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DC BREAKDOWN STRENGTH OF DIELECTRIC MATERIALS AT CRYOGENIC TEMPERATURES*

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Abstract - The HVDC superconducting cable, under development at the Los Alamos Scientific Laboratory will operate at a temperature of 12 K and a helium pressure of 1.38 MPa. Because dc breakdown data of dielectric materials at these operating conditions were not previously available, extensive tests were performed on 11 dielectric materials in sheet form. Three of these materials were impregnated with mineral oil, which increased their dc withstand strength significantly. Four of these 11 materials were selected for further tests at varying temperatures and pressures. The dc-breakdown field of cellulose paper (with and without oil impregnation) and PP/C (cellulose paper/polypropylene-cellulose paper) varied as the exponential of the inverse of temperature. For the two polyethylene materials tested, the dc-breakdown strength showed a peak between 12 and 298 K. Higher pressure increased the breakdown strength of the materials. Higher pressure or lower temperature also decreased the probability of surface flashover.

INTRODUCTION

A dc superconducting cable being developed at the Los Alamos Scientific Laboratory (LASL) has many advantages for transmitting large blocks of electrical power [1-6]. However, much research and development is needed before the dc superconducting cable is ready for industrial application. A reliable dielectric system for operation at cryogenic temperatures is one of the critical needs. The dielectric must function under electrical stress and be mechanically and thermally suitable for handling at room temperature as well. The development of a cryogenic dielectric system is one of the projects under the dc Superconducting Power Transmission Line (dc SPTL) Program at LASL.

Extensive data are available on cryogenic dielectrics for operation under ac conditions, but few data exist for operations under dc conditions. The electrical requirements of a dielectric under dc stress are different from those under ac stress; that is, for ac operation, the corona inception voltage and the dielectric losses are the limiting constraints. For dc applications, the polarity-reversal stress is the limiting factor. The aging mechanisms for the two types of application will also be different for long-term stress applications.

In our tests, dielectric materials required 5 to 6 h to cool from room temperature to 12 K and

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as much time to warm again. The actual electrical test at cryogenic temperatures lasts for 30 min. To obtain statistically significant data would require many years of testing all candidate materials under various electrical conditions; therefore, we first performed screening tests on sheets of dielectric materials under uniform dc electric field. From the results, several dielectric materials were selected for cable sample tests under various electrical conditions (e.g., impulse, switching surge, polarity reversal). The data from the screening tests also provided basic information on the behavior of dielectric materials at cryogenic temperatures under dc stress.

DESIGN OF EXPERIMENTS

Dielectric Specimens

Of the eleven dielectric materials selected, (Table I) most were 3-mil (76.2- μ m) thick. However, Cryovac could be obtained only in 1.5-mil (38.1 μ m) thickness, Pink Poly in 4-mil (101.60 μ m), and PP/C (a composite made up of cellulose paper in the outer two layers and polypropylene in the middle layer) in 5-mil (127- μ m) thickness. The 5-mil-thick (127- μ m) cellulose paper B was selected for direct comparison with the PP/C.

Oil-impregnated cellulose paper is ideal from the manufacturing standpoint, because it is the standard dielectric for all high-voltage cables. Moreover, the oil-impregnated paper is significantly stronger at liquid nitrogen temperature under dc, impulse, and polarity reversal than at room temperature [7]. However, it had not been tested previously at supercritical helium temperatures (i.e., greater than 5.2 K). Therefore, the two types of cellulose paper and PP/C were tested at cryogenic temperatures after impregnation with mineral oil (Univolt 60).

Test Parameters

Most of the tests were performed at 12 K with a helium pressure of 1.38 MPa, the operating conditions of the dc superconducting cable being designed by LASL. Additional tests were performed on the selected systems at 83 K and 298 K with helium pressures of 0.69 MPa and 1.38 MPa. Both polarities of dc were supplied by a filtered HVDC source, with a 1 kV/s-ramp rate of voltage application until breakdown.

The voltage measurement was accurate to $\pm 1\%$, pressure measurement were accurate to ± 7 kPa. The accuracy of the temperature measurement was as follows: ± 50 mK for 12 K, ± 0.5 K for 83 K and 298 K.

