Cryogenic Power Transmission Technology—Cryogenic Dielectrics

MASTER

OAK RIDGE NATIONAL LABORATORY

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$5.00; Microfiche \$2.25

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Contract No. W-7405-eng-26

Activity No. HA 01-01-00-0

CRYOGENIC POWER TRANSMISSION TECHNOLOGY -
CRYOGENIC DIELECTRICS

Thirteenth Quarterly Report
January 1, 1976 - March 31, 1976

Cryoelectrics Section
Engineering Sciences Group
Thermonuclear Division

JULY 1976

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ABSTRACT

The thirteenth Quarterly Report of the Oak Ridge National Laboratory Cryogenic Dielectrics Program covers the period from January 1, 1976 to March 31, 1976. Measurements are reported on partial discharge inception and extinction in various three-layer polymer film samples impregnated with pressurized cold helium gas. The behavior of the inception voltage is described with respect to variations in temperature, pressure, electrode geometry, and location of voids adjacent to the electrodes or midway through the dielectric. Preliminary dc breakdown tests on some of the same samples resulted in external flashover on the sample chamber rather than internal breakdown, but established a lower limit to the dc dielectric strength.

The present status of experimental equipment is reported, including improvements to low-temperature thermometry instrumentation. The first of a series of bimonthly meetings was held in January to promote discussion of cryogenic dielectric problems between members of the various ERDA-supported superconducting power transmission line development projects, and minutes of this meeting are included.

A. INTRODUCTION

Aims and Goals

The major objective of the Cryoelectric Project is to obtain test data on the dielectric behavior of solid, liquid, and gaseous materials at cryogenic temperatures. These data will be used in the design of cryogenic superconducting power transmission lines (SPTL). An SPTL design can be broken down into four major systems: conductor, electrical insulation, coolant, and thermal insulation. Each of these must meet certain design specifications to ensure proper cable operation, as well as withstand the rigors of field installation, thermal cycling, and electrical transients produced by network faults, switch operation, and lightning surges. In order to assess the performance of cryogenic dielectrics under such conditions, breakdown strength tests are being conducted with dc, ac and impulse voltages on cryogenic liquids and on multilayer samples of thin plastic tapes. Flashover voltages will also be measured on solid insulators and wrapped tape stress cones immersed in cryogenic liquids. Attempts will be made to learn the effect of mechanical stresses, resulting from field installation and cooldown, on the electrical performance of the insulation. Partial discharge (electrical arcing in small flaws in the insulation, causing long-term deterioration, but not leading immediately to complete electrical breakdown) will be monitored as a function of the thermodynamic conditions and previous electrical and thermal history. All of these experiments will be carried out under the full ranges of temperature and pressure of interest for practical SPTL designs, that is, for about 4.2-10 K and 0.1-1.2 MPa.

B. ACTIVITY DURING QUARTER

1. Experimental Equipment

a) Cryostats: No further work has been accomplished on the high voltage cryostat following the modifications of last quarter due to lack of funding and a shift of effort to measurements on thin polymer films at lower voltages.

Both 15-cm-diameter intermediate voltage cryostats, IV-1 and IV-2, have been operating satisfactorily. A second pressurized test fixture for thin film samples has been fabricated for use in these cryostats. It is similar to the first test cell described in the last quarterly report.¹ The duplicate test cell will allow simultaneous pursuit of dc and ac studies. The new fixture has eight slightly flattened stainless steel electrode surfaces rather than the rounded electrodes used in the original fixture. Progress has been slow in obtaining a vacuum seal between the closure insulation and the 30-cm-diameter stainless steel bushing of cryostat IV-3, due in part to illness of the technician assigned to this work. Vacuum tightness between the bushing and the external refrigeration system checked out satisfactorily at room temperature on at least two occasions but on cool-down to liquid nitrogen temperature several vacuum leaks occurred. The Mycalex closure insulator at the bottom of the bushing later developed tiny cracks upon cooling. The Mycalex material was replaced with an epoxy-fiberglass G-10 insulator disk. This material is being used successfully on IV-1 and IV-2. Later, however, low temperature vacuum leaks developed in the 30-cm-diameter brass clamping rings and seals used in fastening the G-10 insulator disk to the bushing. New attacks will be made on the bushing closure problem in the next quarter.

b) Instrumentation: Instrumentation to measure elevated pressures in the thin-film test fixtures had previously been completed. In order to measure temperatures accurately above liquid helium temperature, two groups of Allen-Bradley carbon resistors were calibrated against a commercially-calibrated germanium thermometer. Each group consisted of five 1/8-watt 100-ohm carbon resistors. The quoted accuracy of the calibrating Ge thermometer in the range of 5 K to 20 K is 0.01 K.

Calibration points were taken approximately every 0.2 K in the range of 5 K to 10 K and at increasingly larger steps up to about 25 K. The principal range of interest in the cryoelectric program is between 5 and 12 K.

The calibrated points for each of the ten carbon resistors were fitted using computer techniques to an equation of the type employed by Kes, et al.,²

$$\ln R = a + b \ln T + c (\ln T)^2 + \frac{d}{T} .$$

Tables of R vs T for each of the ten carbon resistors were generated by the computer so that readings can be converted to temperature for future experiments.

Last year an impulse memory voltmeter was ordered from Ross Engineering Corporation. The original shipping date of early November 1975 was changed to January 1976, due to factory difficulties with production models. A firm shipping date for the voltmeter of April 16, 1976 subject to cancellation has been received from the Ross Engineering Corporation.

2. Collaborations with other Laboratories, Meetings, and Visits

Continuing contact has been maintained with personnel in the SPTL programs at Brookhaven National Laboratory, Los Alamos Scientific Laboratory, and Union Carbide Corporation Linde Research Laboratories. Table 1 shows that contacts, either by telephone or by personal meetings, have generally occurred at least biweekly, allowing regular opportunities for exchange of information and program input.

The first of a series of bimonthly meetings designed to facilitate discussion of cryogenic dielectric problems among the ERDA-supported SPTL projects was held at ORNL on January 23, 1976. The meeting was attended by Dr. P. Chowdhuri of LASL and Dr. S. J. Rigby of BNL and by several ORNL staff members connected with the Cryoelectric Project. Recent progress in dielectric research at each laboratory was summarized, and plans were solidified for work at ORNL during the remainder of the quarter. The experimental program outlined in Appendix A of the previous quarterly report was endorsed in principle. A report on the meeting is included here as Appendix A. This report was circulated to the participants and other persons interested shortly after the meeting. Following

TABLE 1. Discussions With Other Laboratories

Date	Means	Person Contacted	Institution	ORNL Person	Prime Topics
1/8/76	Telephone	S. Rigby	BNL	S. W. Schwenterly	January meeting
1/8/76	Telephone	P. Chowdhuri	LASL	S. W. Schwenterly	January meeting, dc test samples
1/9/76	Telephone	D. Bosack	UCC-Linde	S. W. Schwenterly	January meeting, helium breakdown, cable spacer tests.
1/16/76	Telephone	W. Anderson	NBS	S. W. Schwenterly	January meeting, PD suppression by mineral oil
1/23/76	Direct Personal	P. Chowdhuri S. Rigby	LASL BNL	H. M. Long W. F. Gauster R. H. Kernohan M. M. Menon F. L. Miller S. W. Schwenterly	ORNL impulse breakdown and partial discharge measurements on polymer film, LASL dc test program, BNL partial discharge studies.
1/26/76	Direct Personal	NBS-Boulder heat transfer and fluid flow personnel	NBS	S. W. Schwenterly	Review of NBS heat transfer and fluid flow studies
1/26/76	Direct Personal	W. Keller	LASL	S. W. Schwenterly	LASL dc test program
1/26/76	Direct Personal	J. Hoffer	LASL	S. W. Schwenterly	LASL dc test program
2/9/76	Telephone	A. McNerney	BNL	M. M. Menon	SF ₆ breakdown strength
2/10/76	Telephone	S. Rigby	BNL	M. M. Menon	PD tests with SF ₆ , April meeting
2/12/76	Telephone	W. Anderson	NBS	S. W. Schwenterly	April meeting, visit by Anderson and Davis
2/11/76	Direct Personal	W. Anderson R. Davis	NBS	S. W. Schwenterly	Recent dielectrics work at NBS and ORNL
2/18/76	Telephone	P. Chowdhuri	LASL	S. W. Schwenterly	April meeting, dc breakdown tests
2/24/76	Direct Personal	NBS-Gaithersburg Electricity and Polymer Division Personnel A. Muller D. Bosack	NBS BNL UCC-Linde	S. W. Schwenterly	Review of dielectric loss and polymer morphology work at NBS, informal discussions of work at ORNL, BNL, and Linde
3/2/76	Telephone	P. Chowdhuri	LASL	S. W. Schwenterly	April meeting, LASL HV test equipment
3/10/76	Telephone	S. Rigby	BNL	S. W. Schwenterly	BNL partial discharge work, further PD work at ORNL
3/19/76	Telephone	P. Chowdhuri	LASL	S. W. Schwenterly	Progress on dc tests at ORNL
3/29/76	Telephone	W. Anderson D. Bosack P. Chowdhuri A. McNerney S. Rigby	NBS UCC-Linde LASL BNL BNL	S. W. Schwenterly	April meeting

receipt of letters from Rigby and Chowdhuri with further comments on the meeting, some changes were made in the experimental plans. Room temperature experiments on partial discharge (PD) in polymer films with SF₆ impregnation were added to the ac program, and a decision was made to modify the pressurized sample holder¹ in order to provide flat-surfaced high voltage electrodes larger in diameter than the butt-gap holes. Helium conditions for the dc tests were set at 12 K and 10 atm, with at least two sheets of dielectric to be used. It was agreed that dc and ac tests would be performed on completely separate samples to prevent possible mutual influences on the data. The next meeting in the series has been scheduled for April 1, at the DEES offices in Washington, D.C.

