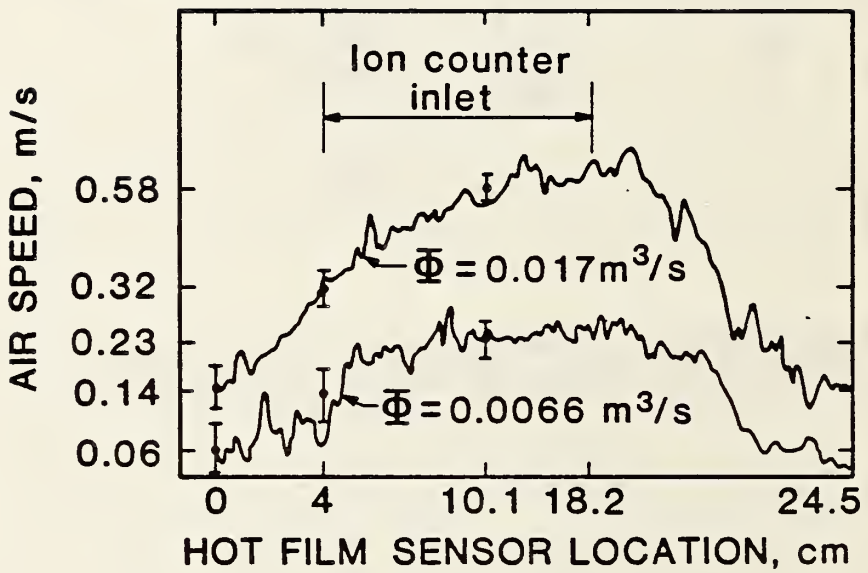

Figure 3. Air speed measurements taken for two different volumetric flow rates as indicated. The probe was 3.5 cm above the inlet and the scan was along a y position of 5.5 cm (see fig. 2). Discrete measurements were taken as indicated. The vertical scale is non-linear (see text). Inlet size was 14.2 x 11 cm.

The error bars on the discrete points indicate the standard deviation for a set of five measurements taken at each point. Air speed values below 0.2 m/s are only approximate since they lie outside the calibration range for the probe. The speed of a small ion in a 10 kV/m field is approximately 1 m/s, so it is clear that the air flow field significantly perturbs the conditions in the parallel plate system, even for the lowest flow rate considered.

Figure 4 compares the air speed for two different size openings. The data presented in figures 3 and 4 are representative of the set taken to characterize the flow region outside the ion counter inlet.

In earlier unreported work, a small commercial ion counter was installed as shown in figure 1. A field mill was located 10.2 cm from the counter opening and current-sensing elements were installed next to the ion counter opening. With no flow through the ion counter, the current to the sensors next to the opening increased by about 10% when the opening to the counter was uncovered. This increase is caused by the perturbation in the electric field due to the opening and is comparable to the theoretical prediction reported previously [4]. A coarse (2 cm x 2 cm mesh) screen covering the hole reduced the change to about 2%. Turning on the air flow through the counter caused the current in the sensors to increase by an additional 2%. The changes in electric field strength recorded by the field mill for any of the conditions was less than 1%. For these measurements the electric field was about 3.4 kV/m. The air speed at the center of the inlet at a distance of 3.5 cm was 0.34 m/s.

The next step in this effort will be to install the laboratory ion counter in the parallel plate system and do a systematic series of measurements to determine the extent to which the ion counter perturbs the system operation. This will be done for different flow rates and ion counter operating conditions. This data base should allow us to make conclusions about the usefulness of this approach to study ion counter operation in the presence of external fields. It does not appear that the system can be modeled without extensive effort, but consideration will be given to this.

Additional experiments will also be done using the monopolar line used to study the off-ground operation of ion counters reported in [4]. For this set of measurements, an elevated ground plane has been constructed to allow the ion counter inlet to be placed in the ground plane. Values of space charge density determined directly from the ion counter will be compared to those obtained from separate J and E measurements. This investigation will supplement the more fundamental work being done with 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

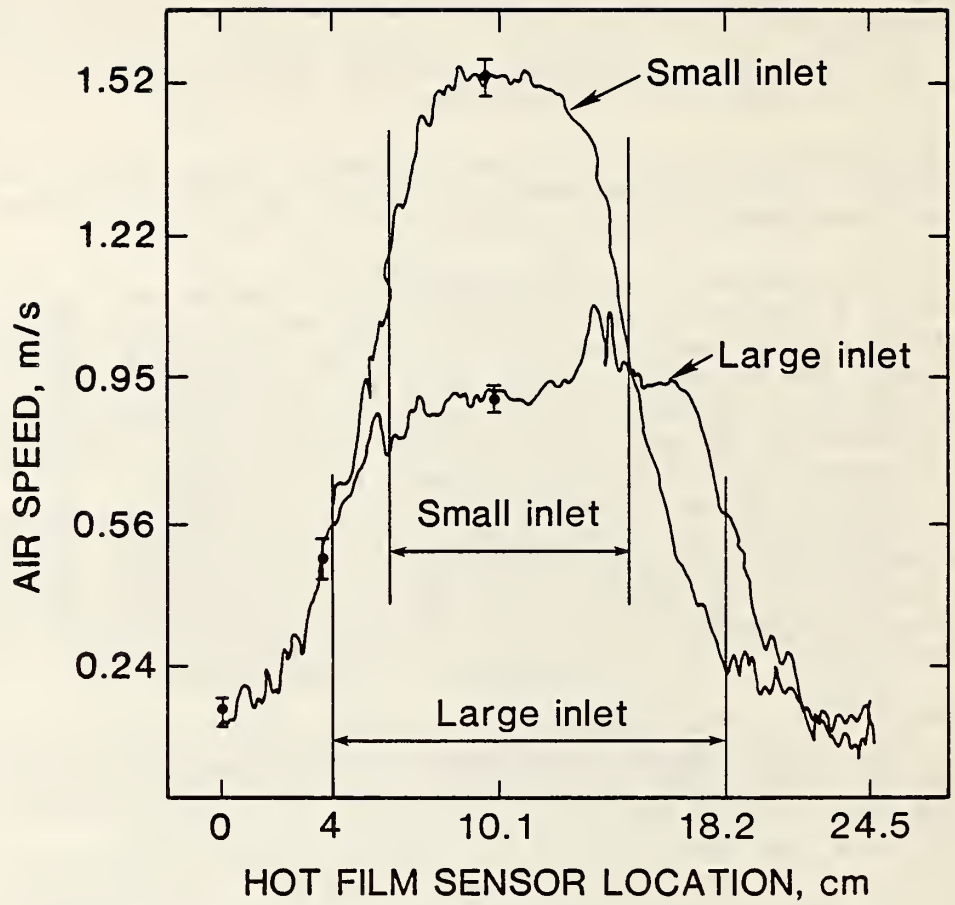

Figure 4. Air speed measurements for two different ion counter inlet geometries. The probe was 1.5 cm above the inlet and the scan was along the y position of 5.5 cm (see fig. 2). The large opening was 14.2 x 11 cm, and the smaller 9 x 8.3 cm, and the relative locations of the openings are shown on the figure. For these measurements the volumetric flow rate was about 0.017 m^3/s. The vertical scale is non-linear (see text).