Design of Equipment

The main part of the cryostat (Fig. 1) providing the environment for the dielectric specimens, is a copper cylindrical chamber, 210-cm long and 15-cm diam, which can be safely pressurized up to 2.1 MPa. The cylinder is cooled by flowing either liquid nitrogen or liquid helium through coils soldered along the outer surface. A second copper cylinder, 21.8-cm

List of Dielectric Materials for Cryogenic Tests

diam, is placed concentrically around the first. Liquid nitrogen, flowing through soldered coils, provides shielding against heat influx. A 27.4-cm-diam steel cylinder provides the vacuum jacket and external support. The annular space between the cylinders is filled with multilayer thermal insulation and is continuously evacuated by a diffusion pump. A hole in the floor accommodates the cryostat.

Fig. 2. Outline drawing of bushing.

As dielectric samples require hours to cool and warm, a multi-electrode dielectric sample holder was designed to speed up accumulation of data. This Plexiglas sample holder contains six pairs of stainless steel electrodes, seated in accurately aligned holes. Electrical contacts are made to each of the six upper electrodes by a rotating electrode attached to the actuating rod in the bushing. Each electrode has an overall diameter of 15.88 mm, a flat surface of 6.45-mm diam, and contour radius of 4.76 mm.

Fig. 1. Outline drawing of test cryostat.

The bushing (Fig. 2) was designed so that connections could be made to the multi-electrode dielectric sample holder by manipulating an actuating rod and a moving arm from outside the cryostat. The actuating rod is inserted through the central hollow conductor that provides the voltage. Tightly wound Mylar sheets serve as the major insulation between the high-voltage conductor and the ground, which is concentrically placed stainless steel tubing. At the upper (room temperature) part of the bushing, the

The sample holder is attached by screws to a stainless steel cylinder (13.9-mm diam) connected at its upper end to the ground plane of the bushing. The sample holder and the rotating electrode are shown in Fig. 3.

Fig. 3. Six-electrode sample holder for multiple breakdown tests.

The cryostat contains three heaters—two around the 13.9-mm-diam stainless steel cylinder, the third around the innermost cylinder of the cryostat. These heaters control the temperature and warm the cryostat to room temperature so that the dielectric samples can be changed.

A 1/8-w carbon-resistor thermometer was used to measure the 12-K temperature, and a copper-constantan thermocouple was used from 83 to 298 K.

Figure 4 shows the test area.

Fig. 4. Test set up.

Test Procedures

Before each test the electrodes were cleaned with freon in an ultrasonic cleaner. They were also polished regularly in a drill press with 1:1 aluminum oxide and water. The dielectric samples, consisting of two 13.33-cm diam sheets, were first tested for electrostatic charges on the surface by a Simco Type SS-1 locator and charges neutralized by polonium irradiation (Staticmaster from Nuclear Products Co.) before installation in the sample holder.

After the sample holder had been fitted to the bushing and the bushing installed inside the cryo-

stat, the test assembly was evacuated for 15 min to about 0.5 torr (66.8 Pa) before the test assembly was flushed several times with helium. The cryostat was then pressurized and precooled by passing liquid nitrogen through the main cooling coils. For tests at 12 K, the cryostat was further cooled by passing liquid helium through the main cooling coils. The temperature of the sample was held at 12 K (± 50 mK) by an automatic temperature controller. The voltage-breakdown tests began after the sample had been in the pressurized helium environment at the required temperature for at least 15 min.

Voltage could be applied and polarity alternately reversed to any of the six electrode pairs by rotating an indexed rod from outside the cryostat. Voltages were applied to the numbered electrode pairs in the order 1,3,5,2,4, and 6.

Two sets of experiments (each with six breakdowns) were performed at 12 K and 1.38 MPa on each of the 14 dielectric samples; one set started with positive-polarity voltage and the other with negative-polarity voltage. Three such replications were performed, each being completely randomized with the help of a Random Number Table.

A second series of tests was performed after five dielectric systems were selected as suitable for the cable-sample tests. The samples were tested in the form of sheets at 83 K and 298 K under 0.69 MPa and 1.38 MPa of helium, as well as at 12 K and 0.69 MPa of helium to determine the effects of temperature and pressure on the dc breakdown voltage levels. Two sets of tests (each with six breakdowns) were performed on the five samples. The 50 sets of tests were randomized; Tables II-V show the summarized results.

ANALYSIS OF RESULTS AND DISCUSSION

Surface charges were a concern, particularly for the plastic dielectric materials. Although these charges were neutralized by polonium irradiation before the dielectric materials were placed in the sample holder, tests showed that they reappeared within a few hours. The paths of the surface discharges could be identified by dark streamer patterns on the dielectric surface.

