NBSIR 81-2283

Development of Power System Measurements -- Quarterly Report January 1, 1981 to March 31, 1981

R. E. Hebner

Electrosystems Division
Center for Electronics and Electrical Engineering
U.S. Department of Commerce
National Bureau of Standards
Washington, DC 20234

April 1981

Prepared for:

Department of Energy
Office of Electric Energy Systems
12th Street & Pennsylvania Ave., N.W.
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Foreword

This report is intended to summarize the progress on four technical investigations during the second quarter of FY 1981. 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

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Robert E. Hebner, Jr., Editor

This report documents the progress on four 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 January 1, 1981 to March 31, 1981. This report emphasizes the errors associated with measurements of the vertical current density in an electrical environment consisting of a dc field with space charge, the measurement of rf attenuation in distribution cables, the onset characteristics of positive and negative corona in compressed SF_6 gas, and the measurement of the space charge density in transformer oil subjected to 60-Hz excitation.

Key words: cables; dc fields; high voltage; incipient fault; insulation; 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 four areas -- the measurement of electric fields, the measurement of the electromagnetic properties of solid insulating materials and cables, the measurement of partial discharge phenomena in gaseous dielectrics, and the measurement of interfacial electrostatic field distributions and of space charge density. The technical progress made during the quarter January 1 to March 31, 1981, is summarized in this report.

2. DC FIELDS AND ION MEASUREMENTS
Project No: A018-EES

The objectives of this effort are to investigate devices and measurement techniques which may be used to characterize the electrical environment near high voltage dc (HVDC) transmission lines, to evaluate methods being used for calibrating such devices, and to develop and establish calibration facilities at NBS which will permit independent verification of the accuracy of user calibrations.

Recent emphasis has been on ion-related measurements, including vertical current density and determinations of homopolar and net space-charge densities.

The study of the errors associated with measurements of the vertical current density in an electrical environment consisting of a dc field with space charge has extended over several reporting periods. During this reporting quarter, this study has been completed and the results are summarized in the following discussion. The measurement approach which was evaluated uses devices which have been used for many years in atmospheric electricity research under the name "Wilson plate." A Wilson plate is a conductor, generally a sheet of metal, which is connected to ground through an ammeter. The current density is determined by dividing the measured current by the appropriate plate area. The work which was completed during the reporting quarter was intended to evaluate the magnitude of the error introduced by the lack of coplanarity between the Wilson plate surface and the ground plane. As shown by the results, raising the Wilson plate above the ground plane increases the measured current in both the ac and the dc cases.

The Wilson plates were constructed from a 0.157-cm thick, copper-clad (on one side), fiber glass sheet. Two different-sized plates were studied; one was a square 10 cm on a side and the other was a square 8.5 cm on a side. For each size of plate, four different active areas were considered. For the 10-cm plate, centrally-located, square, active areas of 2.5, 5.0, 7.5, and 10 cm square were used. For the 8.5-cm plate, centrally-located, square, active areas of 2.5, 5.0, 7.5, and 8.5 cm square were used. In those cases in which the size of the active area was smaller than the size of the plate, a central section of the copper was isolated from the outer section by a narrow slot milled through the copper. The active region is connected to ground through an ammeter while, in those cases in which the active area is smaller than the plate, the square frame around the active area, which is called a guard ring, is grounded directly.

The measurements were performed using an NBS-developed parallel-plate facility [1] which permitted the generation of a known ac field or the generation of a known dc field with space charge. The Wilson plate under test was placed between the parallel plates of the test facility either on or a known distance above the test facility's grounded plate. Using 4 kV, 60-Hz excitation of the parallel-plate structure with a plate separation of about 0.5 m, displacement currents were measured with each of the plates listed above. For the dc tests, the electric fields ranged from 7-33 kV/m and current densities varied from 0.025 to 4 μA/m. Figure 1 summarizes the data taken with ac and the data taken with dc excitation. From this figure, it is seen that the width of the guard ring becomes increasingly significant as the elevation above the ground plane is increased. For example, this figure indicates that elevating a one-meter square Wilson plate 2 cm above the ground plane would introduce an error of the order 5 percent.