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.

The planned activities for FY84 include:

1) Preparation of conference and archival papers presenting results of our measurements on the production rates for the oxyfluorides SOF_2, SO_2F_2 and SOF_4, and SO_2 and H_2O generated by corona discharges in SF_6 or SF_6/H_2O mixtures;

2) Extension of the measurements on by-product production rates in gas discharges to the mixtures, $SF_6 + O_2$, $SF_6 + N_2$, $SF_6 + CO_2$, and $SF_6 + c\text{-}C_4F_8 + CHF_3$;

3) Compilation of a computerized bibliography of electrical breakdown data in insulating gases and publication of this bibliography in an NBS report;

4) Investigation of the effects of trace quantities of water vapor on the enhancement of electron avalanche growth and corona discharge development in SF_6.

During the past reporting period emphasis was given to activities 1, 2, and 3. Some of the progress made in these activities is highlighted in this report.

As part of activity 1, a paper entitled "Production Rates for Discharge Generated SOF_2, SO_2F_2, and SO_2 in SF_6 and SF_6/H_2O Mixtures" by R. J. Van Brunt, T. C. Lazo, and W. E. Anderson has been accepted for publication in the Proceedings of the Fourth International Symposium on Gaseous Dielectrics, Knoxville, Tennessee, 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.

Concerning activity 3, a bibliography of data on electrical breakdown in gases has been completed and is available as an NBS Technical Note [5]. The bibliography contains 1) a list of archival papers and books that present data on electrical breakdown in gases and which have been published since 1950; 2) a computer generated index indicating the references that give particular types of data for each gas; 3) an author index; and 4) a list of relevant technical conferences.

The citations given in the bibliography contain experimental or theoretical data on breakdown which include: 1) sparking potentials; 2) breakdown voltages; 3) critical fields, or field-to-gas density ratios; 4) corona inception voltages; 5) voltage-time characteristics; 6) relative and absolute dielectric strengths; and 7) breakdown probabilities. The types of data which were considered include those which apply to: 1) uniform and nonuniform electric fields; 2) ac, dc, and impulse voltages; and 3) possible special effects associated with particles, surfaces, interfaces, and corona. The bibliography is intended to serve as a guide in locating data on breakdown which are most

relevant to particular applications. All gases likely to be encountered in electrical insulation applications are included. Any omissions are due either to a failure to locate relevant references or to a complete lack of data. Copies of the bibliography are available from the National Bureau of Standards, Electrosystems Division, Gaithersburg, MD 20899 and from the Government Printing Office.

The emphasis of our effort during the past quarter was on activity 2. Measurements were made of the charge and energy rates of production of stable, gaseous, oxygenated species from negative, point-plane corona discharges in SF_6 containing O_2 at levels from 0.5 to 10 percent. Absolute production rates were measured for SOF_2, SO_2F_2, SOF_4, CO_2, CO, and H_2O for a total gas pressure of 200 kPa (~2 atm) and at a constant discharge current of 40 μA. Examples of some of the production data are shown in figures 5-8. Except for the data in figure 7 for carbon monoxide, the results plotted in these figures correspond to absolute concentrations in μ moles versus net charge transported in the discharge gap in coulombs as given by Q = It, where I is the discharge current and t the time at which a measurement of gas composition was made. For CO, only relative concentrations in arbitrary units were determined.

It is seen in figure 5 that the introduction of oxygen into SF_6 results in a net decrease in the SOF_2 production rate, whereas from figure 6 the SO_2F_2 production is only slightly affected by oxygen. The production rates, it should be noted, are given by the slopes of the curves that have been fit to the data. The error bars indicate the maximum uncertainties associated with variations in the response of the gas chromatograph-mass spectrometer (GC/MS) used to perform the quantitative gas analysis. It has been determined that these variations are due primarily to chromatograph-column, membrane, and ion source conditioning effects whereby the transmission (or efficiency) of the column-membrane combination for passage of certain species depends on its past history, in particular the number and frequency of previous injections containing the same gases. For the column used in these measurements, the effect was found to be most noticeable for the more polar gases like H_2O and SOF_2. The conditioning of the ion source in the mass spectrometer is a temperature-dependent effect related to the time that the filament in the electron gun remains on. The effect can be reduced by preheating the ion source prior to injecting a gas sample.

The reduction of about 45 percent in the charge-rate of SOF_2 production at 40 μA brought about by introducing 3.0 percent O_2 is somewhat surprising and possibly indicates that O_2 has a significant effect on the dissociation rate of SF_6 through modification of the electron energy distribution in the discharge. If one assumes, for simplicity, that the production of SOF_2 can be accounted for predominantly by the gas phase reactions

$$e + SF_6 \rightarrow SF_4 + 2F + e, \qquad (1)$$

followed by

$$SF_4 + H_2O \rightarrow SOF_2 + 2\,HF\ , \qquad (2)$$

then, because reaction (2) is known to proceed at an extremely high rate [6], SOF_2 production will be governed by reaction (1), i.e., the electron induced dissociation rate for SF_6 leading to SF_4 fragments. The dissociation rate ν of