The surface charge could also be correlated with surface discharges and flashovers when voltage was applied. On Kapton, surface flashovers were sometimes accompanied by black carbonized paths. Of all the plastic materials, Pink Poly showed the least amount of surface charges and accompanying discharges. Tables II-V show the ratio of puncture to surface flashover for all the materials tested. Comparison of these tables shows higher pressure or lower temperature tends to suppress the surface discharges.

Often, breakdown resulted in multiple punctures of the test sample (Fig. 5). Puncture was associated with fractures for several of the dielectric materials. Some of these materials showed microfractures (Fig. 6) and others (e.g., Pink Poly) showed gross fractures. To determine whether the cool-down process produced the fractures, Pink Poly was cooled to 12 K at 1.38 MPa of helium using the voltage breakdown test procedure. When it was warmed without the application of voltage, no mechanical distress of the material was observed. Tapes of all 11 dielectric materials were immersed in liquid nitrogen. Although these tapes became stiffer, none broke when bent. Tapes of these materials were also wound on aluminum mandrels and plunged into liquid nitrogen. They showed no damage. This was also true of cellulose paper impregnated with Univolt 60. However, Univolt 60, when frozen in liquid nitrogen, became brittle like glass.

TABLE II

DC Breakdown Voltage and Electric Field
at 12 K and 1.38 MPa of Helium

Material	Mean kV(kV/mm)	Lowest Value kV(kV/mm)	Stand. Dev. kV(kV/mm)	No. of Measurement	Distribution	Puncture/ Flashover
Cellulose Paper ¹	11.08(72.70)	9.0(59.06)	1.43(9.38)	34	LN	34/0
Oil-impregnated Cellulose Paper ¹	30.39(199.41)	22.8(149.61)	4.73(31.04)	34	LN/W	34/0
Cellulose Paper ²	15.22(59.92)	12.0(47.24)	1.65(6.50)	36	W	36/0
Oil-impregnated Cellulose Paper ²	44.20(174.02)	34.8(137.01)	4.62(18.19)	36	N	36/0
Cryovac ³	40.63(533.20)	24.0(314.96)	6.88(90.29)	35	W	21/14
Kapton ¹	54.67(358.73)	36.0(236.22)	13.05(85.63)	36	LN	4/32
Mylar ¹	47.00(308.40)	30.0(196.85)	5.86(38.45)	36	LN	5/31
Nomex ¹	14.10(92.52)	10.2(66.93)	2.22(14.57)	35	E	35/0
Pink Poly ⁴	43.93(216.19)	27.6(135.83)	6.28(30.91)	33	N	33/0
PP/C ²	31.08(122.36)	27.0(106.30)	2.34(9.21)	35	LN	35/0
Oil-impregnated PP/C ²	46.37(182.56)	33.6(132.28)	6.33(24.92)	35	N	35/0
Teflon ¹	47.70(312.99)	36.0(236.22)	4.84(31.76)	36	W	18/18
Udel ¹	47.76(313.39)	36.0(236.22)	6.70(43.96)	32	E	15/17
Valeron ¹	46.32(303.94)	30.0(196.85)	4.82(31.63)	35	W	30/5

- ¹ = Two nominal 76.2- μ m-thick sheets
² = Two nominal 127- μ m-thick sheets
³ = Two nominal 38.1- μ m-thick sheets
⁴ = Two nominal 101.6- μ m-thick sheets
E = Extreme-value (Type I) distribution
LN = Log-normal distribution
N = Normal (Gaussian) distribution
W = Weibull distribution

TABLE III

DC Breakdown Voltage and Electric Field
at 12 K and 0.69 MPa of Helium

Material	Mean kV(kV/mm)	Lowest Value kV(kV/mm)	Stand. Dev. kV(kV/mm)	No. of Measurements	Puncture/ Flashover
Cellulose Paper ¹	10.65(41.93)	9.0(35.43)	0.73(2.87)	12	12/0
Oil-impregnated Cellulose Paper ¹	35.30(138.98)	27.6(108.66)	3.84(15.12)	12	12/0
PP/C ¹	26.45(104.13)	19.6(77.17)	3.49(13.74)	12	12/0
Pink Poly ²	37.09(186.52)	30.6(150.59)	4.74(23.33)	11	10/1
Valeron ³	39.30(257.87)	31.8(208.66)	2.93(19.23)	12	1/11

- ¹ Two nominal 127- μ m-thick sheets
² Two nominal 101.6- μ m-thick sheets
³ Two nominal 76.2- μ m-thick sheets

TABLE IV

DC Breakdown Voltage and Electric Field
at 83 K Under 0.69 MPa and 1.38 MPa of Helium