H. M. Long attended the IEEE winter Power Meeting and Tesla Symposium in New York City on January 25-30. On January 28, he attended a meeting of the US-USSR Exchange Participation Committee in Chicago. On February 27, he attended the WATtec conference in Knoxville.

S. W. Schwenterly attended reviews of the National Bureau of Standards programs on helium heat transfer and fluid flow at Boulder, Colorado and on low temperature dielectric losses and morphology of polymer films at Gaithersburg, Maryland. Reports of both trips were prepared and distributed internally.

An abstract (Appendix B) has been submitted for presentation at the 1976 IEEE International Symposium on Electrical Insulation, to be held June 14-16 in Montreal, Canada.

The next round of visits in the U.S.-Soviet collaboration on dielectrics for SPTL development is expected in May or June. It has been proposed that two Soviet scientists work at Oak Ridge for two or three weeks during this period. A letter outlining proposed experiments has been sent to Professor Levitov of the Krzhizhanovsky Power Institute in Moscow.

C. EXPERIMENTAL WORK

Early in the quarter, partial discharge (PD) measurements were initiated on polymer films pressurized with helium in the specimen chamber described in the previous quarterly report.¹ Eight stainless steel rods with 6.35-mm-diameter hemispherical ends, equally spaced on a 6.35-cm-diameter circle in an epoxy disk, served as the top electrodes. Any one of these electrodes could be selected for use by a rotating arm. The bottom plane electrode was a spring-loaded stainless steel disk. The epoxy disc in which the top electrodes were encapsulated served as the high voltage bushing and the wall of the pressure vessel. Fig. 1 is a photograph of the specimen chamber as installed in this cryostat.

A series of experiments was necessary to arrive at the final arrangement and to perfect the experimental technique. We feel that a brief description of the various iterations involved is in order as it will be particularly informative to future researchers in the field.

Experiment 1

In our first experiment a single sheet of 102- μ m-thick "Van Leer Valeron" polyethylene was mounted in the specimen chamber. The chamber was then installed in the cryostat and thoroughly evacuated. After the cryostat was pre-cooled, liquid helium was transferred into the dewar so that the specimen chamber was completely covered by the liquid at 4.2 K. Pre-cooled (77 K) gaseous helium was then injected into the specimen chamber at the desired pressures, resulting in pressurized liquid helium within the chamber at constant temperature (4.2 K). A Wallace and Tiernan gauge with a range of up to 100 psi (689.5 kPa) and calibrated to read correctly to 0.2 psi (1.379 kPa) was used to record the pressure. Prior to conducting PD measurements on the sample, the high voltage arm was raised from the electrodes and the bushing alone was checked and found to be discharge-free for operation up to about 15 kV. This routine was followed in all the experiments described below. PD inception and extinction voltages and discharge magnitudes were measured at absolute pressures of 110 kPa, 207 kPa, 310 kPa and 414 kPa. The discharge inception levels varied from 1.4 to 2.6 kV. No predictable pattern could

be established and no dependence of the discharge inception levels on pressure could be observed. Moreover, the discharge magnitudes were quite high, estimated to be around 10,000 pC. Attempts to obtain the breakdown strength of the specimen when the chamber was pressurized to 414 kPa were not successful due to the build-up of partial discharge. By rapidly increasing the voltage, we could apply about 30 kV across the specimen before the supply kicked off due to excessive current drain resulting from the discharge build-up. Attempts to conduct PD measurements with dc also produced no conclusive results. Breakdown attempts with dc were also unsuccessful due to heavy current drain. Examination of the specimen after opening the chamber showed discharge damage not only near the electrodes but also at the edges of the specimen disk. There was also evidence of particle contamination from the fill-lines.

Experiment 2

In this experiment 3 layers of 25- μ m-thick Cryovac 929 D polyethylene film were assembled, with a 1-mm-wide radial slot (terminating in a 1-mm-diameter hole under an electrode) in the middle film to simulate a butt gap. Since poor contact between the film and the electrode surfaces was suspected in the previous experiment, a thin layer of apiezon N-grease was applied uniformly under the epoxy disc and over the stainless steel electrode. Measurements with this sample at 4.2 K and pressures up to 700 kPa showed no pressure dependence on PD inception levels. However, the discharge magnitudes were generally much lower than in the previous experiment, and at the butt gap position, the magnitude was about two orders higher than at the non-butt gap position. There was wide scatter in inception levels (4.5 - 9.8 kV). Breakdown measurements at different non-butt gap positions yielded 11.2 to 18.8 kV (rms) without showing any clear pressure dependence. On opening the specimen chamber, evidence of voids in the greased surfaces could be seen. Carbonized circles, about a centimeter in diameter, could also be seen at points where breakdowns were conducted. Splashed metal particles and droplets were also present in the vicinity of breakdown points. No visible effects could be seen at the slotted butt gap but this position was not subjected to breakdown.

Experiment 3

In our third experiment, three layers of 61- μ m-thick Makrofol K. G. polycarbonate film, with circular holes (1-mm-diameter) as butt gaps in the middle film, were assembled. Electrode surfaces were greased very carefully. Measurements with this sample at pressures from 138 kPa to 690 kPa showed no pressure dependences on PD inception levels. The results were so erratic that we could not even observe any difference in behavior (i.e., in discharge inception levels or magnitudes) between positions with butt gap and those without butt gap. Breakdown measurements yielded surprisingly low values (8.2 to 14 kV rms). An examination of the film was made after opening, and the grease coatings were found to have severe cracks, which created numerous voids between the specimen and the electrode surfaces. Presumably this occurred because of the differential contraction and crystallization of the grease. The discharge activities were evidently in the voids so created. The epoxy surface appeared carbonized at some positions where breakdown occurred, but the discoloration could easily be wiped off by trichloroethylene, suggesting that the degradation was exclusively in the grease rather than in epoxy.

Experiment 4

There was enough evidence from the experiments described above to conclude that poor contact between the electrode surfaces and the specimen was responsible for the unpredictable performance of the sample. We also learned that the use of grease to increase contact does not solve this problem. A closer examination of the lapped epoxy surface revealed that it was slightly concave at the middle. This was corrected, to a large degree, by skimming a thin layer from the appropriate area and relapping the surface. To ensure that an intimate contact was achieved the following arrangement, illustrated in Fig. 2, was used.

A 11.4-cm flexible styrofoam disk, approximately 3 mm thick, was placed over the spring-loaded stainless steel disk. Three layers of 25- μ m-thick metallized Mylar sheets, of about the same diameter as the styrofoam, were placed over the styrofoam to mask the effect of the coarse surface structure of the styrofoam. Another 25- μ m-thick metallized Mylar film, again of the same diameter as the styrofoam but with two

rectangular protruding strips, was placed above this. The metallized portion of the top layer acted as the cathode. The protruding strips were folded around the ends of the styrofoam to establish an electrical connection with the stainless steel disk. The styrofoam disk in combination with the Mylar acted as a flexible electrode, so that upon clamping of the specimen chamber, an intimate contact was established between the film and the electrode surfaces. Thermal contraction effects perpendicular to the film surface were taken care of by the main spring-loaded disk.

In order to make sure that the arrangement would work satisfactorily we conducted some PD measurements at room temperature using SF_6 , the behaviour of which is well known, as the impregnant. Three layers of 50- μm -thick Mylar, with 1-mm-diameter mid-dielectric butt gaps at four of the eight electrode positions, were used as the sample. The results of the experiment, shown in Appendix C-1, were very encouraging. As expected, the PD inception levels showed a definite increase with increase in pressure. Also, the discharge magnitudes were generally about two orders of magnitude higher for butt gap positions than for non-butt gap positions. While there was some variation in inception levels for different positions regarded as identical, the inception levels for non-butt gap positions were clearly higher than those for butt gap positions. The cavity stress was calculated using the relation

$$E_{\text{gap}} = \frac{\epsilon_r}{\epsilon_r t_1 + t_2 - t_1} V \quad (1)$$

where

V is the partial discharge inception voltage,

ϵ_r is the relative permittivity of the film,

t_1 is the thickness of a single film (butt gap height),

and t_2 is the total thickness of the three films.

The results, shown in Table 2 and plotted in Fig. 3, show good agreement with the work of Gibbons et al.³ on polyethylene films impregnated with SF_6 .

TABLE 2. Partial Discharges Inception Voltages
And Butt Gap Stresses in SF₆ Impregnated
Three Layer Mylar Sample

Pressure (kPa)	Average* PDIV For Non Butt Gap Positions (kV)	Average* PDIV For Butt Gap Positions (kV)	Butt Gap Stress (kV/mm)
103	2.4	1.3	13.8
207	3.1	2.1	22.5
310	3.8	2.9	31.9
414	4.2	3.6	38.8

* Average of PD inception voltages measured at four different electrode positions. Two or three readings are taken at each position (Appendix C-1).

Encouraged by the results with SF₆ we proceeded to conduct measurements in pressurized liquid helium using the same arrangement. Before cooling, the specimen chamber was evacuated and flushed with helium several times. Measurements at two pressure levels, 207 kPa and 310 kPa, showed no pressure dependence on PD inception levels. Moreover, the inception levels were very low (≈ 1 kV). The pressure was then increased to 620 kPa. Subsequent measurements showed about five times the PD inception levels obtained at 310 kPa. However, when the pressure was brought down to 310 kPa the inception levels did not change suggesting that the sudden jump in level was due to better impregnation when the pressure was raised to 620 kPa. In any case, when the experiment was repeated at 207 kPa, 414 kPa and 620 kPa, there was no evidence of a pressure effect.

