PROGRESS IN THE DEVELOPMENT OF GAS-IMPREGNATED LAPPED PLASTIC FILM INSULATION*

CONF-770702--1

E. B. FORSYTH, Member, IEEE
A. J. McNerney, Member, IEEE

A. C. Muller, Member, IEEE
S. J. Rigby†

Brookhaven National Laboratory††
Associated Universities, Inc.
Upton, N.Y. 11973

ABSTRACT

A flexible superconducting power transmission cable is under development. The electrical insulation consists of lapped polymeric film tapes impregnated with supercritical helium. Ways of satisfying the many constraints on the material are described. Although the cable is intended for low-temperature operation good electrical and mechanical characteristics are needed at room-temperature. Results are given for both small-sample tests and a model cable fabricated commercially. The results are compared with those obtained by other workers and the design of the next test cable is given.

INTRODUCTION

The work at Brookhaven National Laboratory (BNL) in this field started as a result of a design study for a superconducting, helium-cooled, power transmission cable. After a review of contemporary development throughout the world it was concluded that a flexible cable offered the best technical and economic features.^[1] The subsequent examination of actual underground transmission systems under construction or consideration by electric utility companies has reinforced the validity of the basic design features.^[2] The choice of a flexible, forced-cooled cable thus sets the general guide for a dielectric development program. In any device designed for low temperature operation great care must be taken to avoid excessive dissipation within the low-temperature environment because the heat must be pumped away by the refrigerator. The inefficiency of this process results in an apparent loss, represented by the power input to the cooling system, which must be optimized within the general framework of the overall operating cost of the complete system. Considerations of this nature lead to the early rejection of many insulating materials, including kraft paper, because of unacceptably high values of dissipation factor. Extruded dielectric is not possible for low

temperature applications because differential contraction inevitably causes cracking. This problem is avoided by using thin tapes applied in a helical winding; the pitch angle is chosen to produce a radial contraction which matches other cable components. The conductors of a superconducting cable are cooled by supercritical helium which also permeates the butt spaces between the insulating tapes.

During the first part of the development program test apparatus was constructed which enabled short samples about two feet long to be tested in a coaxial configuration located within an appropriate high-pressure, low temperature helium environment.^[3] The apparatus allowed us to make quick comparative tests of many possible materials and lead to the early rejection of synthetic paper tape. The poor discharge inception level of this tape illustrates the crucial difference between liquid impregnation and gas impregnation. With liquid impregnation it is usual to find the dielectric constant of the tape and impregnant are nearly equal, thus stress intensification within the butt space or at interfaces is avoided. With synthetic paper tape this problem is exacerbated because of the numerous voids within the tape. It was found that solid film made of various polymers gave the best promise of a successful design. In choosing the best material for this application a compromise has to be made between acceptable electrical and mechanical characteristics. For example, polyethylene has excellent, low loss, electrical properties but in a pure form it is relatively weak and hard to wind. Various methods are available to improve the mechanical properties, these are described below. After the comparative tests of various polymeric materials the small sample apparatus was used to evaluate screen design. With ideal electrodes a partial discharge inception level was achieved which corresponded with observations of other workers on the breakdown properties of helium. This suggests that helium breakdown sets the design limit for this type of construction unless rather elaborate steps are taken to reduce the electric field intensity in the butt spaces.

*Work Supported by the U.S. Energy Research and Development Administration, the Electric Power Research Institute and the National Science Foundation.

† Present Address: Pirelli General Cable Works, Ltd, Leigh Road, Eastleigh SO5 5YU, Hampshire, England.

†† Operated by Associated Universities, Inc., Under Contract to the Energy Research and Development Admin.