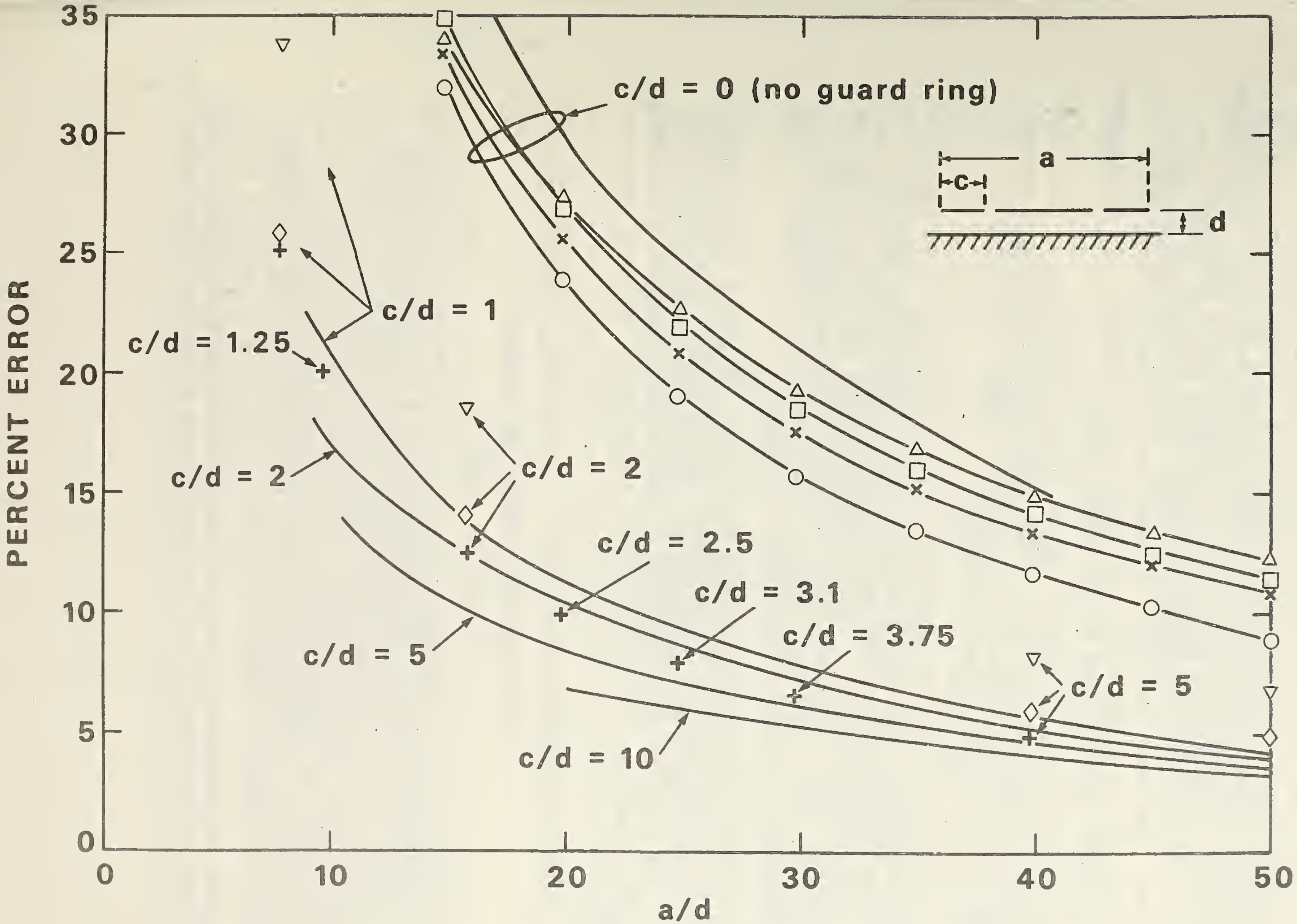

Figure 1. Summary of errors in Wilson plate current density measurements. For c/d = 0 (no guard ring), the upper solid line (with no data points shown) represents the ac data while those lines on which the data points are shown are the dc data. For c/d ≠ 0, the solid lines are the ac data and the data points are the data. The different symbols for these dc data represent different amounts of space charge with "+" indicating the lowest space charge contribution.

As shown in figure 1 measurements of the dc field with space charge indicate that, except for the case in which there is low space charge density and a guard ring, the ac and dc results were not the same.