After these measurements were concluded, the helium was boiled away to a level below the specimen chamber and the rate of temperature rise of the chamber was noted. This rate was found to be sufficiently low (less than 0.03K/minute up to about 7 K and less than 0.05 K/minute above 7 K) to allow PD measurements to be made cyclically at all electrode positions at constant pressures as a function of temperature.

Experiment 5

In this experiment we used three layers of 61- μ m-thick Makrofol K G polycarbonate as the specimen. The specimen assembly inside the chamber was exactly as described for the previous experiment. There were 1-mm-diameter mid-dielectric butt gaps at all positions except one. Moreover, alternate butt gaps were connected to the central area where pressurized helium enters the chamber through radial cuts in the film. This was done to see whether there is any impregnation problem in a closed butt gap as opposed to an open butt gap. Also, in order to make sure that cooling does not hinder impregnation, the chamber was kept under helium over-pressure while cooling.

Measurements conducted at 4.2 K with the above arrangement are shown in Appendix C-2. The observations were quite reproducible. It can be seen that there is no obvious pressure effect for PD inception levels in liquid helium. This is understandable in view of the fact that while liquid helium is a compressible liquid, its compressibility is small. The change in density of liquid helium when pressure is increased from 207 kPa to 620 kPa is only about 10%. This falls within the scatter observed in PD inception level measurements. However, a definite pressure effect should be observable if the measurements are extended to a temperature range in which helium is supercritical. Such higher temperature measurements were conducted next.

As before, the temperature was varied by boiling off the liquid helium to a level below the specimen chamber and allowing the chamber to warm up. The temperature of the specimen was measured by a carbon resistance thermometer mounted on the bottom of the chamber. (Unfortunately, at this point in the experiment, the carbon resistance thermometer was not calibrated in terms of absolute temperature. This led to the rather limited range of temperature over which measurements were conducted. The thermometer was later calibrated to obtain the correct temperatures as mentioned in Section B.1.)

The results of PD measurements as a function of temperature when the pressure is kept constant are shown in Appendix C-3. A definite decrease in PD inception values with increase in temperature can be seen (Fig. 4).

The butt gaps with and without the slots behaved more or less in the same way. For a given temperature, an increase in pressure resulted in an increase in PD inception levels. The peak voltage across the gap is obtained from

$$V_{\text{gap}} = \sqrt{2} E_{\text{gap}} t_1 \quad (2)$$

and is plotted against the density-gap product in Fig. 5.

After PD measurements, the discharge detector was disconnected and breakdown strengths were measured for different positions. The results are shown in Table 3. At most positions voltage could be reapplied, which suggested flashover rather than breakdown. It is believed that the intense PD activity triggered the Schmitt trigger circuit that kicked the high voltage supply off. The voltage collapse was accompanied by a rise in pressure and temperature inside the specimen chamber. After the chamber was opened, breakdown punctures were observed at the 225° and 315° positions only. Both these positions had butt gaps that were connected to the central helium inlet area by a slit. Discharge tracking along these slits could also be observed.

TABLE 3. Breakdown Attempts in Polycarbonate Films Impregnated by Supercritical Helium

Pressure kPa	Position [*] (Degrees)	Temperature (K)	Maximum Voltage (kV rms)	Comments
1014	315, BS	5.56	19.7	Pressure rose to 1140 kPa, temperature to 5.7 K, voltage could not be reapplied above 6 kV.
1014	270, B	5.77	23.3	Pressure rose to 1170 kPa, temperature to 5.7 K, voltage above 10 kV could be reapplied
1014	225, BS	5.92	22.7	Pressure rose to 1241 kPa, temperature to 6.1 K, voltage above 10 kV could be reapplied
1014	180, B	6.07	22.3	Pressure rose to 1210 kPa and temperature to 6.3 K, did not reapply to the voltage
1014	90, B	6.17	21.6	Pressure rose to 1140 kPa and temperature to 6.3 K
1014	90, B	6.21	23.5	Pressure rose to 1290 kPa and temperature to 6.6 K
1014	135, BS	6.54	21.9	Pressure rose to 1140 kPa, temperature to 6.7 K, did not reapply the voltage
1014	0, NB	6.51	23.8	Pressure rose to 1220 kPa and temperature to 6.9 K, did not reapply the voltage

* BS, Butt gap with a radial slot; B, Butt gap; NB, No butt gap.

Experiment 6

A three-layer specimen of 102- μm Van Leer Valeron was installed in the test cell, with a flexible foam-backed ground electrode identical to that used in Experiment 4. Butt gap holes one millimeter in diameter were punched in the center layer at every electrode position except 0° . Since the cuts to alternate holes in Experiment 5 appeared to have no effect, all holes were closed for Experiment 6. As before, the sample chamber was held at a pressure of about 700 kPa during cooldown to promote impregnation of the films. A calibrated carbon resistor, as described in Section B.1, was used to measure the temperature.

After the bushing was conditioned at 4.2 K, the helium bath was boiled down below the sample chamber and partial discharge data were taken as the chamber warmed up at constant pressures of 350, 690, 1030, and 1380 kPa. The results are shown in Figs. 6 through 9 and in Appendices C-4 through C-7. The reason why previous experiments near 4.2 K showed little pressure dependence in the inception voltage is clear from the figures, since the curves nearly overlap in the region around 5 K. At temperatures above 6 K a clear pressure effect is apparent. The pressure effect becomes more pronounced as the temperature rises and the compressibility of helium increases. Generally, the discharge magnitude at inception was on the order of 1 pC, although in some cases it began to grow spontaneously to values in excess of 10 pC. This happened particularly when the voltage was raised slightly above the inception voltage. The discharge magnitude was more stable at higher pressures. Whenever the large discharges occurred, it was found that a few very small discharges persisted to a voltage much lower than the original inception voltage. The inception and extinction levels of subsequent larger discharges were unaffected. When the sample chamber was warmed and pumped out overnight, the small discharges disappeared. Usually the discharge pulses were concentrated between the 0° and 90° and the 180° and 270° portions of the ac cycle at inception. As the voltage was lowered, they moved back back up toward the peaks and disappeared at extinction. At the higher pressures of 1030 and 1380 kPa, the inception voltage was generally between 5% and 10% higher than the extinction voltage. For the lower pressures, the inception voltage was between 10% and 20% higher.

The 0° sample position, which had no gap, displayed lower inception voltages than the other positions. Furthermore, the discharge magnitude had more of a tendency to grow spontaneously, after which the inception voltage would decrease by a factor as high as two. This effect was reduced at high pressures.

The voltages across the gaps at inception were calculated using Eq. 2, and plotted vs ρd to produce the Paschen plot shown in Fig. 10. The densities ρ were calculated with the National Bureau of Standards HEHT4 computer program.⁴ Also shown are the low temperature Paschen curve for helium and the 125 μm gap data of Meats⁵ for metallic electrodes at 5.5 K. The Paschen plots for the gaps agree with Meats data up to $\rho d \approx 10^5 \text{ kg} \cdot \mu\text{m}/\text{m}^3$, and then begin to rise quickly. For $\rho d < 10^5 \text{ kg} \cdot \mu\text{m}/\text{m}^3$,

$$V_g \propto (\rho d)^{0.33}.$$

Breakdown measurements with dc voltage were attempted at the 180° sample position after completion of the partial discharge measurements. However, at 1030 kPa and 10 K, external flashover on the sample chamber occurred at 40 kV. Hence, the dc dielectric strength of a three-layer Valeron sample containing a void is in excess of 131 MV/m. When the sample chamber was opened, very little damage by the discharges was apparent. Microphotographs of one of the holes were compared with those for an undischarged dummy hole (Fig. 11). Very faint radial discolorations could be seen at the edge of the discharged hole. At the zero degree (non-gap) position, two small brownish tree-shaped tracks were observed in the top layer where it contacted the edges of the high voltage electrode.

Experiment 7

For this experiment, the epoxy top piece of the sample chamber was replaced with another having flat rather than the near-spherical high voltage electrodes, in order to subject the voids to a more uniform field. The electrodes were 6.3 mm in diameter, as compared to the 1.0 mm diameter of the voids. The edges of the electrodes were rounded to a radius of 0.8 mm in accordance with ASTM D-149.

Another three-layer Valeron sample was used. This sample was arranged to allow investigation of the effect of butt gap location on inception voltage. Two positions had no voids. The remaining six positions were divided into three pairs with voids in the top, middle, or bottom layer.

So far, only pressures of 1030 and 1220 kPa have been investigated. Partial discharge data are presented in Figs. 12 and 13 and in Appendices C-8 and C-9. The results for 1030 kPa agree well with the spherical electrode data at the same pressure from Experiment 6. To facilitate interpretation of the data, each set of inception voltage readings at a given position (which all occurred close to the same temperature due to the slow warming rate) was averaged and the average inception voltages plotted vs temperature. Such a plot for the 1220 kPa pressure is shown in Fig. 14. It can be seen that the inception voltages for the electrode-adjacent voids are higher than those for the mid-dielectric voids, and that the positions with no voids show the lowest inception voltages of all. However, for the electrode-adjacent gaps, the discharge magnitude was between 1000 and 10,000 pC, as opposed to a few pC for the others. So far, not enough measurements have been taken to allow plotting a complete Paschen curve. However, the data at the two pressures investigated agree well with Fig. 10.

D. VISITORS

The following visitors were received during the quarter:

January 23:	P. Chowdhuri, LASL
	S. Rigby, BNL
February 10:	K. D. Srivastava, University of Waterloo, Canada.
March 9:	K. Wyatt, Interviewee, Tennessee State University.
March 16, 17, and 23:	G. L. Sommerman, consultant.

E. FUTURE PLANS

The partial discharge measurements on the three-layer Valeron sample with flat electrodes will be carried out at several different pressures. A few more experiments at room temperature with impregnating gases such as SF_6 will be carried out for comparison with similar studies in the literature. Other candidates for partial discharge measurements include samples with aluminized layers around the voids to shield the enclosed helium from high fields, and multilayer embossed film samples. Tests will be carried out on other materials, such as polypropylene, polysulfone, and polyamide.