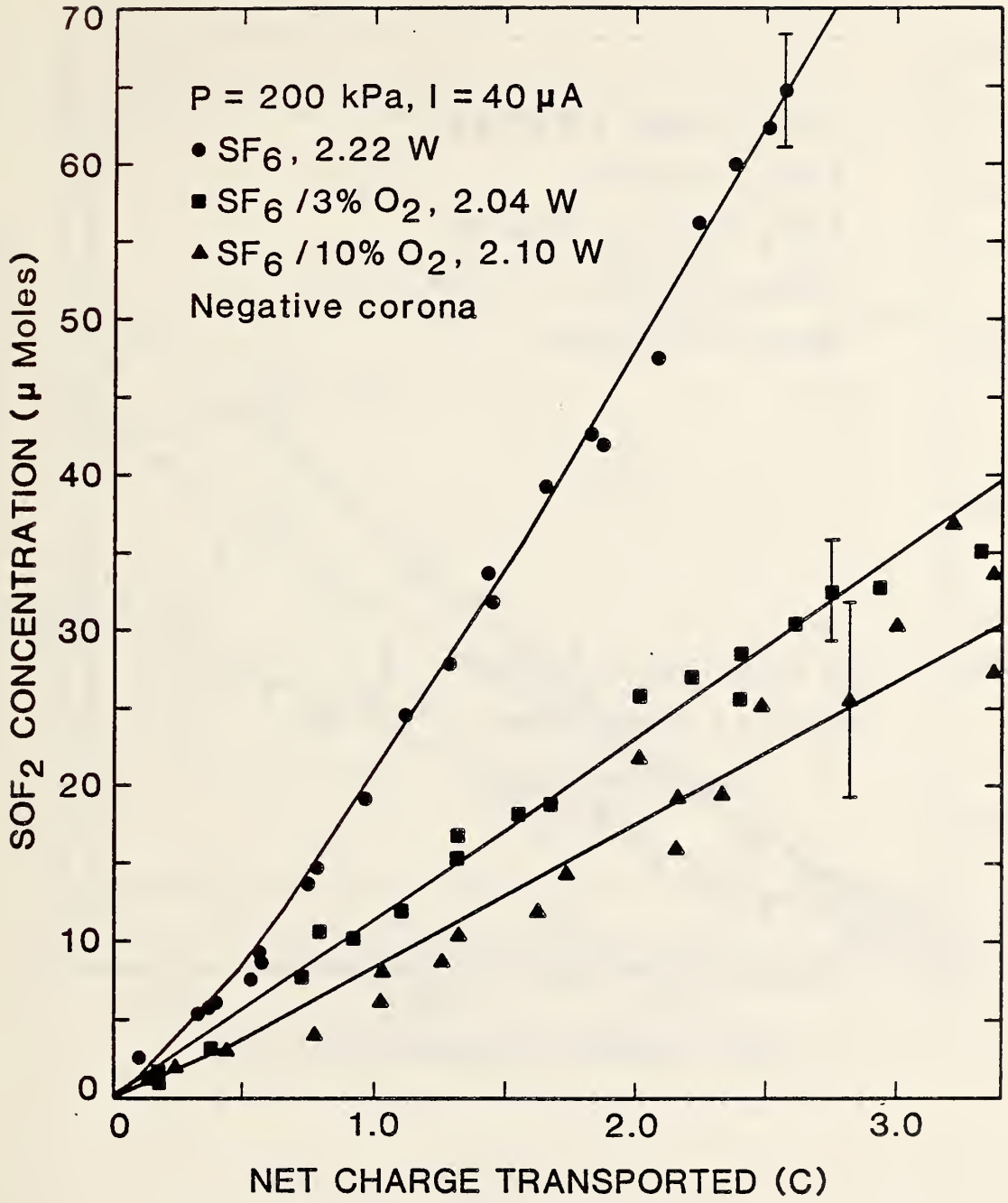

Figure 5. Measured concentrations of SOF_2 versus net charge transported in a point-plane negative corona discharge in SF_6 and SF_6/O_2 mixtures at the indicated discharge power levels. The absolute gas pressure is 200 kPa (~ 2 atm) and the discharge current is 40 μA for all data.

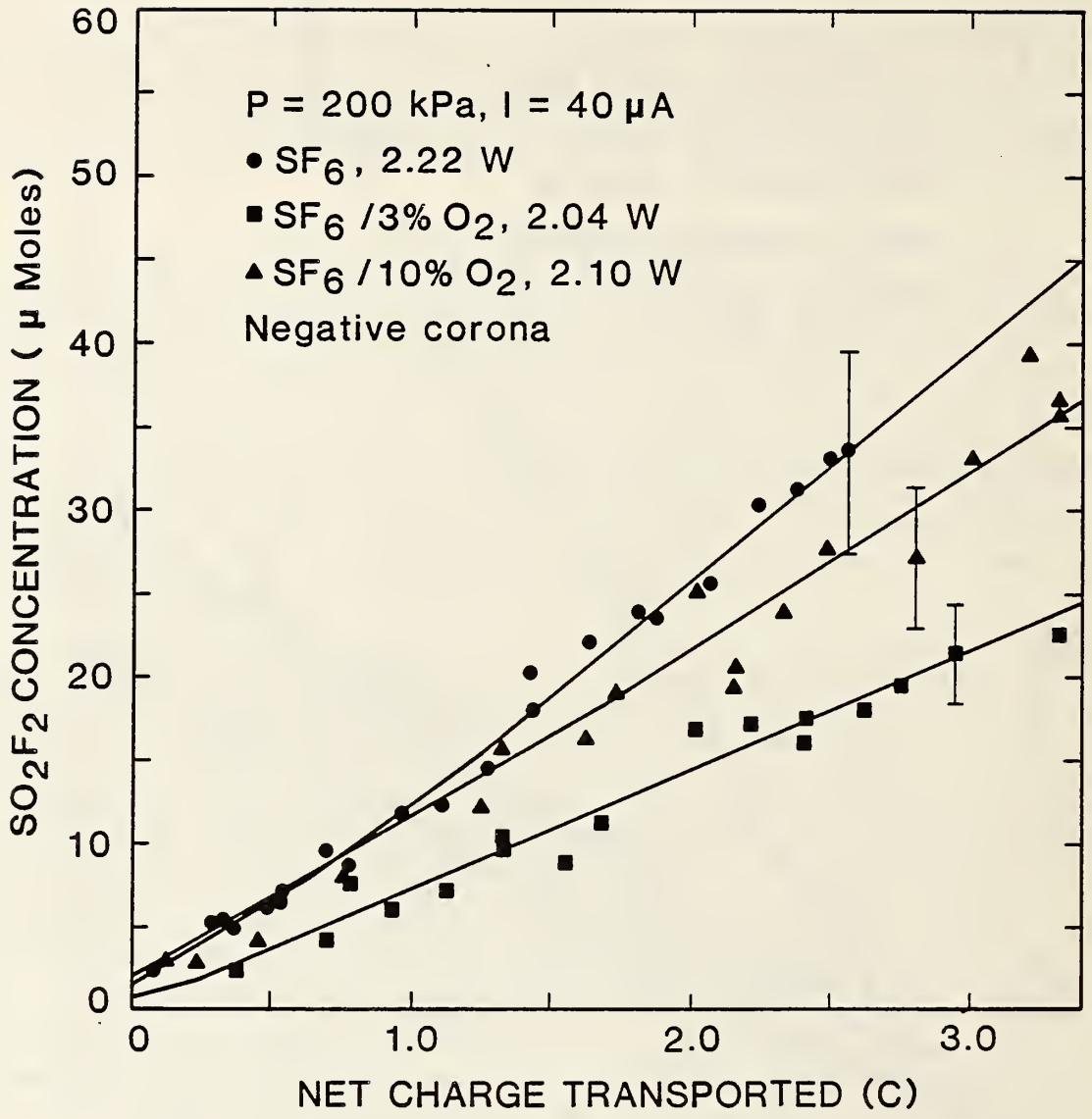

Figure 6. Measured concentrations of SO_2F_2 versus net charge transported in a point-plane negative corona discharge in SF_6 and SF_6/O_2 mixtures at the indicated discharge power levels. The absolute gas pressure is 200 kPa (~ 2 atm) and the discharge current is 40 μA for all data.