It is postulated that the error in figure 1 is due to field distortion introduced by the Wilson plate and, in the dc case, because the space charge increases the conductivity of the air. It should also be emphasized that for the plates with no guard ring the dc data lies well below the ac data. This effect is presumably a result of the plate design used in this study. The fiber glass backing permitted the ions to reach only the top side of the copper plate. In the ac case, however, the displacement current coupled to both sides of the copper plate.

The conclusion of this study is that, in general, unguarded Wilson plates should be used only if the sensor plane can be made to coincide very closely with the ground surface. More flexibility is available if the sensing plate is guarded.

In addition to measuring the vertical current density, it is also important to measure the space charge density. During the reporting quarter, measurements were made on a high efficiency particulate air (HEPA) or "absolute" filter. It was determined that for a wide range of air flows and space charge densities, the filter removes more than 99 percent of the ions. The measurements suggest that the filtration devices can be developed for use in calibrating ion counters.

In the coming quarter, the summary of the work done with the absolute filter will be prepared for publication. NBS staff will also participate in a measurement field day to be held at Project UHV in Massachusetts. Finally, the study of ion-counters will continue with emphasis on modeling and on the comparison of calculations and measurements for parallel-plate ion counters.

For further information, contact Dr. R. H. McKnight, (301) 921-3121.

3. INCIPIENT FAULT DETECTION/LOCATION
Project No: A063-EES

The objective of this program is to identify and, insofar as practical, remove technical barriers to the development of a successful incipient fault detector/locator for underground power transmission use. NBS responsibility includes conducting an experimental program that will aid the development of an incipient fault detection/location system by measuring the rf characteristics of power cables and evaluating the frequency content of partial discharge pulses emanating from incipient fault sites in a cable dielectric.

Previous measurements at NBS had indicated that the attenuation of the high-frequency components in the applied voltage pulse limits the resolution.

One possibility is that the attenuation occurs because of the impedance mismatch between the TDR unit (output impedance of 50 ohms) and the power cable. Mismatched impedances between the TDR unit and the cable create a double loss inasmuch as both the incipient wave and the reflected wave (forward and reverse traveling waves) must pass through the mismatch interface. Also, multiple reflections can occur within the cable under these conditions which further complicate the analysis and understanding. A second possibility is that the high-frequency attenuation is caused by the inherent characteristics of the power cable.

Measurements had been made with a variety of impedance transitions (e.g., abrupt, resistively-adapted, tapered) between the test system and the cable in an attempt to separate the attenuation of the high-frequency components due to the transition coupler from the attenuation in the cable. By using the same transition couplers and cable terminations while measuring two different lengths of the same cable, we were able to study attenuation in the cable itself. The results were in good agreement with previous data obtained on single-length sections implying that the reflection problem had been properly treated. Since the results using the different techniques are consistent, we feel the systematic errors are negligible. Figure 2 shows the attenuation of a distribution cable sample (insulated with cross-linked polyethylene) as a function of frequency. These measurements indicated that of order 5 dB/m at 1 GHz. The implication of this attenuation in practical cables is demonstrated, by an example, in figure 3. This figure shows a comparison of the measured reflection from a short at the end of a 4 cm sample with the same coefficient for a 163 cm sample. The transition time of the reflection signal is about a factor of 2 less for the shorter cable than for the longer one because the longer cable attenuates the high frequency components of the signal.

Preliminary results suggest that the loss occurs primarily in the semiconducting screening layers adjacent to the inner and outer conductors. For the one cable studied, the removal of the outer screen layer reduced the attenuation from 4.1 dB/m to 1.8 dB/m at 1 GHz and further removal of the inner screen reduced the attenuation to 0.7 dB/m.

In summary, the high intrinsic attenuation of rf signals in extruded polyethylene distribution and transmission cables makes conventional time or frequency domain reflectometry techniques using frequencies below a gigahertz impractical for the detection of incipient faults. In a cable with modified screening layers detection at a distance of a few meters may be feasible. Since most of the losses do occur in the screening layers, another possibility exists. If higher frequency (several GHz) waveguide modes could be excited in the polyethylene in a frequency range of minimal attenuation, these modes should be extremely sensitive to the presence of small defects in the dielectric. Present efforts at NBS are aimed in that direction.