Breakdown measurements with dc on cellulose paper and polymer film samples will begin immediately. The first materials to be tested will be polycarbonate, polyester, and cellulose.

Development of a short cylindrical test specimen will be undertaken. The objective is to make the specimen as easily fabricable as possible. It is expected that the ends of the specimen will be graded resistively.

The ac and dc measurements mentioned above will be carried out with frequent consultation with personnel in the BNL and LASL superconducting cable programs.

REFERENCES

1. See Figs. 3 and 4 of ORNL/TM-5302, Cryogenic Dielectrics Quarterly Report, October 1, 1975 - December 31, 1975.
2. P. H. Kes, C. A. M. Van der Klein, and D. Deklerk, Cryogenics 14, 3 (1974).
3. J. A. M. Gibbons, P. R. Howard, and D. J. Skipper, Proc. IEE 112 89 (1965).
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FIGURE CAPTIONS

1. Pressurized test cell mounted on vacuum bushing.
2. Exploded cross section of pressurized test cell. 1) High voltage electrode; 2) retaining ring, 3) brass insert; 4) epoxy disk; 5) three-layer specimen; 6) aluminized Mylar electrode; 7) aluminized Mylar padding; 8) ground electrode connecting tab; 9) plastic foam disk; 10) stainless steel disk; 11) spring; 12) indium O-ring seal; 13) lower shell; 14) slotted center support screw; 15) lead O-ring seal; 16) pressurized helium inlet fitting.
3. E_{gap} vs pressure for SF_6 impregnated, three-layer Mylar sample. $T = 300 \text{ K}$; film thickness = $50 \text{ }\mu\text{m}$.
4. Partial discharge inception voltage (PDIV) vs temperature at various pressures. Three layers of $62 \text{ }\mu\text{m}$ Makrofol polycarbonate. Center layer had butt gap holes at all positions except 0° . Positions at 45° , 135° , 225° , and 315° had slits in film connecting butt gap holes to central helium inlet. Tick marks on symbols indicate position.
5. Paschen curve for data of Fig. 4.
6. PDIV vs temperature at $P = 350 \text{ kPa}$. Three layers of $102 \text{ }\mu\text{m}$ Valeron polyethylene. Center layer had butt gap holes at all positions except 0° . No slits were cut in center layer.
7. PDIV vs temperature for same sample as Fig. 6 at $P = 690 \text{ kPa}$.
8. PDIV vs temperature for same sample as Fig. 6 at $P = 1030 \text{ kPa}$.
9. PDIV vs temperature for same sample as Fig. 6 at $P = 1380 \text{ kPa}$.
10. Paschen curve for data of Figs. 6-9.
11. Photomicrograph of typical butt gap hole.
 - (a) Undischarged hole in a dummy sample.
 - (b) Hole at 45° position in sample of Figs. 6-10, after about 30 voltage applications.
12. PDIV vs temperature at $P = 1030 \text{ kPa}$. Three layers of $102\text{-}\mu\text{m}$ Valeron with flat surfaced high voltage electrodes. Butt gap holes were in upper, lower, or center layer as shown.
13. PDIV vs temperature for same sample as Fig. 12 at $P = 1220 \text{ kPa}$.
14. Average PDIV vs temperature for data of Fig. 13.

PHOTO 4320-76

Fig. 1

ORNL-DWG 76-10235

Fig. 2

ORNL - DWG 76-10236

Fig. 3

ORNL-DWG 76-10240

Fig. 4

JRNL-DWG 76-10237

Fig. 5

Fig. 6

ORNL-DWG 76-10242

Fig. 8

Fig. 10

PHOTO 2820-76

Fig. 11

Fig. 13

Fig. 14

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APPENDIX A*

AC DIELECTRIC PERFORMANCE OF LIQUID HELIUM IMPREGNATED
MULTI-LAYER PLASTIC FILM INSULATION†

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ABSTRACT

Several types of thin-film plastic insulation are being evaluated for possible use in ac superconducting underground transmission cables. The materials include polyolefins, polycarbonates, polysulphones, and nylons, in thicknesses ranging from 25 μ to 125 μ . Multiple-layer samples of the films are placed between 9.5-mm-diameter, spherical stainless steel electrodes, and the film and electrodes encapsulated in epoxy. The epoxy casting is arranged to allow injection of liquid or gaseous helium between the plastic layers, at pressures up to 5 atm and a temperature of 4.2 K. Each casting contains eight pairs of electrodes.

Partial discharge (PD) measurements are made on each sample to determine the dependence of the PD inception voltage and magnitude on helium density. The samples are then broken down with ac voltage at various pressures.

Preliminary measurements with a two-layer sample of 37- μ polyolefin indicate a dielectric strength in excess of 160 MV/m, with PD onset occurring at about one-half this level.

Butt gaps will be simulated by punching holes in some of the film layers. The results of tests with impulse voltages will be discussed, and progress will be reported on the extension of the measurements to coaxial geometries.

* Abstract submitted to 1976 IEEE Symposium on Electrical Insulation.

† Research sponsored by the Energy Research and Development Administration.

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APPENDIX B

REPORT OF FIRST BIMONTHLY
CRYOGENIC DIELECTRICS DISCUSSION MEETING

On January 23, 1976, a meeting was held at ORNL to review the current collaborations with the BNL and LASL Superconducting Power Transmission Line (SPTL) programs. The meeting was attended by Dr. S. J. Rigby of BNL, Dr. P. Chowdhuri of LASL, and by ORNL staff members H. M. Long, W. F. Gauster, R. H. Kernohan, M. M. Menon, F. L. Miller (Mathematics Research Division) and S. W. Schwenterly. Dr. D. Bosack of the UCC-Linde SPTL program had planned to attend, but due to bad weather was unable to meet his flight.

The morning was spent in discussing recent progress at each of the laboratories. Brief informal presentations were given by each laboratory representative present. Menon and Schwenterly first summarized the results of the latest ORNL impulse breakdown measurements on six BNL polymer film samples in liquid helium boiling at 1 atm. Considerable discussion followed on the possible influence of charge storage in the dielectric for succeeding impulse shots. It was also suggested by Chowdhuri that accurate observations of time to breakdown vs peak impulse voltage be made.

The first ORNL measurements of ac partial discharge (PD) and breakdown at 4.2 K on a pressurized 3-layer sample of 25- μ m Cryovac polyethylene were next reported. Discharge at the interfaces between the outer layers and the electrodes was suppressed successfully by coating the electrodes with Apiezon N grease. At 4.2 K, the pressure was varied from 0.2 MPa to 0.7 MPa. No significant variation with changing pressures was observed in the PD inception voltages. At all test sites but one, the PD magnitudes were stable. At this test site, a 1-mm-wide slit had been cut in the center layer to simulate a butt gap. Here, the PD magnitude at 0.2 MPa and at the inception voltage of 67 MV/m was found to grow spontaneously. The voltage was lowered and the pressure raised to 0.4 MPa. The PD inception voltage was then even lower than before, and the magnitude grew to above 10,000 pC over about one minute. At this point very heavy discharge occurred, and voltage could not be reapplied, preventing tests at higher pressures. Rigby said that he had observed a similar effect in

coaxial tape samples impregnated with liquid nitrogen, and attributed it to gradual growth of the ionization in the butt gap. The lack of dependence of the PD inception voltage on pressure observed with the small amount of data taken so far is surprising, and will be investigated further. It may be that the dependence appears only at higher temperatures.

Rigby then discussed his measurements of PD inception voltage vs helium density for coaxial samples wrapped with 25- μ m polymer tape. We suggested that he also try using N grease between the inner and outer tape layers and the electrodes. He is instrumenting a mandrel with thermocouples to investigate thermal gradients in the insulation. He said that a new 21-m length of test cable insulated with Makrofol polycarbonate has been installed in the Kabelmetall dewar and will soon be cooled down.

Chowdhuri summarized his plans for a high voltage test facility with 300 kVdc and 600 kV impulse capabilities. He has been studying the surface properties of various papers and polymer films and showed several 400X photomicrographs of paper and polymer surfaces. He is also interested in studying area and volume effects on insulation performance. Miller suggested that statistical methods be applied to choose a set of test lengths which would give the best estimate of the lifetime vs length relationship.

The afternoon was spent in discussing the ORNL test programs for BNL and LASL, which were summarized in a previous communication dated January 21, 1976. Rigby and Chowdhuri both agreed that no changes were necessary in the programs. Since the most recent version of the pressurized sample holder appears to show PD behavior similar to that of wrapped coaxial samples, it was decided to duplicate it and continue both ac and dc measurements, using higher temperatures. Samples of 75- μ m cellulose paper and mylar for Phase I of the LASL program were received from Chowdhuri. Makrofol will also be tested, using samples from BNL. Chowdhuri said that LASL is still interested in tests on oil-impregnated paper after the first round of tests on the other dielectrics is complete. Rigby gave us sheets of the teflon bedding material being evaluated for the BNL cable.

The question of surface flashover studies for stress cone design was also discussed. We expressed our doubts as to whether an idealized experiment can really duplicate the behavior of an actual stress cone. It was suggested that design studies for terminations and joints in

conventional oil paper cables be consulted. The cable manufacturers may also be a source of advice. Chowdhuri felt that electrolytic tank studies or computer calculations would be useful in estimating electric fields for various stress cone designs, and we agreed to look into the availability of appropriate equipment and computer programs at ORNL.

We asked about the possibility of performing dc and ac measurements on the same sample in a single cooldown. Rigby and Chowdhuri preferred separate runs for the BNL and LASL measurements. The LASL and BNL tests will be carried out in parallel in order to provide both laboratories with data as soon as possible.