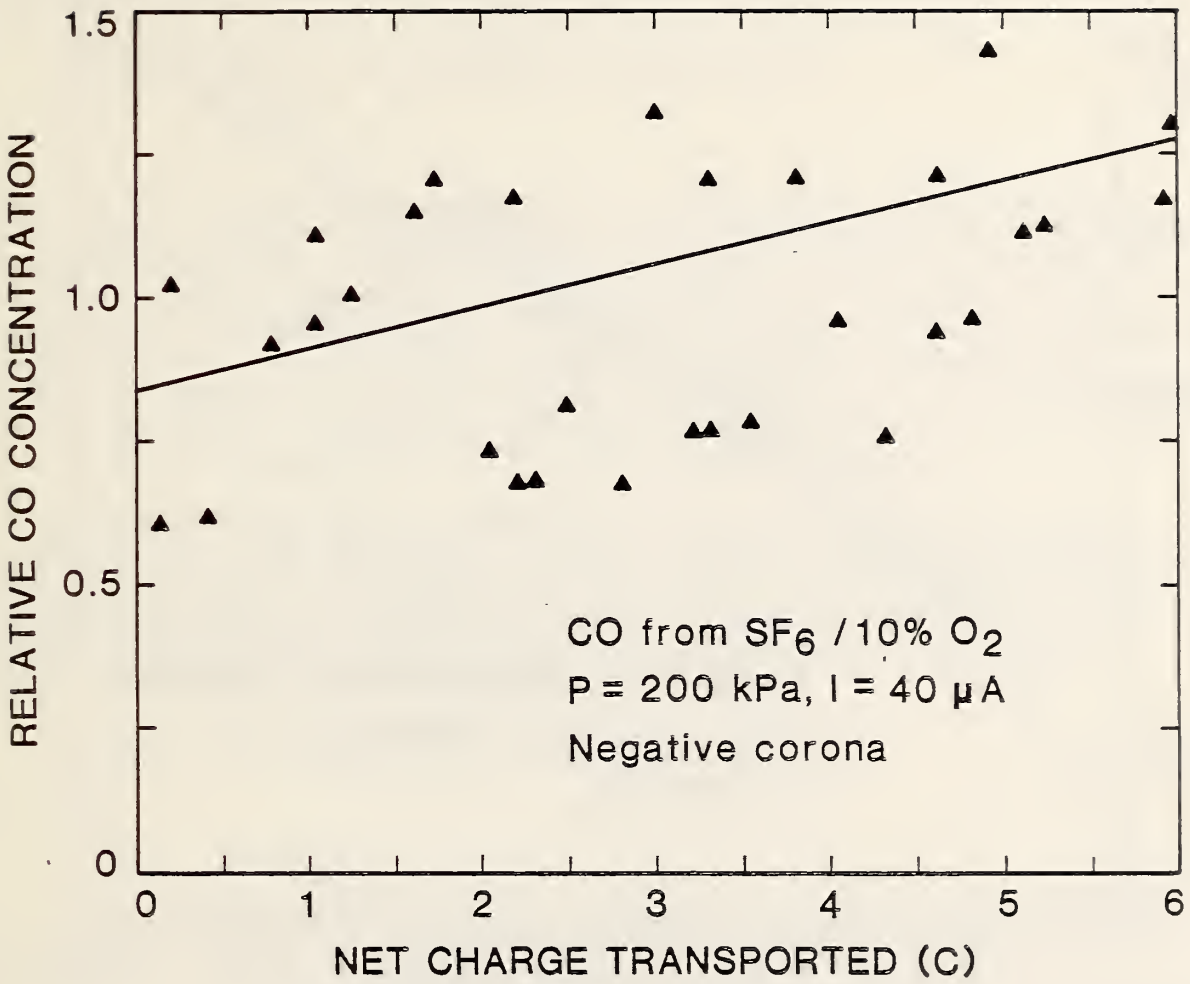

Figure 7. Measured relative concentration of gaseous carbon monoxide versus net charge transported in a point-plane negative corona discharge in an SF_6/10% O_2 mixture. The absolute gas pressure is 200 kPa and the discharge current is 40 µA.