Material	Mean KV (KV/mm)	Lowest Value KV (KV/mm)	Stand. Dev. (KV (KV/mm)	No. of Measurement	Puncture/ Flashover
Cellulose	6.50 (25.59) ⁴	5.4 (21.26)	0.84 (3.31)	12	12/0
Paper ¹	8.40 (33.07) ⁵	6.0 (23.62)	1.95 (7.68)	11	11/0
Oil-impregnated	31.95 (125.79)	27.6 (108.66)	2.61 (10.28)	10	6/4
Cellulose Paper ¹	33.60 (132.28)	15.6 (61.42)	6.62 (26.06)	12	10/2
PP/C ¹	21.11 (83.11)	17.4 (68.50)	3.02 (11.89)	11	11/0
	27.76 (109.29)	18.6 (73.23)	5.47 (21.54)	11	11/0
Pink Poly ²	53.93 (265.40)	43.2 (212.60)	7.50 (36.91)	12	0/12
	70.58 (347.34)	51.6 (73.23)	11.53 (56.74)	11	1/10
Valeron ³	46.20 (303.15)	37.2 (244.09)	5.64 (37.01)	12	1/11
	55.72 (365.62)	40.8 (267.72)	9.37 (61.48)	12	7/5

¹ Two nominal 127- μ m-thick sheets

² Two nominal 101.6- μ m-thick sheets

³ Two nominal 76.2- μ m-thick sheets

⁴ At 0.69 MPa

⁵ At 1.38 MPa

TABLE V

DC Breakdown Voltage and Electric Field
At 298 K Under 0.69 MPa and 1.38 MPa of Helium

Material	Mean KV (KV/mm)	Lowest Value KV (KV/mm)	Stand. Dev. KV (KV/mm)	No. of Measurement	Puncture/ Flashover
Cellulose	6.25 (24.61) ⁴	4.2 (16.54)	1.52 (5.98)	12	12/0
Paper ¹	8.10 (31.89) ⁵	4.8 (18.90)	2.34 (9.21)	12	12/0
Oil-impregnated	25.35 (99.80)	15.0 (59.06)	4.73 (18.62)	12	1/11
Cellulose Paper ¹	28.80 (113.39)	18.6 (73.23)	6.90 (27.17)	12	8/4
PP/C	19.55 (76.97)	12.0 (47.24)	5.08 (20.00)	12	4/8
	24.40 (96.06)	20.4 (80.32)	3.57 (14.06)	12	8/4
Pink Poly ²	22.95 (112.94)	21.0 (103.35)	1.76 (8.66)	12	0/12
	31.60 (155.51)	22.2 (109.25)	6.63 (32.63)	12	3/9
Valeron ³	23.00 (150.92)	11.4 (74.80)	5.32 (34.91)	12	1/11
	38.84 (254.86)	24.6 (161.42)	5.71 (37.47)	11	5/6

¹ Two nominal 127- μ m-thick sheets

² Two nominal 101.6- μ m-thick sheets

³ Two nominal 76.2- μ m-thick sheets

⁴ At 0.69 MPa

⁵ At 1.38 MPa

Fig. 5. Photomicrograph of punctures on Teflon caused by voltage breakdown (75x)

Fig. 6. Photomicrograph of microfractures surrounding puncture on Teflon caused by voltage breakdown (300x).

An investigation was made of four probability distributions to find the best fit in describing the breakdown voltage. The normal (Gaussian), lognormal, Weibull, and extreme value (type I) distributions were selected for study [8]. The maximum distances between the sample cumulative distribution function (c.d.f.) and the respective theoretical c.d.f.'s were used as measures to form the basis of comparison between distributions. These are similar to Kolmogorov-type statistics [9]. No attempt was made to attach significance levels; they were used only for comparison purposes.

Maximum likelihood estimates of the Weibull and extreme value parameters were used to compute the respective c.d.f.'s. The sample mean and standard deviation (bias corrected) provided the theoretical normal c.d.f. The theoretical lognormal c.d.f. was obtained by taking natural logarithms of the data, finding the corresponding normal c.d.f., and then making the appropriate transformation.

Figure 7 shows the empirical c.d.f. and the four theoretical c.d.f.'s for two sheets of 127- μ m cellulose paper. The maximum absolute difference between the empirical c.d.f. and each theoretical c.d.f. is also given. The Weibull distribution best fits the data for cellulose paper under these experimental conditions.

Fig. 7. Comparison between sample breakdown voltage cumulative distribution function (c.d.f.) with four types of c.d.f.'s. Two layers of 127- μ m thick cellulose paper at 12 K and 1.38 MPa of helium.