MASTER

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any legal warranty, express or implied, or assumes any liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

As the field of potential materials narrowed it was decided to construct a test cable using three of the best candidates. This was made to a Brookhaven specification by the Anaconda Cable and Wire Company. Sections of this cable about 75 ft (22 m) long have been tested at Brookhaven for the last two years. The results are presented below and a comparison is made with the small sample results. Although the insulation thickness of the Anaconda Cable is only 0.1 in (2.5 mm) it is merely the forerunner of cables which in the next year or two will possess insulation 0.4 in (10 mm) thick. The problem of bending cables lapped with plastic film of this thickness is severe. The classical analysis of the construction of bendable cable^[4] has been extensively applied to kraft paper insulation^[5] but not to the use of polymers. In a cooperative study by Brookhaven and Phelps Dodge Cable and Wire Company sponsored by the Electric Power Research Institute (EPRI) these problems were investigated with the aim of further defining desirable goals for the materials development program. It is apparent that highly anisotropic tapes will perform more like paper and permit bending without buckling of the tapes.^[6] This requires material with a high ten-

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

side modulus and low compressive modulus. Methods of achieving these goals are described below.

It can be seen that the design has features in common with conventional cables. Paper-oil cables under nitrogen pressure have been used for many years, however,⁷ the bending performance of these is not determined by the gas impregnant. Within the past decade polyethylene cables impregnated with SF₆ have been developed.⁸ These share many problems with the Brookhaven design. In order to obtain a quick test of the cable sample we came to test the Anaconda Cable at room temperature with N₂ and SF₆ impregnation before cooling to the operating temperature appropriate for a superconducting cable. These tests also provide comparative results with room temperature developmental cables.

Up to the present time we have not investigated the long-term degradation of this type of insulation, although workers using liquid nitrogen have suggested that deterioration proceeds more slowly than at room temperature.⁹

TAPE PROPERTIES

A summary of desirable characteristics for the dielectric tape for use in an ac superconducting cable is given in Table I. Our concern with refrigerator loading has placed emphasis on the selection of tapes with very low values of loss tangent and dielectric constant. Although present BNL experimental cables are using higher loss tapes such as polycarbonate and polysulfone,^[10] the long range materials program has been directed towards tailoring the mechanical properties of the non-polar, low-loss plastics to meet the design requirements.

A recent study of loss tangent value versus antioxidant type, performed with sample of polyethylene prepared by Battelle Columbus Laboratories (BCL) for BNL, indicated that a satisfactory loss tangent could be obtained by proper selection of the antioxidant employed. The data in Table II show that in polyethylene loss tangent is a function of both type and concentration of this additive and that one antioxidant, Topanol, leads

Table I. Specifications for Dielectric Tapes for Use in AC Superconducting Cables

A. Dielectric (4.2 K)

1. Dielectric Strength:
 - a. Operating Stress - 10 MV/m min.[†]
 - b. Impulse Strength - 100 MV/m min.[†]
2. Dielectric Constant - 2.5 max.
3. Dissipation Factor - 2×10^{-5} max.

B. Mechanical

1. Tensile Modulus (293 K) - 500,000 psi min.
(35.2×10^3 kg/cm²)
2. Yield Strength (293 K) - 5,000 psi min.
(35.2 kg/cm²)
3. Tensile Strength (293 K) - 20,000 psi min.
(1.4×10^3 kg/cm²)
4. Friction Coefficient (293 K)
 - a. Static - 0.250 max.
 - b. Dynamic - 0.200 max.
5. Total Elongation (4.2 K) - 3.0% min.

C. Thermal

1. Total Contraction (293 to 4.2 K) - 0.8 to 1.5%
2. Conductivity (4.2 K) - 5×10^{-5} to 3×10^{-4} W/cm-K

[†] Stress at Inner Conductor Surface

Table II. Effect of Antioxidant Type and Concentration on Loss Tangent of Phillips Marlex Type 6006 Polyethylene