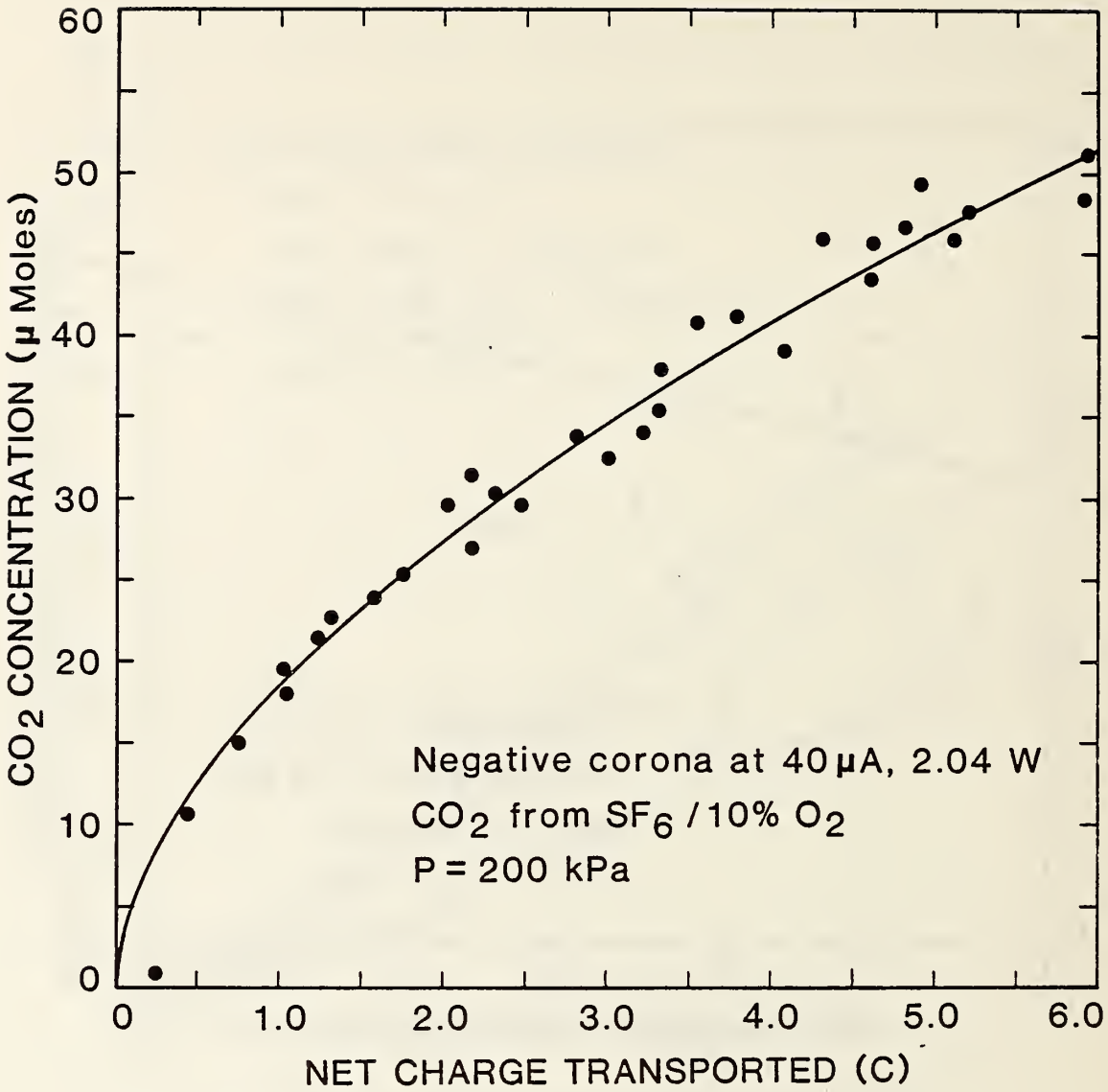

Figure 8. Measured concentration of carbon dioxide versus net charge transported in a point-plane negative corona discharge in an SF_6/10% O_2 mixture. The absolute gas pressure is 200 kPa and the discharge current is 40 μA.

SF_6 corresponding to SF_4 production is related to the spatially dependent electron energy distribution function $f(\varepsilon, x)$ by the expression

$$\nu = \frac{N}{m^{1/2}} \int_V n_e(\vec{x}) \sum_n \int_0^\infty \varepsilon^{1/2} f(\varepsilon, \vec{x}) \sigma_n(\varepsilon) d\varepsilon \, d^3x \ , \tag{3}$$

where N is the SF_6 gas number density, m, ε, and x are the electron mass, kinetic energy, and position respectively in the discharge volume V, $n_e(x)$ is the spatially dependent electron density, and $\sigma_n(\varepsilon)$ is the cross section for excitation to the nth antibonding state of SF_6 which yields an SF_4 fragment. It is conceivable that the well known [7] resonantly enhanced inelastic scattering of electrons from O_2 in the energy range of 0.3 to 1.4 eV gives rise to a significant lowering of the mean electron energy as given by $f(\varepsilon, x)$ sufficient to affect the rate ν. It would be desirable to verify this by attempting to solve the Boltzmann Equation for $f(\varepsilon, x)$ with SF_6/O_2 mixtures.

The fact that the SO_2F_2 production is relatively unaffected by the introduction of O_2 and even shows a possible increase between the 3 and 10 percent O_2 mixtures is consistent with the proposed reaction scheme for its formation. In particular, formation of SO_2F_2 in the gas phase necessarily involves reactions of O_2 with the lower valence sulfur fluorides and free radicals from SF_6 dissociation such as

$$SF_3 + O_2 \rightarrow SO_2F_2 + F \tag{4}$$

and

$$SF_2 + O_2 \rightarrow SO_2F_2 \ . \tag{5}$$

Since SO_2F_2 formation in the gas phase from direct two-body encounters requires the presence of O_2, it is to be expected that as the O_2 concentration is increased, free radicals will be more readily removed from the gas by the oxygen thus inhibiting recombination which could form SF_4 as well as SF_6 and yielding a higher relative SO_2F_2 rate of production as compared to SOF_2 which, according to reactions (1) and (2) above, need not require O_2 for its formation.

This is consistent with previous investigations of decomposition in SF_6/O_2 mixtures resulting from laser-induced multiphoton processes [8] and spark or arc discharges [9]. It is also consistent with measurements on processes relevant to plasma etching of silicon and silicon oxide in SF_6/O_2 mixtures [10].

The presence of O_2 also seems to affect the production of SOF_4. A preliminary analysis of the results for this species suggests that the effect in this case is like that for SOF_2.

With the introduction of O_2, the production of CO was found to be insignificant as indicated by the data in figure 7. The CO which was observed appeared to be a contaminant of the O_2 gas used and exhibited very little change in concentration during the course of the experiment. The production of CO_2 however was dramatically increased by the presence of O_2. Its production rate in pure SF_6 was too low to measure. Figure 8 shows its production in the SF_6/10% O_2 mixture. It is seen that the CO_2 production rate is initially quite high and then diminishes in time, or equivalently with charge transported. This is in contrast to the production rates for the oxyfluorides which are either

constant or exhibit a slight increase with time. The behavior of the CO_2 production with time appears to be consistent with a formation mechanism involving direct reaction of O_2 with carbon at the hot surface of the stainless steel point electrode. As the carbon from the electrode surface is depleted, it can be expected that the production of CO_2 will decline as observed.

Another significant difference between the discharge-induced decomposition of SF_6 with and without O_2 appeared in the rate of solid sulfur deposition on the planar anode surface. Sulfur deposits had previously been observed in pure SF_6 at 200 kPa only for negative corona discharges at currents in excess of 60 μA. The deposits which have been observed are roughly uniform within a circle of about 1.2 cm diameter centered about a perpendicular line from the point electrode. This pattern suggests a condensation of S^- ions originating in the discharge region. The sulfur ions would tend to follow the circularly symmetric field lines from the point thus giving the circular pattern observed. No attempt has yet been made to measure the amount of sulfur deposited; therefore no rates of deposition could be estimated. Nevertheless, there appeared to be no noticeable sulfur deposition from pure SF_6 for negative corona at 40 μA after 24 hours of operation. When O_2 was introduced at the 3 percent level, a significant and easily recognized sulfur deposit appeared at 40 μA after a comparable discharge duration. Deposits also appeared in the mixture containing 10 percent O_2 at the same current level. This observation tends to confirm the suggestion made above that O_2 inhibits the recombination of free radicals resulting from dissociation of SF_6. In this case the O_2 effectively removes free fluorine radials to form the oxyfluorides, thereby preventing recombination with S^- ions. The S^- ions, because they have a higher mean drift velocity in the direction of the field, will tend to exit the active discharge region more readily and are consequently more likely to survive and be deposited than neutral fragments like free sulfur atoms. The fact that S^- ions are formed is in itself a significant observation, for it indicates that there exists sufficient energy within the discharge to effectively completely dissociate SF_6 molecules. It is doubtful, however, that this occurs in a single step. The formation of S^- probably results from electron induced dissociation of free radical fragments like SF_2 and SF generated by previous electron collision processes in the gas. Again, removal of these by O_2 should reduce the rate of recombination thus yielding a higher probability for dissociative attachment of free radials leading to S^- formation.

The data on H_2O formation in the mixtures containing O_2 appeared to be similar to the data for pure SF_6. However, from measurements made before and after the discharge was extinguished for a prolonged time (> 16 h) there appeared to be less change in the H_2O content for the oxygen containing gases. This suggests that the discharge in these mixtures is less effective in suppressing the equilibrium level of water vapor than is the case in pure SF_6. This observation is consistent with the decrease in SOF_2 production which occurs when O_2 is added since formation of this species via reaction (2) could account for the consumption of H_2O in the gas phase.