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APPENDIX C-1
PARTIAL DISCHARGE DATA IN SF₆ IMPREGNATED MYLAR

POSITION (DEGREES)	PRESSURE (kPa)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)
0, No Gap	103	2.68	2.50	50
0, No Gap	103	2.64	2.50	50
0, No Gap	103	2.67	2.54	50
45, No Gap	103	2.20	2.09	50
45, No Gap	103	2.22	2.04	50
90, Butt Gap	103	1.38	1.11	2000
90, Butt Gap	103	1.40	1.22	2000
135, Butt Gap	103	1.37	1.22	5000
135, Butt Gap	103	1.26	1.18	5000
180, Butt Gap	103	1.15	1.04	6000
180, Butt Gap	103	1.20	1.10	6000
225, Butt Gap	103	1.16	1.06	5000
225, Butt Gap	103	1.19	1.10	5000
270, No Gap	103	2.30	2.23	15
270, No Gap	103	2.35	2.28	15
315, No Gap	103	2.40	2.22	25
315, No Gap	103	2.38	2.25	25
0, No Gap	207	3.30	3.17	20
0, No Gap	207	3.39	3.20	20
45, No Gap	207	2.90	2.80	50
45, No Gap	207	2.88	2.80	50
90, Butt Gap	207	2.24	1.94	3000
90, Butt Gap	207	2.05	1.98	3000
90, Butt Gap	207	2.05	1.97	3000
135, Butt Gap	207	2.13	1.99	5000
135, Butt Gap	207	2.10	1.95	5000
180, Butt Gap	207	2.08	1.88	5000
180, Butt Gap	207	1.93	1.78	5000

APPENDIX C-1 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)
225, Butt Gap	207	2.03	1.87	6000
225, Butt Gap	207	1.92	1.85	6000
270, No Gap	207	3.14	2.98	15
270, No Gap	207	3.15	2.90	15
315, No Gap	207	3.01	2.92	20
315, No Gap	207	3.05	2.93	20
0, No Gap	310	4.15	3.87	20
0, No Gap	310	4.10	3.82	20
45, No Gap	310	3.53	3.12	60
45, No Gap	310	3.40	3.31	60
90, Butt Gap	310	2.93	2.74	2000
90, Butt Gap	310	3.01	2.70	2000
135, Butt Gap	310	3.02	2.78	5000
135, Butt Gap	310	3.08	2.73	5000
180, Butt Gap	310	2.81	2.62	5000
180, Butt Gap	310	2.88	2.58	5000
225, Butt Gap	310	2.82	2.60	5000
225, Butt Gap	310	2.80	2.49	5000
270, No Gap	310	3.97	3.62	15
270, No Gap	310	3.84	3.63	15
315, No Gap	310	3.71	3.41	10
315, No Gap	310	3.79	3.62	10
0, No Gap	414	4.62	4.43	20
0, No Gap	414	4.66	4.44	20
45, No Gap	414	3.66	3.41	200
45, No Gap	414	3.70	3.59	200
45, No Gap	414	3.80	3.69	200
90, Butt Gap	414	3.59	3.34	3000
90, Butt Gap	414	3.66	3.32	3000

APPENDIX C-1 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)
135, Butt Gap	414	3.80	3.36	3000
135, Butt Gap	414	3.59	3.24	2000
180, Butt Gap	414	3.48	3.33	1000
180, Butt Gap	414	3.51	3.30	1000
225, Butt Gap	414	3.49	3.10	1000
225, Butt Gap	414	3.30	3.08	100
270, No Gap	414	4.43	4.12	10
270, No Gap	414	4.32	4.15	5
315, No Gap	414	4.30	3.92	5
315, No Gap	414	4.34	4.14	5

APPENDIX C-2

PARTIAL DISCHARGE DATA IN A THREE-LAYER MAKROFOL
 POLYCARBONATE SAMPLE IMPREGNATED BY LIQUID
 HELIUM AT HIGH PRESSURES AT 4.2 K

POSITION* (DEGREES)	PRESSURE (kPa)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)
0	207	6.44	6.20	5
0	207	6.63	5.91	5
45	207	5.88	5.43	1000
45	207	5.89	5.67	1000
90	207	6.95	4.82	3000
90	207	6.57	5.19	1500
135	207	6.07	--	20-30
135	207	5.40	4.70	20-30
180	207	7.00	--	>10,000
180	207	4.95	4.50	0.5
0	414	7.33	7.10	5
0	414	7.28	6.58	5
45	414	6.9	6.2	> 1000
45	414	6.5	6.0	1
90	414	6.98	6.51	5000
90	414	7.12	6.51	5000
135	414	5.40	5.23	1
135	414	5.65	5.33	2-3
180	414	7.88	7.22	3000
180	414	7.88	7.10	3000
180	414	7.48	6.9	3000
225	414	7.32	6.97	1000
225	414	7.35	6.65	1000
270	414	7.70	--	>10,000
270	414	7.40	7.05	5

APPENDIX C-2 (continued)

POSITION* (DEGREES)	PRESSURE (kPa)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)
315	414	7.00	6.28	500
315	414	7.20	6.55	500
0	621	7.06	6.58	1
0	621	6.59	6.00	1
45	621	6.94	6.30	2
45	621	6.95	6.41	2
90	621	7.42	7.25	2-3
90	621	7.31	7.19	2-3
135	621	6.40	5.77	3
135	621	6.42	5.81	2-3
180	621	7.87	7.43	10
180	621	8.20	7.82	10
225	621	7.41	7.12	> 10
225	621	7.96	7.38	500
270	621	7.59	6.93	500
270	621	7.51	7.12	5
315	621	6.44	6.18	5
315	621	7.17	6.50	5

* 0° - No butt gap; 45°, 135°, 225° and 315° - Butt gap with radial slots; 90°, 180°, 270° - butt gaps.

APPENDIX C-3

PARTIAL DISCHARGE DATA IN A THREE LAYER POLYCARBONATE SAMPLE IMPREGNATED BY SUPERCRITICAL HELIUM

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
315	310	5.55	2.92	2.35	200	85.4	5209	2.21	25.66
315	310	5.52	3.20	2.32	200	88.8	5417	2.42	28.12
315	310	5.52	3.05	2.32	200	88.8	5417	2.31	26.80
45	310	5.52	3.05	2.55	100	88.8	5417	2.31	26.80
45	310	5.52	3.03	2.50	100	88.8	5417	2.30	26.62
45	414	5.73	3.82	3.62	1	100.3	6118	2.89	33.56
45	414	5.70	3.82	3.31	3	100.2	6112	2.89	33.56
45	414	5.68	3.71	3.22	2	102.7	6265	2.81	32.60
315	414	5.89	3.83	3.10	300	92.2	5624	2.90	33.65
315	414	5.82	3.56	3.00	300	96.2	5868	2.70	31.30
315	414	5.80	3.71	3.02	300	97.3	5935	2.81	32.60
315	517	5.94	4.52	3.05	500	105.9	6462	3.43	39.71
315	517	5.93	4.48	3.58	200	106.3	6484	3.39	39.36
315	517	5.93	4.48	3.21	--	106.3	6484	3.39	39.36
45	517	5.93	4.48	4.05	3	106.3	6484	3.39	39.36
45	517	5.93	4.45	3.98	3	106.3	6484	3.37	39.10
45	517	5.94	4.22	3.72	2	105.9	6462	3.20	37.08

APPENDIX C-3 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
45	620	6.07	4.92	4.58	3	111.4	6794	3.73	43.23
45	620	6.07	4.93	4.33	> 100	111.4	6794	3.74	43.31
45	620	6.08	4.82	4.30	500	111.1	6777	3.65	42.35
315	620	6.10	5.15	3.32	> 1000	110.6	6746	3.90	45.25
315	620	6.11	4.82	3.32	> 1000	110.3	6728	3.65	42.35
315	620	6.13	4.30	3.35	> 1000	109.7	6694	3.26	37.78
315	690	6.27	5.15	3.85	1000	111.3	6789	3.90	45.25
315	690	6.28	5.14	3.59	1000	111.1	6774	3.89	45.16
45	690	6.30	4.98	4.61	2	110.5	6743	3.77	43.76
45	690	6.33	4.82	4.58	1.5	109.8	6696	3.65	42.35
45	690	6.55	4.60	4.10	1.5	103.8	6330	3.49	40.42
45	690	7.06	4.20	3.25	> 100	88.0	5368	3.18	36.90
45	690	7.20	3.90	3.15	> 100	83.6	5098	2.96	34.27
45	690	7.39	3.66	3.31	1-2	77.9	4751	2.77	32.16
45	690	7.63	3.56	3.18	1-2	71.4	4356	2.70	31.28
45	690	5.92	5.46	4.8	1-2	119.4	7282	4.14	47.97
45	793	4.70	8.38	7.83	2-3	142.1	8667	6.35	73.63
45	896	4.85	> 8.7	--	2-3	142.7	8703	--	--
45	896	4.88	7.9	7.80	1	142.3	8682	5.99	69.41
45	986	4.95	8.4	--	1	143.8	8770	6.37	73.80