BNL Sample No.	Additive Content	Extraction Solvent	Tan $\delta \times 10^6$ at 100 Hz				
			4.2K	5.1K	6K	8K	10K
1	None	None	-	7	-	4	5
2	None	Methanol	6	-	3	7	5
3	Ional	None	-	26	-	11	9
4	Ional 0.05%	None	-	16	-	11	7
5	Ional 0.01%	Methanol	-	9	-	28	7
6	Ional 0.1%	Cyclohexane	-	2	-	0	0
7	Ional 0.26%	None	-	88	-	4	21
8	Ional 0.5%	None	232	-	126	73	50
9	DLTDP 0.05%	None	25	-	17	15	9
10	DLTDP 0.11%	None	14	-	5	19	2
11	DPTDP 0.11%	Methanol	8	-	6	2	2
12	Topanol 0.5%	None	14	-	10	0	0
13	Topanol 0.1%	Methanol	0	-	0	0	1
14	Topanol 0.1%	None	9	-	9	5	9

to 60 Hz losses less than 10×10^{-6} at 6 to 8 K in a concentration of 0.1%.

In order for the dielectric medium to perform satisfactorily at 6 - 8 K, the tape should also possess certain thermal properties. Cryofracture can be avoided if the elongation to fracture is considerably greater than the contraction experienced by the tape during cooldown. An elongation to contraction ratio greater than 1.3:1 appears necessary to avoid detrimental effects upon cooldown. Elongation to contraction ratios of tapes under evaluation at BNL are given in Table III.^[11] Calculations made of the effects of thermal conductivity of the dielectric medium indicate that the conductivity should be between the limits of 5×10^{-5} to 3×10^{-4} W/cm-K. Recent measurements performed at BCL show that the conductivities of the major films under evaluation at BNL fall within these limits. (See Table IV.)

Taping precision of plastics appears to be proportional to the tensile modulus over the range of 10^5 to 10^6 psi (7.03 to 70.3×10^3 kg/cm²). A modulus of approximately 5×10^5 psi (35.2×10^3 kg/cm²) seems to be the minimum value for commercial lapping of acceptable quality, and a modulus of 1×10^6 psi (70.3×10^3 kg/cm²) appears to be the optimum value for this operation. A high tensile modulus has recently been found to have a second important advantage in the technology of lapped plastic cable design. The recent EPRI sponsored study^[6] has shown that the bending performance of plastic cables is probably proportional to the ratio of tensile modulus in the machine direction to the compressive modulus normal to the tape surface. This ratio, designated as E_1/E_3 or "n" in the Pirelli formulae,^[4,5] normally has a value of 900 - 1000 for electrical grade paper. However, measurements of "n" for Valeron polyethylene show that this value is only approximately 50 at typical taping pressures, i.e., 20 psi (1.4 kg/cm²). This difference is due to both the relatively low tensile modulus

Table III. Mechanical Properties of Dielectric Tapes

Polymer Type	Tensile Modulus, psi(kg/cm ²) at 293K	293K to 4.2K Contr'n, %		Elong'n at 4.2K%	Ratio of Elong'n to Contr'n
		Long	Trans.		
Low Density P'eth.	25,000 (1.76x10 ³)	2.740	2.690	2.8	1.02
High Density P'eth.	105,000 (7.38x10 ³)	2.595	2.519	3.3	1.27
P'amide (Nylon 11)	106,000 (7.45x10 ³)	1.924	1.852	3.1	1.61
Oriented P'prop.	329,000 (23.1x10 ³)	1.755	0.255	2.3	1.31
Laminated High Density Oriented P'eth.	110,000 (7.73x10 ³)	1.706	1.255	3.1	1.80
P'sul.	248,000 (17.4x10 ³)	1.160	1.070	3.0	2.58
P'carb.	490,000 (34.5x10 ³)	0.474	0.471	10.8	23.0

Table IV. Thermal Conductivities of Dielectric Films as a Function of Helium Gas Pressure at 6 K

Material	k - Values in Watt/cm K			
	0(0)	25(1.76)	75(5.27)	100(7.4)
Pressure, psi(kg/cm ²)				
Polycarbonate, Makrofol KG (75 μ m)	9.0x10 ⁻⁵	2.1x10 ⁻⁴	2.5x10 ⁻⁴	2.0x10 ⁻⁴
Polyethylene, Valeron (100 μ m)	6.0x10 ⁻⁵	1.5x10 ⁻⁴	1.4x10 ⁻⁴	1.6x10 ⁻⁴
Polysulfone, Udel (100 μ m)	2.0x10 ⁻⁵	8.4x10 ⁻⁵	8.4x10 ⁻⁵	9.7x10 ⁻⁵

of commercially produced polyethylene and to the greater degree of isotropy in plastics than in papers.