With assistance from Dr. Darryl DesMarteau of Clemson University, samples of pure SOF_4 gas were prepared in the past quarter by direct reaction of SOF_2 with F_2 in a high pressure vessel at elevated temperatures. This gas can be used to prepare standard samples to calibrate the GC/MS system for quantitative measurements of SOF_4 production in gas discharges. Test samples containing known trace quantities of SOF_4 in SF_6 have already been prepared and successfully analyzed with the GC/MS. A calibration method was devised

employing a determination of the relative GC/MS responses to SOF_4 and SOF_2 at a particular mass-to-charge ratio corresponding to the SOF_2^+ ion (mass 86). This method will enable analysis of all previous GC/MS data on SOF_4 to determine its absolute production rate in SF_6 corona discharges under a wide range of conditions. Preliminary analysis of some existing data has revealed that SOF_4 is generated at a rate that is comparable to that of the other oxyfluoride species SOF_2 and SO_2F_2 under most conditions. The results of our analysis of SOF_4 production should be highlighted in our next report.

Planned activities for the next quarter include the following:

1) An archival paper describing all of the results on production of stable, oxygenated, gaseous species from corona discharges in SF_6 as well as giving detailed information about the analytical techniques employed will be prepared.

2) Further measurements will be made on the influence of O_2 on decomposition rates of SF_6 in point-plane corona discharges. The measurements may also be extended in the next quarter to SF_6/N_2 mixtures.

3) Analysis of all previously acquired data on SOF_4 production in SF_6 corona discharges will be completed in order to determine the absolute production rates for this species.

4) New procedures for minimizing errors associated with GC/MS column and ion source conditioning effects in quantitative analysis of gases will be investigated. The purpose of this is to improve the accuracy and reliability of our measurements on discharge-generated gas species production rates.

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

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 the interfacial electric field and space-charge density in materials for electric power equipment and systems, to understand the interfacial prebreakdown and breakdown processes in specified insulating systems, and to demonstrate the applicability of the developed instrumentation and the procedures in the development and design of future systems.

The 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 the liquid and liquid-solid system:

   a. The electric field between conductors and in the vicinity of interfaces,

   b. Breakdown strengths of selected interfacial systems and liquids,

c. The characteristics of the prebreakdown streamers in liquids and in the vicinity of interfaces.

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

Since it is impossible to clean a system perfectly, it is not possible to draw a clear dividing line between these two areas of interest, but experiments can be conducted which concentrate on specific areas of interest. To perform this study, two experimental systems have been developed:

1. Optical Field Measurement (OFM) system to determine the electric field in transformer-oil with and without interfaces and with and without the addition of specific contaminants. This apparatus is capable of regulating the temperature of the oil under study.

2. Electrical Breakdown Photography (EBP) system to provide high-speed photographs of the time-evolution of the entire breakdown process, both pre- and post-breakdown.

The OFM system supports electro-optical field measurements in liquids as well as temperature-dependent breakdown studies. The EBP system is generally used to document streamer propagation characteristics in liquids.

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 outstanding results have been the documentation 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 uncertainty of the experiment. These results clarify the role of space charge and surface charge in the failure of practical insulation systems. The work this quarter extends these results to include an interface perpendicular to the field.

With the EBP system many liquids have been investigated and a general picture of the electrical breakdown process has been obtained. These methods can now be extended to investigate a broader range of experimental conditions. 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 [11,12]. These results were obtained with liquids alone using both the point-plane and quasi-uniform electrode geometries. The work this quarter focuses on the initiation of the streamer.

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 [13]. Such results were achieved using carefully prepared paper samples and careful liquid-handling procedures -- the data were taken at room temperature. This is not to say that in practical systems the interface will not break down at a lower voltage. The effects of the voids or particles which might be found in practical systems were not

systematically investigated. Last quarter a cell was developed to permit the extension of this work to higher temperatures. This quarter's work corrected several deficiencies of that cell and obtained the first complete set of data for a range of temperatures.

4.1 Temperature Dependence of Breakdown Voltage of Transformer Oil With and Without a Paper Interface

A paper interface is placed between uniform field electrodes touching both electrodes and aligned with the direction of the field, and the assembly is placed in transformer oil. As described in the previous quarterly report, the interface can be changed from outside the cell so that high-temperature data may be obtained rapidly. This cell required several modifications this quarter before sustained high-temperature operation could be accomplished.

The paper was carefully dehydrated by baking in a vacuum oven and the transformer oil was dehydrated by bubbling dry nitrogen through it after which it was degassed in a vacuum. The temperatures used in this were 27°C, 76°C, 100°C, and 125°C. The results are presented in figure 9. When an interface was present the breakdown did not necessarily occur at the interface and the interfacial breakdown voltage was not necessarily lower -- the same results as were obtained previously when the study was initially conducted several years ago at room temperature. It is interesting to note that previous work [14] showed a variation of the breakdown voltage with temperature while no similar tendency is shown by these data. The reason for the difference will be addressed in future experiments, but there is a plausible explanation for the difference if one is willing to assume that the breakdown voltage can be influenced by the electric field distortion induced by space charge. Previous work has shown a tendency for greater field distortion under dc than under ac voltage and for the distortion to increase with increasing temperature. In light of these results, one would expect to record the largest effect under direct voltage at elevated temperatures. This expectation is consistent with our measurements. An additional confounding factor arises because it has been observed that the amount of space charge formed may vary significantly from sample to sample of oil [15]. Thus, if one uses different samples to investigate waveform and/or temperature effects, care should be taken to assure that the levels of space charge are comparable in all of the samples.

It is important to note that these results do not suggest that an interface parallel to the field is always just as strong as the oil but they suggest that it can be. The paper used in these experiments is carefully handled to eliminate the possibility of voids and water as much as possible. In the near future, further experimentation will employ oil and paper which will not be so carefully prepared. It is anticipated that under less favorable conditions the interface will be found to be weaker than the oil.