For further information contact Dr. W. E. Anderson, (301) 921-3121.

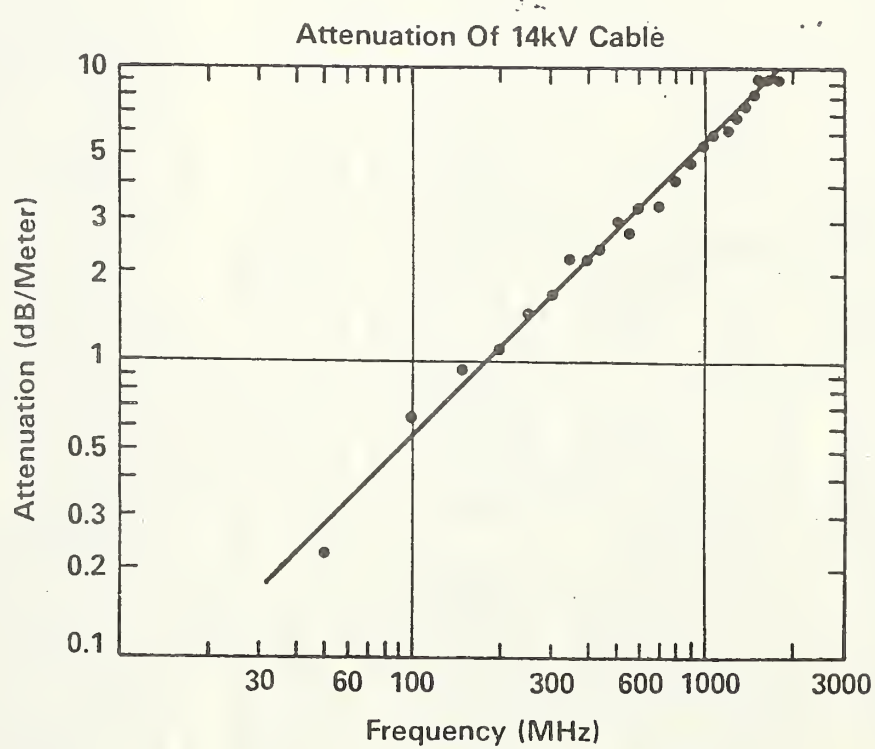

Figure 2. Attenuation in a distribution cable as a function of frequency.