In order to determine the feasibility of further increasing the "n" value of polyethylene by modifying the tensile modulus of this plastic, a short-term contract was placed with the Polymer Chemistry section of Battelle to perform a literature search and theoretical study of the possibility of producing high modulus, high strength polyethylene tapes. This literature search revealed that the theoretical modulus of highly crystalline polyethylene is 1.45×10^7 psi (1.02×10^6 kg/cm²), a value several orders of magnitude greater than the modulus normally found with standard, nonoriented, high density polyethylene (HDPE).

The conclusions reached in the BCL study are that the tensile moduli of both polyethylene and polypropylene can probably be increased by a factor of 10 or more by orienting these films to a much greater degree than is normally employed. The variables to be manipulated in this endeavor would be the draw ratio, degree

of crystallinity, molecular weight, and processing temperature. The first very high modulus polyethylene (VHMPE) samples fabricated for BNL by BCL, were found to possess tensile moduli of 1×10^6 psi (70.3×10^3 kg/cm²). Assuming that the compressive modulus, E_3 , remained constant during orientation this increase in the value of E_1 would lead to "n" values of approximately 500. In order to develop a tape that will possess mechanical properties which match those of kraft paper, embossing techniques are also under consideration. Reduction of the compressive modulus, E_3 , by a factor of two should lead to final "n" values of approximately 1000. Although a gross embossing pattern appears to give rise to unacceptably high partial discharge activity (see the section on short sample tests), very fine patterns may be a compromise solution. As an interim measure, while the high modulus materials are undergoing development, BNL is studying commercially available intermediate modulus, $3-5 \times 10^3$ psi ($21-35 \times 10^3$ kg/cm²) polypropylene films, comprising several one mil (0.025 mm) thick films laminated together to provide the proper tape thickness.

In terms of shielding materials Brookhaven has developed two novel types of screening tapes. The first, an aluminized polyethylene tape with 3/32" (2.4 mm) wide borders on either side, has already been demonstrated to be an effective aid for raising partial discharge inception levels. The second tape is a carbon-loaded, compressible, porous Teflon film. This material simultaneously acts as a screen and as a compressive bedding layer.

Radiographic Analysis

Nondestructive radiographic analysis of the insulation of both conventional and plastic lapped cables is now routinely used as part of the BNL cable development program. The microfocus x-ray system has been shown to have several important applications for use with both types of lapped cables.^[12] One major use of the system will be as a quality control device for monitoring the lapping precision in effect during fabrication of cables. Another application of the microfocus x-ray appears to be as a probe with which to locate wrinkles, soft spots, and various defects present in cables that have experienced severe thermomechanical bending in the field.

Figure 1 is a radiograph illustrating the butt-gap distribution in a 30 layer, lathe wound, cable model fabricated to test the sensitivity of the unit for locating registrations in newly lapped cables. Layer No. 16 was applied in registration with No. 15 and the resulting disturbance is clearly evident in the photograph. The radiograph shown in Fig. 2 shows the severe gap between insulation and conductor in a test cable caused by improper cable armoring. This gap in the region of high field stress is unacceptable and would drastically weaken the cable. Figure 3 illustrates the mechanical damage to polysulfone insulation of a test cable that had suffered electrical breakdown during impulse testing. In addition, the microfocus unit has already been used in the field to locate areas of local tape migration in the paper-oil cables that have experienced thermomechanical bending. Work is in progress to incorporate a closed circuit TV monitoring system to provide more efficient use of this device.