APPENDIX C-3 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
315	986	4.99	8.28	7.62	> 10	143.3	8742	6.27	72.75
315	1007	5.08	8.39	7.40	30	142.3	8678	6.36	73.72
45	1007	5.10	8.57	7.90	10	142.0	8664	6.49	75.30
45	1000	5.32	8.24	7.80	10	139.5	8512	6.24	72.40
45	1000	5.47	7.93	7.18	10	137.7	8401	6.01	69.68
45	1000	5.66	7.48	7.40	10	135.3	8254	5.67	65.72
45	1000	5.76	7.30	--	10	134.0	8173	5.53	64.14
45	1000	6.00	6.97	--	500	130.7	7970	5.28	61.24
45	1000	6.15	6.50	6.22	< 1	128.5	7836	4.93	57.11
45	1000	6.27	6.30	5.70	500	126.6	7725	4.77	55.35
0	310	4.66	6.22	5.70	2-3	126.4	--	--	No butt gap
45	310	4.71	6.22	--	2-3	125.2	7639	4.71	54.65
90	310	4.74	6.70	5.90	20	124.0	7564	5.08	58.87
135	310	4.78	5.40	4.95	50	123.5	7534	4.09	47.45
180	310	4.82	4.80	4.42	20	122.7	7485	3.64	42.17
225	310	4.83	5.40	4.60	> 1000	121.9	7437	4.09	47.45
270	310	4.87	6.21	5.58	30	120.9	7375	4.71	54.56
315	310	4.89	4.88	--	> 1000	120.5	7351	3.70	42.87
315	517	5.05	6.50	5.9	10	128.0	7807	4.93	57.11

APPENDIX C-3 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
270	517	5.08	6.45	6.20	3	127.4	7771	4.89	56.67
225	517	5.09	6.42	6.20	5	127.4	7771	4.87	56.41
180	517	5.10	5.12	4.78	6	127.2	7758	3.88	44.98
135	517	5.11	5.70	5.30	10	127.0	7735	4.32	50.08
90	517	5.12	6.50	--	10	126.8	7730	4.93	57.11
45	517	5.13	6.50	6.32	1-2	126.5	7714	4.93	57.11
0	517	5.15	6.22	5.90	< 1	126.2	--	--	No butt gap
0	724	5.27	7.18	6.80	1-2	132.5	No butt gap	--	No butt gap
45	724	5.27	7.31	--	2	132.5	8082	5.54	64.23
90	724	5.27	7.01	6.78	5	132.5	8082	5.31	61.59
135	724	5.27	6.22	5.8	10	132.5	8082	4.71	54.65
180	724	5.28	5.60	5.2	10	132.3	8068	4.24	49.20
225	724	5.28	6.70	6.22	5	132.3	8068	5.08	58.87
270	724	5.30	6.63	6.20	3	131.9	8045	5.02	58.25
315	724	5.31	6.80	6.20	10	131.9	8045	5.15	59.75
0	930	5.39	7.50	7.02	1-2	136.9	No butt gap	--	No butt gap
45	930	5.40	6.92	6.10	--	136.9	8349	5.24	60.80
90	930	5.40	7.90	6.75	> 100	136.9	8349	5.99	69.41
135	930	5.42	6.05	5.51	5	136.6	8330	4.59	53.16

APPENDIX C-3 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
180	930	5.45	6.20	5.33	5	136.0	8298	4.70	54.47
225	930	5.46	6.95	6.6	5	136.0	8298	5.27	61.07
270	930	5.47	7.60	7.05	1	135.9	8290	5.76	66.78
315	930	5.49	7.40	6.52	10	135.7	8278	5.61	65.02

APPENDIX C-4

PARTIAL DISCHARGE DATA THREE LAYERS OF VALERON, $\rho = 350$ kPa

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
90	350	5.18	9.05	8.70	< 1	115.5	11781	6.62	45.89
90	350	5.24	9.15	7.80	< 1	113.5	11577	6.69	46.38
135	350	5.32	7.20	6.75	1.1	110.5	11271	5.26	36.46
135	350	5.34	7.30	5.55	1.7	109.2	11138	5.34	37.02
180	350	5.39	7.70	6.20	2.0	107.4	10955	5.63	39.03
180	350	5.42	7.40	7.30	1.3	106.5	10863	5.41	37.50
225	350	5.47	6.88	6.00	1.7	104.0	10608	5.03	34.87
225	350	5.49	6.74	5.74	1.4	102.4	10445	4.93	34.18
270	350	5.53	6.60	6.30	1.1	100.5	10251	4.82	33.41
270	350	5.56	6.61	6.28	1.1	98.7	10067	4.83	33.48
90	350	5.67	5.75	5.40	< 1	92.2	9404	4.20	29.12
90	350	5.86	5.97	5.35	< 1	75.5	7701	4.36	30.23
135	350	5.91	5.30	4.30	< 1	70.0	7140	3.87	26.83
135	350	5.96	5.20	4.40	1.1	64.0	6528	3.80	26.34
180	350	6.02	5.70	4.75	1.2	61.8	6304	4.16	28.84
180	350	6.04	5.45	4.75	1.1	61.0	6222	3.98	27.59
225	350	6.09	5.20	4.25	1.1	58.2	5936	3.80	26.34
225	350	--	--	--	> 10 ⁴	Huge discharge prevented further data.			

APPENDIX C-4 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
270	350	6.33	5.10	--	< 1	48.0	4896	3.73	25.86
270	350	6.36	5.20	4.95	< 1	47.0	4794	3.80	26.34
90	350	6.69	5.10	4.40	< 1	39.0	3978	3.73	25.86
90	350	6.72	5.05	--	< 1	38.6	3937	3.69	25.58
135	350	6.84	4.30	3.90	1.1	36.7	3743	2.93	20.31
135	350	6.89	4.30	3.80	1.1	36.0	3672	2.93	20.31
270	350	7.13	4.75	4.45	< 1	33.1	3376	3.47	24.06
270	350	7.20	4.70	4.40	< 1	32.3	3294	3.44	23.85
135	350	7.55	4.30	2.60	30	29.3	2989	3.14	21.78
270	350	7.84	4.65	3.90	1.1	27.4	2794	3.40	23.57
270	350	7.90	4.40	4.10	1.1	27.0	2754	3.22	22.32
270	350	7.97	4.30	4.10	1.1	26.7	2723	3.14	21.78
270	350	8.80	4.40	--	< 1	22.8	2326	3.22	22.32
270	350	8.80	3.15	--	30	22.8	2326	2.30	15.94

APPENDIX C-5

PARTIAL DISCHARGE DATA THREE LAYERS OF VALERON, $\rho = 689$ kPa

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
90	689	5.12	10.40	9.65	1	134.6	13729	7.60	52.7
90	689	5.14	10.20	9.30	1	134.3	13698	7.46	51.7
90	689	5.16	9.67	9.38	1	133.9	13658	7.07	49.0
135	689	5.18	9.72	8.70	1-2	133.3	13597	7.11	49.3
135	689	5.19	9.77	9.10	1	133.3	13597	7.14	49.5
180	689	5.22	9.02	8.28	0.5	132.9	13556	6.59	45.7
180	689	5.24	8.62	8.30	0.5	132.7	13535	6.30	43.7
225	689	5.29	9.15	8.60	1	131.7	13433	6.69	46.4
225	689	5.30	9.00	7.60	1-2	131.5	13412	6.58	45.6
270	689	5.32	8.10	7.28	0.5	131.2	13382	5.92	41.0
270	689	5.34	8.18	7.16	0.5	130.9	13352	5.98	41.5
270	689	6.02	6.80	6.20	0.5	118.3	12067	4.97	34.5
270	689	6.03	6.80	6.12	0.5	118.0	12036	4.97	34.5
225	689	6.04	7.80	--	0.7	117.8	12016	5.70	39.5
225	689	6.07	7.90	6.90	1.0	117.0	11934	5.78	40.1
180	689	6.11	8.00	7.10	0.5	116.3	11863	5.85	40.6
180	689	6.12	8.20	7.30	0.5	116.4	11873	5.99	41.5
135	689	6.14	7.12	6.25	1.0	115.7	11801	5.20	36.1
135	689	6.15	7.15	6.36	1.0	115.3	11761	5.23	36.3

APPENDIX C-5 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
90	689	6.16	6.95	6.23	0.5	115.0	11730	5.08	35.2
90	689	6.17	7.60	6.80	0.7	114.8	11710	5.56	38.6
270	689	6.34	6.45	6.22	0.5	110.8	11302	4.72	32.7
270	689	6.36	6.58	6.20	0.5	110.5	11271	4.81	33.4
225	689	6.36	7.13	6.00	1	110.2	11240	5.21	36.1
225	689	6.38	7.02	6.05	1	109.7	11189	5.13	35.6
180	689	6.40	8.10	--	0.7	109.2	11138	5.92	41.0
270	689	6.69	6.77	5.72	1	101.5	10353	4.95	34.3
270	689	6.71	6.45	5.98	0.5	101.0	10302	4.72	32.7
225	689	6.72	6.78	5.68	0.7	100.8	10282	4.96	34.4
225	689	6.74	6.78	5.60	0.7	100.2	10220	4.96	34.4
180	689	6.77	6.88	--	0.6	99.5	10149	5.03	34.9
180	689	6.81	6.75	6.02	0.5	98.1	10006	4.93	34.2
135	689	6.84	6.60	5.72	0.8	97.2	9914	4.82	33.4
135	689	6.88	6.75	5.72	0.8	96.2	9812	4.93	34.2
90	689	6.90	6.74	5.71	0.6	95.6	9751	4.93	34.2
90	689	6.91	6.75	5.72	0.6	95.2	9710	4.93	34.2
270	689	8.10	5.20	5.00	0.5	63.8	6508	3.80	26.3
270	689	8.13	5.32	5.00	0.5	63.1	6436	3.89	27.0