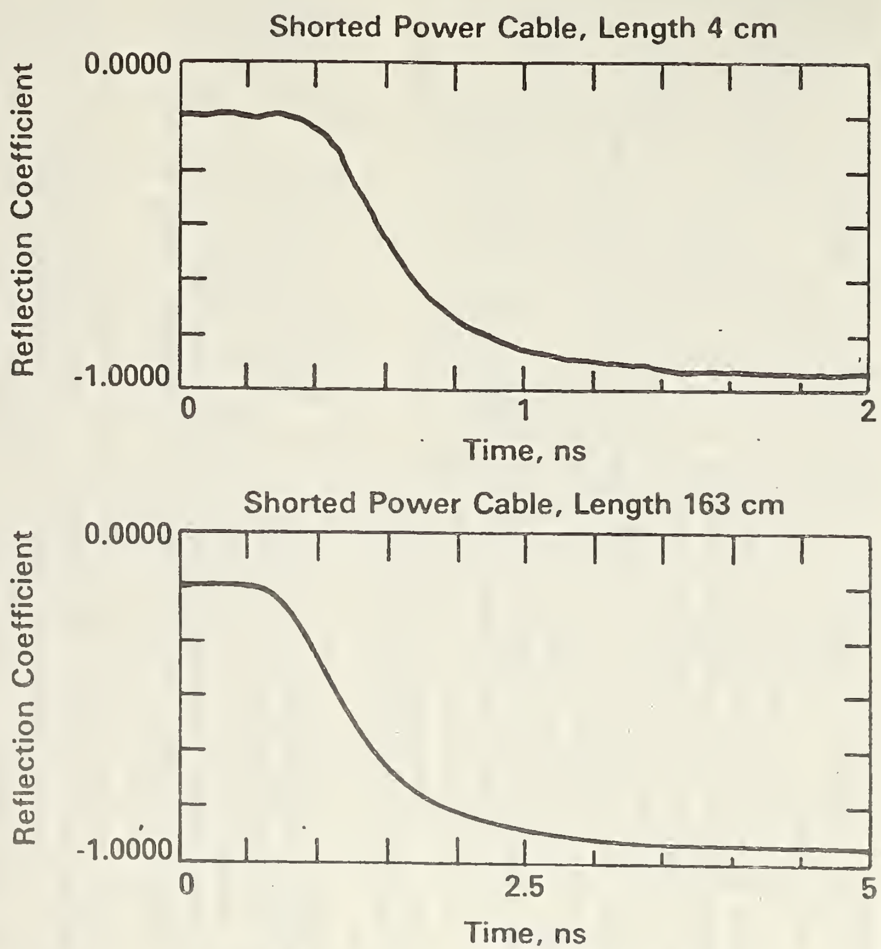

Figure 3. The upper drawing shows the reflection coefficient from a short encountered after a signal propagates through 4 cm of cable while the lower one shows the coefficient after 163 cm. The increase in transition time for the longer cable is attributed to high frequency attenuation.

4. TECHNICAL ASSISTANCE FOR FUTURE INSULATION SYSTEMS RESEARCH
Project No: A053-EES

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. Focus is on the fundamental information and data needed to improve test design and performance evaluation criteria. The investigation of partial discharges (corona) in gaseous dielectrics is emphasized. This phenomenon gives rise to degradation of the gas under high electrical stress and may lead to breakdown. Measurement of partial discharge inception in highly nonuniform fields may also prove to be a preferred method to determine dielectric strength of electronegative gases.

Planned activities for FY-81 include: (1) estimate the sensitivity of low-frequency dielectric constant measurements as a monitor of polar molecules in SF_6; (2) determine effects of trace amounts of H_2O and other polar gas molecules on partial discharge behavior in SF_6; (3) prepare an archival publication on pulse characteristics of positive and negative dc corona in SF_6; (4) examine the effect of radiation on electron avalanche development and measure the radiation emitted by corona; (5) identify gaseous decomposition products resulting from corona in mixtures of SF_6 with N_2, CO_2, c-C_4F_8 and CHF_3, and, for corona in SF_6, determine the rate of buildup of oxyfluorides as a function of discharge power; (6) model discharge inception and test these models in a controlled-ionization-zone test cell (in collaboration with MIT); and (7) initiate a program to evaluate electrical breakdown data for gases (in collaboration with NBS-JILA). In addition, there was an incomplete investigation in FY-80, namely, the measurement of laser-induced optogalvanic signals in electric discharges of rare gas-SF_6 mixtures to determine the effectiveness of SF_6 in quenching metastable species.

Progress was made during the reporting quarter on all activities except (1) which is completed and (2) which is nearly complete. The major effort, however, has been the completion of activity (3). An example of a recent accomplishment in this area at NBS is a study of the effects of point electrode diameter, uv radiation, and voltage polarity on the onset and pulse characteristics of dc corona for pressures from 50-500 kPa.

Previous measurements performed in our laboratory [2-4] and elsewhere [5] have shown that over the pressure range considered here, the onset of negative corona occurs at a lower voltage than does positive corona and the difference between the two increases with increasing gas pressure. This polarity effect is attributed to the longer time lag associated with initiating-electron production for positive corona compared to negative corona, i.e., once the electric field is high enough to permit development of electron avalanches of sufficient size, the probability for initiating electron formation is lower for a positive point electrode.

It is hypothesized that, in the absence of radiation, the electron-avalanche-initiating electrons for negative corona at onset are predominately produced by field emission from the point electrode surface, and for positive corona by collisional detachment of negative ions [6]. For the negative case, the extent to which field emission is possible is, of course, determined by the point electrode surface conditions [4]. If the work function of the surface is too high, or if the field at the surface is too low, as for points of relatively large radii of curvature, then the conditions for electron emission may not be satisfied and considerable overvoltage may be necessary to achieve inception. For such cases, the positive corona inception voltage may actually be lower than the negative inception voltage. If uv radiation is present, the probability for initiating electron production may be enhanced in the negative case by the photoelectric effect and in the positive case by photodetachment of negative ions.