There is also a possible systematic effect due to the temperature dependence of the oil's viscosity. At room temperature the oil seems to be more likely to be contaminated with particles which inevitably are always present despite the cleaning methods. However, at higher temperatures where the oil exhibits lower viscosity, the ability of the oil to support larger particles is impaired. Additionally, the effectiveness of the pump increases so that more liquid is filtered per unit time during the course of the experiment. This potential problem with dirt may explain the difference in the data at room

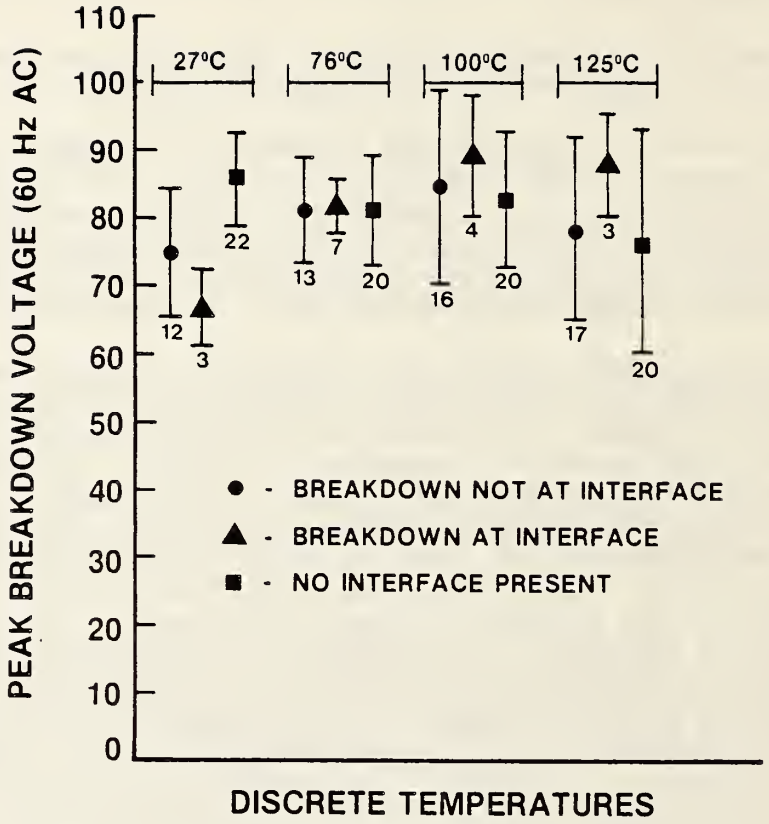

Figure 9. Breakdown voltage of transformer oil with and without a paper interface bridging the uniform-field gap under the application of 60 Hz ac voltage. At each temperature, ten breakdowns are made without an interface present in the gap and then twenty interfaces are employed after which ten more breakdowns are made without an interface present. When interfaces are present, a new interface is used after each breakdown. The numbers beneath the error bars are the number of breakdowns used to determine each point. The error bars are the standard deviations associated with each group of measurements.

temperature compared with the data taken at higher temperatures. The room temperature data exhibits the "expected" behavior in that the breakdowns occurring at the interface occurred at the lower voltage. Even so, not all the breakdowns occurred at the interface. It is expected that better data will be obtained if the temperature cycling time can be reduced as is planned in a forthcoming revision of the apparatus.

4.2 Space and Surface Charge Associated With a Pressboard Interface Perpendicular to the Field

In a previous research effort, the field in the vicinity of an oil-pressboard interface was investigated with the interface parallel to the uniform field direction. It was determined that there was no measurable field enhancement due to surface charging of the interface. This quarter, the interface was placed perpendicular to the applied uniform field. Electro-optical field measurements were made and revealed that the field on either side of the interface was reduced from what it would be if the interface were not present, see figure 10. The positive 60 kV applied voltage over the 1 cm gap was from 60% to 80% of the breakdown voltage of the interfacial system.

Since the relative permittivity of oil is about 2.2 and for dehydrated pressboard it is 4.4, one would expect to see the field stronger in the oil outside the pressboard. This is not what is observed. Figure 10 shows that the field in the oil on either side of the pressboard is roughly 20% lower than the uniform field value E_u. This proves that there is surface charging of both sides of the interface and that the field inside of the pressboard is larger than E_u. Given the geometry and field shown in figure 10, calculations showed a minimum surface charge on the order of 40 nC/cm^2 with a positive surface charge on the surface of the pressboard nearest the anode and a negative surface charge on the surface of the pressboard nearest the cathode. The resulting field within the solid pressboard appears to be about four times larger than it would be without the surface charge.

At elevated temperatures, 107°C and 125°C, space charge field enhancement became apparent in the liquid -- again, it was negative space charge near the anode which is typical for the oil used. The presence of the space charge did not seem to modify the above observed surface-charging phenomena, because the field on each side of the interface was substantially reduced from what it would have been if the interface were not present. Because of measurement difficulties associated with the higher temperatures, the possible temperature dependence of the magnitude of the surface charge has not been measured yet.

4.3 Electrical Breakdown in Liquids -- Streamer Initiation

There has been some informal debate concerning the role of the local field in the initiation and development of streamers in liquids. During discussions at conferences, some have speculated that the origin of the streamer is as independent upon surface features of the metal or even sub-surface features as it is upon the field at the surface. Experiments were initiated this quarter to address this issue. The work was done in collaboration with E. O. Forster and G. J. FitzPatrick of Exxon Research and Engineering Company.

The needle-plane electrode geometry in cyclohexane was analytically modeled by a hyperboloid above a plane to determine the field strength along the metal

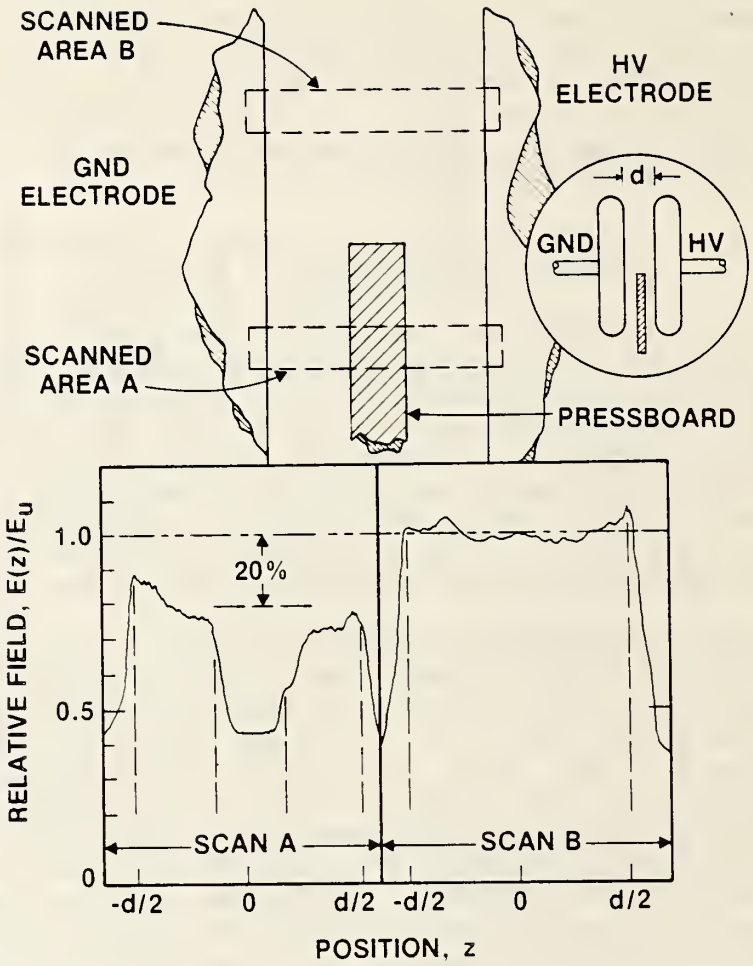

Figure 10. The field on each side of a pressboard interface placed perpendicular to the uniform field. 60 kV was applied, the gap was 1 cm. The inset shows the entire view of the electrode geometry. The electro-optical scanner measures the field in the oil only. The field on each side of the pressboard interface can be compared with the field between the plates where the interface is not present -- E_u, the uniform field. The important feature to note is that the field on each side of the pressboard is roughly 20% lower than the uniform field. Any nonuniformity in the field which may be indicated cannot be taken too seriously in view of the problems with dirt and cellulous "hairs" on the surface of the pressboard which serve to either obscure the light or produce a slight intensification of the light due to depolarized scattering. Generally speaking, the field measurements at the midpoints of the regions between the pressboard and the plates are probably quite accurate, within ±5% of their true value -- the overall measurement accuracy of the measurement system.