APPENDIX C-5 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
225	689	8.16	5.22	5.05	0.6	62.8	6405	3.82	26.5
225	689	8.19	5.85	--	> 10	62.1	6334	4.28	29.7
225	689	8.21	5.35	4.70	1 → 100	61.8	6304	3.91	27.1
180	689	8.24	6.05	5.35	0.7	61.2	6242	4.42	30.6
180	689	8.24	5.98	5.28	0.6	61.2	6242	4.37	30.3
135	689	8.28	5.30	5.08	1	60.6	6181	3.87	26.8
135	689	8.30	5.13	4.82	0.8	60.2	6140	3.75	26.0
90	689	8.33	5.50	4.90	0.8	59.8	6100	4.02	27.9
90	689	8.36	5.50	4.90	0.8	59.3	6048	4.02	27.9
270	689	10.11	4.46	3.16	40	41.4	4223	3.26	22.6
270	689	10.19	4.80	3.15	40	40.9	4172	3.51	24.3
225	689	10.22	4.50	3.15	40	40.7	4151	3.29	22.8
225	689	10.25	4.78	3.20	40	40.4	4121	3.49	24.2
180	689	10.38	5.12	3.20	40	39.8	4060	3.74	25.9
180	689	10.42	4.20	3.20	35	39.5	4029	3.07	21.3
180	689	10.46	4.80	3.20	35	39.2	3998	3.51	24.3
135	689	10.51	4.80	3.20	40	38.9	3968	3.51	24.3
135	689	10.55	4.45	3.20	40	38.7	3947	3.25	22.5
90	689	10.63	5.52	2.80	65-70	38.2	3896	4.04	28.0
90	689	10.67	4.80	2.90	65-70	38.0	3876	3.51	24.3

APPENDIX C-6

PARTIAL DISCHARGE DATA THREE LAYERS OF VALERON, $\rho = 1030$ kPa

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
0	1030	5.26	8.75	5.48	2	140.4	--	No Butt gap	--
0	1030	5.27	7.75	7.35	3	140.2	--	No Butt gap	--
45	1030	5.30	10.27	8.80	3	140.0	14280	7.51	52.1
45	1030	5.32	13.20	12.60	1-3	139.8	14260	9.65	66.9
45	1030	5.37	13.40	11.20	2-3	139.0	14178	9.80	67.9
45	1030	5.40	12.82	3.40	> 10	138.7	14147	9.37	65.0
90	1030	5.45	10.91	10.38	1.3	138.0	14076	7.98	55.3
90	1030	5.47	10.60	10.20	1.2	137.8	14056	7.75	53.7
90	1030	5.49	10.98	--	~ 2	137.5	14025	8.03	55.7
135	1030	5.50	11.42	10.78	~ 2	137.3	14015	8.35	57.9
135	1030	5.52	10.91	10.30	0.7	137.1	13984	7.97	55.3
135	1030	5.57	10.72	9.91	0.7	136.6	13933	7.84	54.4
135	1030	5.60	10.59	9.62	1.0	136.1	13882	7.74	53.7
180	1030	5.63	11.40	9.20	0.7	135.8	13852	8.33	57.8
180	1030	5.66	10.20	9.20	0.6	135.5	13821	7.46	51.7
180	1030	5.68	9.90	8.85	0.6	135.0	13770	7.24	50.2
225	1030	5.83	10.20	9.48	1.0	133.2	13586	7.46	51.7
225	1030	5.86	9.85	9.10	0.7	132.9	13556	7.20	49.9
225	1030	5.88	10.02	9.68	0.7	132.5	13515	7.32	50.8

APPENDIX C-6 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
270	1030	5.96	9.85	7.15	0.9	131.8	13444	7.20	49.9
270	1030	5.93	8.05	6.68	0.9	131.3	13393	5.88	40.8
270	1030	6.03	7.72	6.80	0.6	130.8	13342	5.64	39.1
315	1030	6.06	9.10	7.50	0.7	130.3	13291	6.65	46.1
315	1030	6.10	10.55	9.10	1.5	129.8	13240	7.71	53.5
315	1030	6.14	9.55	--	0.6	129.1	13168	6.98	48.4
270	1030	6.16	7.12	6.30	0.5	128.9	13148	5.12	35.5
270	1030	7.41	6.58	5.52	.5 $\rightarrow$ 1	106.8	10894	4.81	33.4
270	1030	7.39	6.20	5.50	0.5	107.1	10924	4.53	31.4
315	1030	7.35	7.65	--	5 $\rightarrow$ 10	107.9	11006	5.59	38.8
225	1030	7.30	7.50	6.35	0.8	109.0	11118	5.48	38.0
225	1030	7.28	7.15	6.55	0.8	109.4	11159	5.23	36.3
180	1030	7.26	7.68	7.15	0.5	109.8	11200	5.61	38.9
180	1030	7.26	7.67	7.30	0.5	109.8	11200	5.61	38.9
135	1030	7.26	7.40	6.90	0.8	109.8	11200	5.41	37.5
135	1030	7.26	7.50	6.95	0.7	109.8	11200	5.48	38.0
90	1030	7.26	7.50	7.50	0.5	109.8	11200	5.48	38.0
90	1030	7.26	7.65	7.45	0.7	109.8	11200	5.59	38.8

APPENDIX C-7

PARTIAL DISCHARGE DATA THREE LAYERS OF VALERON, $\rho = 1380$ kPa

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
90	1380	5.03	14.10	13.40	1-2	151.0	15402	10.31	71.5
90	1380	5.09	14.10	13.55	1	150.3	15331	10.31	71.5
135	1380	5.52	13.75	13.21	1-2	146.0	14892	10.05	69.7
135	1380	5.57	13.60	13.10	1-2	145.7	14861	9.94	68.9
180	1380	5.63	13.51	12.72	1	145.0	14790	9.73	67.5
180	1380	5.69	13.15	12.60	1	144.3	14719	9.61	66.6
225	1380	5.81	13.25	12.70	1	143.1	14596	9.69	67.2
225	1380	5.86	13.45	12.72	1	142.8	14566	9.83	68.1
270	1380	6.00	9.90	9.20	1-2	141.2	14402	7.24	50.2
270	1380	6.04	9.80	9.30	1	140.9	14372	7.16	49.6
90	1380	6.59	12.30	11.35	1	134.4	13709	8.99	62.3
90	1380	6.71	12.42	11.65	1	133.0	13566	9.08	63.0
135	1380	6.78	10.58	10.30	1-2	132.1	13474	7.73	53.6
135	1380	6.90	11.00	10.30	3	130.7	13331	8.04	55.7
180	1380	7.09	11.30	10.65	1	128.3	13087	8.26	57.3
180	1380	7.17	11.70	10.90	1	127.1	12964	8.55	59.3
225	1380	7.35	9.80	9.08	2	124.8	12730	7.16	49.6
225	1380	7.42	10.28	9.09	1.5	123.8	12628	7.51	52.1
270	1380	7.48	8.60	7.78	< 1	123.0	12546	6.29	43.6
270	1380	7.52	8.53	7.80	< 1	122.4	12485	6.24	43.3

APPENDIX C-7 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
90	1380	7.80	10.43	9.61	< 1	118.4	12077	7.62	52.8
90	1380	7.85	10.61	9.51	< 1	117.8	12016	7.76	53.8
135	1380	7.91	8.95	8.60	1	116.9	11924	6.54	45.3
135	1380	7.98	9.50	8.55	2	115.9	11822	6.94	48.1
180	1380	8.05	10.10	9.58	1.5	115.0	11730	7.38	51.2
180	1380	8.11	9.91	8.93	1.5	114.0	11628	7.24	50.2
225	1380	8.23	8.45	7.60	1	112.2	11444	6.18	42.8
225	1380	8.27	8.70	8.07	1	111.5	11373	6.36	44.1
270	1380	8.34	7.92	7.08	--	110.5	11271	5.79	40.1
270	1380	8.37	7.85	7.18	--	110.0	11220	5.74	39.8
90	1380	9.12	8.40	7.55	1	98.7	10067	6.14	42.6
90	1380	9.17	8.33	7.25	1	97.9	9986	6.09	42.2
135	1380	9.24	6.79	6.28	1.5	96.9	9884	4.96	34.4
135	1380	9.30	6.80	6.30	1.5	96.0	9792	4.97	34.5
180	1380	9.37	7.20	6.95	1.2	94.9	9680	5.26	36.5
180	1380	9.42	7.55	6.90	1.2	94.0	9588	5.52	38.3
225	1380	9.48	6.70	6.23	1.5	93.0	9486	4.90	34.0
225	1380	9.53	6.95	6.38	1.5	92.3	9415	5.08	35.2
270	1380	9.64	6.60	6.08	---	90.9	9272	4.82	33.4
270	1380	9.70	6.52	6.18	---	90.0	9180	4.77	33.1

APPENDIX C-7 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
90	1380	10.11	7.44	6.55	--	84.7	8639	5.44	37.7
90	1380	10.20	7.50	6.25	--	83.5	8517	5.48	38.0
135	1380	10.37	5.92	5.65	--	81.4	8303	4.33	30.0
135	1380	10.42	6.25	5.88	1.5	80.8	8242	4.57	31.7
180	1380	10.47	6.72	6.42	--	80.0	8160	4.91	34.0
180	1380	10.50	6.56	6.44	--	79.8	8140	4.87	33.8
225	1380	11.09	6.30	5.88	--	73.3	7477	4.61	32.0
225	1380	11.11	6.43	5.90	--	73.1	7456	4.70	32.6
270	1380	11.15	6.55	5.85	--	72.8	7426	4.79	33.2
270	1380	11.15	6.52	5.90	--	72.8	7426	4.84	33.6