Ignoring the probability for initial electron formation, theory based on the streamer criterion predicts that the positive and negative corona inceptions for SF_6 should be nearly the same [5,7]. Thus, if the probabilities for initiating electron production can be made comparable for each polarity, then the differences in inception should be reduced. This condition can be achieved either by irradiating the gap with uv-light or by increasing the size of the point electrode, i.e., diminishing the degree of field nonuniformity in the gap. In either case, the effect should be greatest for positive corona because the electron initiation probability for this case is lower due to the fact that the avalanche-forming electrons originate from a small active volume in the gas. This active volume is infinitesimally small at the theoretical inception and becomes larger with increasing voltage.

These predicted trends were verified by measurement of corona inceptions in SF_6 performed during the past reporting period. The results are indicated in figures 4a-d which show data on corona pulse rate and average discharge current versus applied dc voltage for two point-electrode diameters and two gas pressures. For figures 4a and 4c the point diameter was 0.94 mm and for figures 4b and 4d it was 0.1 mm. For the smaller point, data for both irradiated and nonirradiated gaps are shown. For the larger point, it was necessary to irradiate to observe corona. For negative corona in this case, the measured average discharge current is also shown. Details of the measurement system used to obtain these data have previously been given [2,4]. A comparison of the data in figures 4a and 4c with those respectively in figures 4b and 4d clearly indicate that the polarity difference was lower for the larger electrode. In figures 4b and 4d it is seen that the presence of uv radiation also reduces the effect. These observations are consistent with the proposed mechanisms for discharge initiation.

For the larger point diameter (0.94 mm), measurements were performed to determine the pulse-height distribution of the corona pulses. The trends in these data are consistent with those reported for corona from the 0.1 mm point [2,4,8]. In particular, the positive corona begins as relatively small electron avalanches with a mean amplitude less than 1.0 pC which changes abruptly at higher voltages (see the arrow in fig. 4c) into large streamer pulses, or pulse bursts with a mean amplitude greater than 10 pC.