surface of the tip. The data obtained from the experiment suggested that the first streamer initiated only in the highest field region near the point of the tip. After the streamer initiates it is hypothesized that the streamer grades the field at the tip so that a high-field region occurs further down the shaft of the needle. Computer modeling of this possibility is presently being explored by the team at Exxon. It is anticipated that the results of these studies will show that the location of streamer initiation is dominated by the local field intensity at the metal surface. It is of interest to note that with a gap of 1 cm and tip radius of 25 μm the initiation fields at the tip were on the order of 4 MV/cm for the approximately 3 μs rise-time pulses used.

4.4 Plans for Next Quarter

A thorough study of the effects of temperature, space charge, additives, and electrode material upon the breakdown strength of transformer oil will be continued. Additionally, to successfully complete the study of the problem of the interfacial breakdown of a paper interface parallel to the field, an experimental arrangement needs to be developed to permit the rapid changing of the temperature of the experimental system. Presently, more than three days is required to take the present system to 150°C and back to room temperature. It is anticipated that the new apparatus will permit the same cycle to be reduced to less than three hours -- neglecting the time needed to take data, of course. Completion of this new apparatus is scheduled for the next quarter.

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

5. REFERENCES

[1] R. H. McKnight, F. R. Kotter, M. Misakian, and J. N. Hagler, 1981 Annual Report: Electric and Magnetic Field Measurements, Nat. Bur. Stand. (U.S.), NBSIR 82-2527 (1982).

[2] R. H. McKnight and P. M. Fulcomer, Operation of Ion Counters Near High Voltage DC Transmission Lines, presented at the 4th International Symposium on High-Voltage Engineering, Athens, Greece, Sept. 1983.

[3] M. Misakian, Generation and Measurement of DC Electric Fields with Space Charge, J. Appl. Phys., Vol. 52, pp. 3135-3144, 1981.

[4] "Development of Power System Measurements -- Quarterly Report, January 1 - March 31, 1983," R. Hebner, ed., Nat. Bur. Stand. (U.S.) NBSIR 83-2761, (1983).

[5] R. J. Van Brunt and W. E. Anderson, "Bibliography of Data on Electrical Breakdown in Gases," NBS Tech Note 1185 (1984).

[6] I. Sauers, H. W. Ellis, L. C. Frees, and L. G. Christophorou, "Studies of Spark Decomposition Products of SF_6 and SF_6 Perfluorocarbon Mixtures," Gaseous Dielectrics III (L. G. Christophorou, ed.) Pergamon Press, New York (1982) pp. 387-401.

[7] G. J. Schulz, "Resonances in Electron Impact on Diatomic Molecules," Rev. Mod. Phys., Vol. 45, pp. 423-486 (1973).

[8] I. O. Leipunskii, A. K. Lyubimova, A. I. Nadeikin, and V. L. Talroze, "Investigation of the Process of Formation of Oxygen-Containing Products as a result of multiphoton Dissociation of SF_6 by Radiation from a High-Power Pulsed CO_2 Laser," Sov. J. Quantum Electron., Vol. 12, pp. 413-417 (1982).

[9] C. Boudene, J. Cluet, G. Keib, and G. Wind, "Identification and Study of Some Properties of Compounds Resulting from the Decomposition of SF_6 under the Electrical Arcing in Circuit Breakers," Revue Generale de l'Electricite (RGE), pp. 45-78 (1974).

[10] R. d'Agostino and D. L. Flamm, "Plasma Etching of Si and SiO_2 in SF_6-O_2 Mixtures," J. Appl. Phys., Vol. 52, pp. 162-167 (1981).

[11] G. J. FitzPatrick, E. O. Forster, E. F. Kelley, and R. E. Hebner, "Effects of Chemical Impurities on Prebreakdown Events in Toluene," 1982 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Oct. 17-21, 1982, IEEE Service Center, Piscataway, NJ, pp. 464-472, 1982.

[12] E. F. Kelley, R. E. Hebner, G. J. FitzPatrick, and E. O. Forster, "Effects of Aromatic Impurities on the Positive Streamer Growth in Marcol 70," IEEE International Symposium on Electrical Insulation, in press.

[13] E. F. Kelley and R. E. Hebner, "Electrical Breakdown in Composite Insulating Systems: Liquid-Solid Interface Parallel to the Field," IEEE Trans. on Elec. Insul. EI-16, pp. 297-303 (1981).

[14] "Development of Power System Measurements -- Quarterly Report, July 1 - September 30, 1983," R. Hebner, ed., Nat. Bur. Stand. (U.S.) NBSIR 84-2818, (1984).

[15] E. F. Kelley and R. E. Hebner, "Measurements of the Electric Field in the Vicinity of an Oil-Pressboard Interface Parallel to the Field," Conf. Record of 1983 Interfacial Phenomena in Practical Insulating Systems, Sept. 19-20, 1983, IEEE 83 CH1946-3, IEEE Service Center, Piscataway, NJ, pp. 19-22, 1983.

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 84-2898	2. Performing Organ. Report No.	3. Publication Date July 1984

4. TITLE AND SUBTITLE

Development of Power System Measurements -- Quarterly Report -- January 1, 1984 to March 31, 1984

5. AUTHOR(S) R. E. Hebner, Editor

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

Prepared for
Department of Energy
Division of Electric Energy Systems
1000 Independence Avenue, SW
Washington, DC 20585

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. 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 documents the progress on three technical investigations sponsored by the Department of Energy and performed by the Electrosystems Division, the National Bureau of Standards. The work described covers the period from January 1, 1984 to March 31, 1984. The report emphasizes the performance of ion counters like those used to measure the ions near dc transmission lines, the production rates of oxyfluorides in SF_6 corona discharges, and the measurement of space charge associated with a pressboard interface in transformer oil.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

cables; composite insulation; electric fields; high voltage; incipient fault; insulation; liquid breakdown; SF_6; space charge; transformer oil.

13. AVAILABILITY

☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES 29

15. Price $8.50

USCOMM-DC 6043-P80