APPENDIX C-8

PARTIAL DISCHARGE DATA THREE LAYERS OF VALERON, FLAT ELECTRODES, $\rho = 1030$ kPa

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
0	1030	6.20	8.05	7.72	3	128.1	13005	5.88	40.8
0	1030	6.27	8.05	7.72	--	127.2	12903	5.88	40.8
0	1030	6.31	7.89	--	10	126.7	12832	5.77	40.0
0	1030	6.37	8.22	--	--	125.7	12741	6.01	41.7
0	1030	6.40	7.92	7.35	5-10	125.0	12700	5.79	40.1
45	1030	6.50	7.62	5.80	1	123.4	12548	5.57	38.6
45	1030	6.54	6.20	5.67	1	122.8	12476	4.53	31.4
45	1030	6.57	6.20	5.75	1	122.4	12426	4.53	31.4
90	1030	6.62	8.12	--	3	121.6	12334	5.94	41.2
90	1030	6.66	7.82	6.27	2000	120.9	12263	5.72	39.7
90	1030	6.69	7.83	6.20	2000	120.3	12202	5.72	39.7
135	1030	6.81	7.62	--	1000	118.2	11999	5.57	38.6
135	1030	6.85	8.16	6.80	3000	117.4	11918	5.97	41.4
135	1030	6.92	7.65	--	3000	115.3	11796	5.59	38.8
180	1030	7.00	7.65	5.62	3000	114.7	11654	5.59	38.8
180	1030	7.01	7.81	5.25	2000	114.5	11623	5.71	39.6
180	1030	7.06	7.62	7.05	1.5	113.8	11532	5.57	38.6
180	1030	7.10	7.92	--	2.0	112.9	11460	5.79	40.1
180	1030	7.10	8.31	4.88	2000	112.9	11460	6.07	42.1

APPENDIX C-8 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (nC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE EUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
180	1030	7.15	7.80	6.90	2.5	112.0	11359	5.70	39.5
225	1030	7.23	7.70	6.45	0.7	110.5	11206	5.63	39.0
225	1030	7.25	7.25	6.57	0.9	109.9	11146	5.30	36.7
225	1030	7.29	7.26	6.50	3.0	109.1	11074	5.31	36.8
0	1030	8.45	5.05	4.82	2-3	85.2	8666	3.69	25.6
0	1030	8.56	5.18	4.87	5	83.2	8463	3.79	26.3
0	1030	8.62	5.12	4.87	5	82.0	8352	3.74	25.9
45	1030	8.73	4.62	--	0.5	79.3	8067	3.37	23.4
45	1030	8.83	4.60	4.22	--	78.5	7986	3.36	23.3
45	1030	8.90	4.82	4.23	0.5	77.0	7854	3.52	24.4
90	1030	9.04	4.80	4.29	1300	74.9	7610	3.51	24.3
90	1030	9.12	4.98	4.56	1300	73.7	7498	3.64	25.2
90	1030	9.22	4.80	4.31	1300	72.0	7346	3.51	24.3
135	1030	9.55	4.89	4.30	1500	67.2	6838	3.57	24.8
135	1030	9.70	4.93	4.28	1500	65.8	6706	3.64	25.2
180	1030	9.85	4.92	3.52	1200	64.0	6523	3.60	25.0
180	1030	9.88	4.73	3.48	1500	63.8	6482	3.49	24.2
180	1030	10.01	4.73	3.28	1300	62.2	6330	3.49	24.2
225	1030	10.24	4.85	4.18	1.5	59.9	6116	3.55	24.6
225	1030	10.31	4.91	4.18	1.2	59.0	6055	3.59	24.9

APPENDIX C-8 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
0	1030	11.27	3.90	3.51	2	51.4	5253	2.85	19.8
0	1030	11.36	3.90	3.51	2	50.7	5192	2.85	19.8
0	1030	11.45	3.85	--	2	50.0	5131	2.81	19.5
45	1030	11.54	4.48	3.37	2	49.4	5037	3.27	22.7
90	1030	11.74	3.91	3.60	500	48.1	4938	2.86	19.8
90	1030	11.84	4.10	3.62	500	47.6	4877	3.00	20.8
90	1030	11.89	4.09	3.69	--	47.2	4836	2.99	20.7
135	1030	12.05	4.13	3.67	600	46.3	4745	3.02	20.9
135	1030	12.10	4.30	3.50	600	46.0	4714	3.14	21.8
135	1030	12.15	3.75	3.40	600	45.8	4684	2.74	19.0
180	1030	12.26	3.71	3.30	600	45.1	4633	2.71	18.8
180	1030	12.32	3.82	3.06	600	45.0	4602	2.79	19.3
180	1030	12.37	3.48	3.13	600	44.8	4572	2.54	17.6
225	1030	12.49	4.30	3.70	2	44.0	4511	3.14	21.8
225	1030	12.55	4.25	3.61	1.5	43.8	4481	3.11	21.6
225	1030	12.66	4.08	3.53	1.2	43.2	4430	2.98	20.7

APPENDIX C-9

PARTIAL DISCHARGE DATA THREE LAYERS OF VALERON, FLAT ELECTRODES, $\rho = 1220$ kPa

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
0	1220	5.41	8.58	8.48	< 1	143.3	14617	6.27	43.47
0	1220	5.45	8.83	8.40	< 1	143.0	14586	6.46	44.78
45	1220	5.68	9.91	8.76	1-2	140.4	14321	7.24	50.19
45	1220	5.79	8.91	8.20	1	139.1	14188	6.51	45.13
45	1220	5.88	9.25	8.65	1	138.1	14086	6.76	46.86
90	1220	6.02	10.42	10.28	2-3	136.5	13923	7.62	52.83
90	1220	6.24	11.90	--	1 $\rightarrow$ 1000	133.8	13648	8.70	60.31
90	1220	6.31	10.79	9.50	500	132.9	13556	7.89	54.70
135	1220	6.44	11.05	10.63	1-2	131.2	13382	8.08	56.01
135	1220	6.52	11.60	10.70	2-5	130.1	13270	8.48	58.79
135	1220	6.90	11.25	--	2-5	124.8	12730	8.22	56.98
180	1220	7.19	9.68	7.21	2000	120.4	12281	7.08	49.08
180	1220	7.35	9.90	9.40	1-10	117.9	12026	7.24	50.19
180	1220	7.44	10.65	9.90	3-10	116.3	11863	7.79	54.00
225	1220	7.66	9.95	8.80	3	112.9	11516	7.30	50.60
225	1220	7.71	9.30	8.80	2	111.7	11393	6.80	47.13
225	1220	7.80	9.68	8.62	4	106.8	10894	7.08	49.05
270	1220	8.02	7.39	6.61	> 10 ⁴	106.3	No gap	No gap	No gap
270	1220	8.10	6.90	6.52	> 10 ⁴	105.0	No gap	No gap	No gap

APPENDIX C-9 (continued)

SITION EGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
315	1220	8.20	5.25	4.51	1	103.0	No gap	No gap	No gap
315	1220	8.25	4.97	4.32	1	102.2	No gap	No gap	No gap
0	1220	8.38	7.13	6.79	1	100.0	10200	5.21	36.13
0	1220	8.43	7.40	6.90	1-2	99.0	10098	5.41	37.50
45	1220	8.70	6.23	5.90	1	94.4	9629	4.55	31.57
45	1220	8.75	6.20	5.89	1	93.4	9527	4.53	31.42
90	1220	8.90	6.85	6.30	1000	91.1	9292	5.01	34.71
90	1220	8.94	7.04	6.25	1500	90.6	9241	5.15	35.67
135	1220	9.15	7.10	6.50	1000	88.0	8976	5.19	35.98
135	1220	9.20	7.15	6.40	2000	86.0	8772	5.23	36.24
180	1220	9.70	7.06	5.68	2000	78.8	8037	5.16	35.78
180	1220	9.75	7.16	5.81	2000	77.9	7946	5.23	36.28
225	1220	9.96	6.89	5.95	2	75.3	7681	5.04	34.92
225	1220	10.07	6.30	5.40	1	74.0	7548	4.61	31.92
225	1220	10.12	6.18	5.50	1	73.5	7497	4.52	31.32
270	1220	10.28	4.90	--	1	71.5	No gap	No gap	No gap
270	1220	10.34	5.20	4.35	2-5	70.8	No gap	No gap	No gap
315	1220	10.64	3.92	--	1	67.6	No gap	No gap	No gap
315	1220	10.69	3.95	--	1	67.1	No gap	No gap	No gap

APPENDIX C-9 (continued)

POSITION (DEGREES)	PRESSURE (kPa)	TEMP (K)	PDIV (kV)	PDEV (kV)	DISCHARGE MAGNITUDE (pC)	HELIUM DENSITY, ρ (kg/m ³)	ρd (kg/m ³ · μ m)	PEAK VOLTAGE ACROSS THE BUTT GAP (kV)	GAP STRESS (rms) (kV/mm)
0	1220	10.85	5.79	5.59	2-3	65.7	6701	4.23	29.34
0	1220	10.90	5.91	5.43	2-3	65.2	6650	4.32	29.95
45	1220	10.99	6.28	5.50	2	64.3	6559	4.59	31.83
45	1220	11.03	6.10	5.40	2	64.0	6528	4.46	30.91
90	1220	11.27	5.40	5.28	2	61.9	6314	3.95	27.36
90	1220	11.33	5.62	5.33	3	61.5	6273	4.11	28.48
135	1220	11.43	5.30	4.96	1000	60.7	6191	3.87	26.86
135	1220	11.83	5.62	4.68	1000	57.8	5896	4.11	28.48
180	1220	12.24	5.50	5.30	1-2	55.0	5610	4.02	27.88
180	1220	12.29	5.99	3.80	1000	54.8	5590	4.38	30.36
180	1220	12.34	4.68	--	1000	54.3	5539	3.42	23.72
225	1220	12.47	5.53	4.60	2	53.7	5477	4.04	28.02
225	1220	12.50	5.46	4.55	2	53.4	5447	3.99	27.67
270	1220	12.58	4.50	4.30	1-2	53.0	No gap	No gap	No gap
270	1220	12.64	4.60	4.31	5	52.7	No gap	No gap	No gap
315	1220	12.80	3.56	3.02	< 1	51.7	No gap	No gap	No gap
315	1220	12.86	3.35	--	< 1	51.3	No gap	No gap	No gap

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