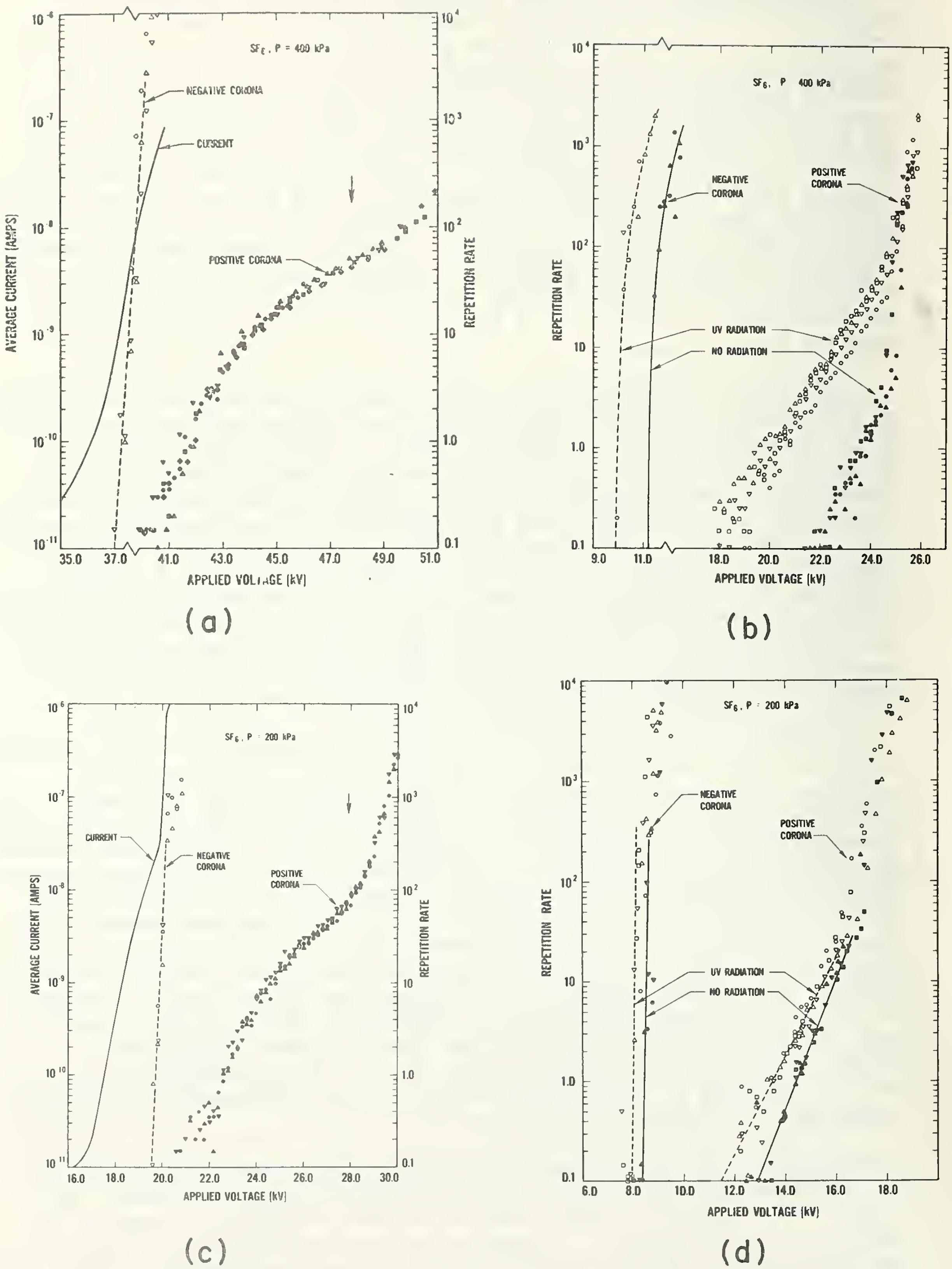

Figure 4. Corona inception measurements in SF_6. The data were taken for point-plane geometry; for (a) and (c) point diameter 0.94 mm, for (b) and (d) 0.1 mm. The repetition rate is the number of pulses measured per second.

During the next quarter, major emphasis will be placed on completing an archival paper on the comparison of ac and dc corona inceptions in SF_6. This is considered a follow up to the work presented at the 1980 CEIDP [3], and will indicate completion of activity [6]. An effort will be made to begin the measurements associated with activity [5]. More work will be performed on optogalvanic spectroscopy and on effects of uv radiation on corona in SF_6, activity [2]. The emphasis of the latter measurements will be on determination of wavelength dependence of the effect. Electric field calculations will be performed to aid the theoretical prediction of corona inceptions. Investigations will be carried out to improve the quantitative analysis of trace H_2O content in compressed SF_6.

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

5. OPTICAL MEASUREMENTS FOR INTERFACIAL CONDUCTION AND BREAKDOWN
Project No: A057-EES

The objective of this project is to develop techniques to measure the interfacial phenomena which influence the electrical breakdown characteristics of composite insulation systems. This study concentrates on oil-paper (pressboard) systems. The measurement of the electric field and/or the space charge is made electro-optically using the Kerr effect in transformer oil. This study is limited to those cases in which the solid insulator is either parallel or perpendicular to the electric field.

Previous NBS investigations have shown that for a clean, well-characterized system, breakdown does not necessarily occur at an oil-paper interface [9]. The study has been extended to include oils which are not of laboratory purity. Oil samples were obtained of two levels of contamination (one a rinse oil and the other oil removed from a transformer which had failed) from the Westinghouse Electric Corporation, Large Power Transformer Division, Muncie, Indiana.

Before the breakdown studies were performed, measurements of the space charge density were attempted by measuring the electric field as a function of position between parallel plates. Using the clean oil and the rinse oil, the distortion of the electric field due to space charge was less than ±3% of the average field. These measurements were made under nearly uniform field conditions, 60-Hz ac excitation, and at room temperature. More extensive measurements, however, were carried out in the most heavily contaminated oil. These measurements suggest that space charge effects may become significant at higher temperatures.

This contaminated oil, which had been removed from a transformer that failed, had the levels of particulate contamination shown in table 1 [10].

Table 1. Summary of particulate contamination

Particle Size µm	Number of Particles/ml Contaminated Oil	Normal Oil
3 - 150	1221	40 - 70
50 - 150	60	0.1 - 0.2

About 98-99% of the particulates were cellulose (from the paper or pressboard in the apparatus) with the remaining being iron or copper.