Column 6 of Table II contains the analysis for each of the dielectric materials tested at 12 K under 1.38 MPa of helium pressure. No single distribution appears to be favored over the others. Six of the 14 materials experienced both puncture and flashover. Perhaps no c.d.f. should have been tried; however, data for the eight materials that experienced 100% puncture also failed to support any particular type of c.d.f. Considerably more work needs to be done before anything definitive can be stated concerning the statistical distribution of breakdown.

The effects of temperature and pressure on the breakdown voltage for five selected materials (Figs. 8 and 9) were studied. For cellulose paper (with and without impregnation with Univolt 60) and PP/C dependence of puncture breakdown on temperature followed the relationship,

$$E = E_0 \exp(a/T), \quad (1)$$

where E = breakdown electric field (kV/mm)
 T = temperature (K)
 E_0, a = constants

For these three materials, E_0 and a were computed and the values shown in Table VI. For Pink Poly and Valeron, the breakdown electric field increased to a peak at 83 K. The reason for such abnormal behavior is not readily understood. As the data was taken at only three temperatures, neither the exact temperature at which the peak occurred nor the magnitude of the peak electrical strength could be obtained. However, because of the randomized design of the experiments, a peak electrical strength certainly exists for Pink Poly and Valeron. In computing the data for Figs. 8 and 9, only the puncture breakdown values were considered for those cases where 50% or more of the breakdowns were caused by puncture. For those cases where 50% or more of the breakdowns were caused by surface flashovers, all numerical results including puncture and surface flashover, were considered and the assumption made that the average of puncture breakdown would be higher than that shown.

Fig. 8. Relationship between breakdown electric field and temperature for five dielectric materials at 0.69 MPa of helium.

Fig. 9. Relationship between breakdown electric field and temperature for five dielectric materials at 1.38 MPa of helium.

Higher pressure generally increased the breakdown strength of a material. For cellulose paper and

TABLE VI

Parameters for $E = E_0 \exp(a/T)$

Material	Pressure MPa	E_0 KV/mm	a K
Cellulose Paper	0.69	23.8	6.80
Cellulose Paper	1.38	30.1	8.27
Oil-impregnated Cellulose Paper	0.69	129.0	0.89
Oil-impregnated Cellulose Paper	1.38	122.0	4.26
PP/C	0.69	79.0	3.32
PP/C	1.38	104.5	1.89

PP/C, this effect can be explained by considering the porous nature of the cellulose paper matrix (Fig. 10); helium gas at higher pressure in the pores of the material matrix would improve breakdown strength. For plastic materials (Fig. 11) there are two possible reasons for this apparent improvement in breakdown strength. Two sheets of the dielectric material were used as the test samples. As helium gas was trapped between the two sheets, higher gas pressure should have improved the breakdown strength. In addition, surface flashover should have prevented puncture for some of the plastic materials. As pressure increased, flashover strength improved, and the apparent breakdown strength of the plastic materials showed higher values at higher pressures.

Based on the results of the screening tests, four dielectric materials were selected for further testing in actual cable configuration. The criteria for selection were high electrical breakdown strength and minimal surface discharges. These materials are: cellulose paper (with and without oil impregnation), Pink Poly, PP/C, and Valeron. Although cellulose paper showed the lowest breakdown strength, it was selected because it is the standard dielectric material for high-voltage cables. Cellulose paper with interspersed layers of plastic materials will also be tested as a possible dielectric system for the dc superconducting cable.

Fig. 10. Photomicrograph of cellulose paper (400x).

Fig. 11. Photomicrograph of Pink Poly (4000x).

CONCLUSIONS

- [1] Impregnation of cellulose paper with mineral oil improved its dc-withstand strength significantly even at cryogenic temperatures.
- [2] The dc breakdown field of cellulose paper (with and without oil impregnation) and PP/C varied as the exponential of the inverse of temperature.
- [3] For some plastic materials, the dc breakdown strength showed a peak between 12 K and 298 K.
- [4] Higher pressure increased the breakdown strength of the materials under test.
- [5] Higher pressure or lower temperature decreased the probability of surface flashover.
- [6] Four dielectric materials (cellulose paper, Pink Poly, PP/C, and Valeron) showed sufficient strength under helium pressure and cryogenic temperature to warrant testing in actual cable configuration.
- [7] Impulse, switching-surge, and polarity-reversal tests will be performed on cable samples wound with the four materials, and the results will be incorporated into the final design of the dielectric system for the HVDC superconducting cable.

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