Figure 5 summarizes the electric field measurements in the contaminated oil. At room temperature, this oil exhibited no measureable field distortion, that is the electric field was uniform to within 2% of its average value. Near 55°C, the field was uniform to within about ± 2%; there may, however, have been some enhancement at the anode and a decrease of the electric field strength at the cathode.

For the temperature near 68°C a distortion was observed in the electric field profile. The change in the field from one plate to the other was about 5% of the average electric field between the plates. If this is space-charge field distortion, and not an artifact of the apparatus, then the space charge density which could produce such a distortion would be about -1.5 nC/cm^3. It must be stressed that this is a preliminary measurement and must be further substantiated before confidence in such a result is established. In comparison, the amounts of space charge which are found in nitrobenzene are easily a factor of 200 times larger than the value listed above for oil.

Measurements of the Kerr coefficient of transformer oil as a function of temperature were started this quarter and will continue the next quarter. These measurements are needed to quantify the space charge as higher temperature transformer oil is analyzed.

Drawing from the indication of space charge obtained this quarter, efforts will be made next quarter to measure field distortions in transformer oil at higher temperatures with 60-Hz stress and dc. Both clean and contaminated oil will be employed. Known contaminants will also be injected into the clean oil system to explore their effects. Attempts will also be made to employ spacers parallel and perpendicular to the field.

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

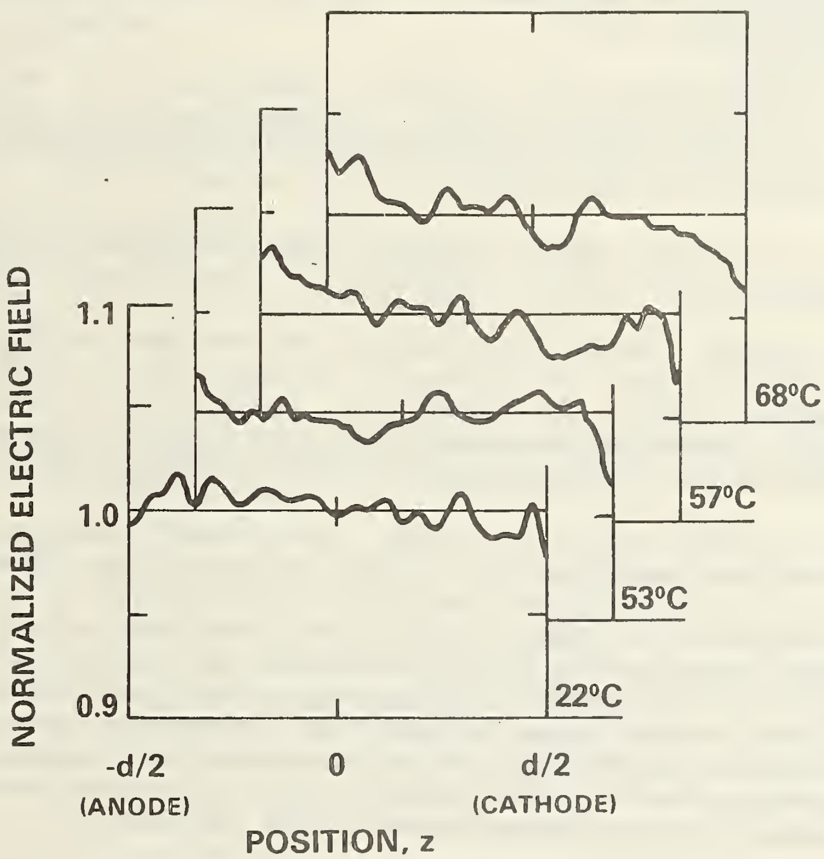

Figure 5. The electric field as a function of position between parallel plates in transformer oil at four different temperatures. The data at 68°C suggests that the space charge density may be making a significant (~5%) contribution to the electric field.

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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 four 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 January 1, 1981 to March 31, 1981. This report emphasizes the errors associated with measurements of the vertical current density in an electrical environment consisting of a dc field with space charge, the measurement of rf attenuation in distribution cables, the onset characteristics of positive and negative corona in compressed SF_6 gas, and the measurement of the space charge density in transformer oil subjected to 60-Hz excitation.

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

cables; dc fields; high voltage; incipient fault; insulation; SF_6; space charge; transformer oil.

13. AVAILABILITY

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