ELECTRICAL PERFORMANCE

The key parameters which determine the electrical performance of a gas-impregnated plastic cable are partial discharge inception, impulse strength and dissipation factor. Partial discharges lead to erosion of the dielectric with a subsequent decrease in cable life.

CONDUCTOR

Figure 1. Radiograph of lathe-wound 30 layer paper dielectric test cable with 1/3 - 2/3 overlay pattern. Layer No. 16 applied in registration with No. 15.

Also in the case of a superconducting cable partial discharges can lead to an excessive heat load for the refrigerator. The operating stress of the cable will be 10 MV/m (rms) at the center conductor with discharge inception specified to be greater than 20 MV/m (rms).

Impulse strengths greater than 100 MV/m are required to ensure that the cable under development will pass present-day system test requirements with adequate safety margin. For a gas-impregnated plastic cable, impulse breakdown occurs well above partial discharge inception.

It is usual to choose the dissipation factor $\tan \delta$, and the dielectric constant so that the dielectric component of the refrigerator load is no greater than other sources of heat, a criteria which leads to a maximum value of $\tan \delta$ or 2×10^{-5} for practical designs, see Table I.

SHORT SAMPLE TESTS

We have evolved test procedures for short samples which are representative of cable dielectric conditions.^{3,13} The measurements carried out are discharge inception voltage, discharge extinction voltage and impulse breakdown voltage. The minimum discharge magnitude detectable is ~ 0.05 pC. Inception is usually of the order of 0.2 to 0.5 pC at high, 250 psi (1.72 MPa), pressure and as high as 2 pC at low, 100 psi (0.69 MPa), pressure. Time at inception voltage, or below, usually has no effect.

Partial discharge inception measurements are made by raising the voltage until activity is observed on the output of a Biddle type 17000 detector. The voltage is then lowered until extinction occurs. This is repeated, at each pressure, with different rates of rise, and it is found that inception is very reproducible: to be expected if butt-gap breakdown is occurring. In the majority of cases extinction is 5% below inception.

Impulse tests are carried out at 7-9K and 205 psia (1.4 MPa) with a negative waveform of 1.5×50 μ s. These conditions correspond to the worst case hot-spot in a cable cooling loop.

Helium Conditions

According to Paschen's Law the breakdown voltage, V , of a gas-filled gap is given by:

$$V = f(\rho d)$$

where ρ is the gas density and d the gap depth.

The results given by the curve A in Fig. 4 show that inception is density dependent. This variation with density is consistent with that obtained by other workers.^[14,15] The plateau in the density region between 60 and 100 kg/m³ is similar to helium breakdown between smooth electrodes. The sample depicted in curve A, Fig. 4 was wound between plastic covered electrodes.

Table V gives a summary of the short sample results. The discharge inception at a helium density of 115 kg/m³ and impulse withstand at a density of 100 kg/m³ are listed. The first group of samples tested in Table V were constructed using intercalated, metalized polyethylene screens^[16,17] using the standard sample construction shown in Fig. 5. The partial discharge results are mixed and ranged from a low of 5.5 MV/m for the embossed polycarbonate to a high of 21.4 MV/m for the thin 1.5 mil (38 μ m) polypropylene. The seemingly anomalous results for the two layer ethyl-vinyl acetate sample is probably due to the small number of tapes used.

There is a clear correlation of discharge inception level with the kind of conductor screen used. Impulse strengths were good except for the embossed polycarbonate and provide an adequate margin for cable design.

Effect of Screens

In a conventional cable system it is usual to have some form of screen at both the conductor and the outside of the dielectric. The screen, usually in the form of carbon-black paper, was introduced by Rosch.^[18] Since a superconducting cable will have a conductor consisting of tapes laid up on a core, a screen improves the breakdown characteristics of the dielectric by smoothing out roughness due to conductor tape edges.

CONDUCTOR

Figure 2. Radiograph of defective section (arrow) in the Anaconda Cable showing gap between conductor and insulation.

CONDUCTOR

Figure 3. Radiograph of damage due to impulse breakdown of lapped polysulfone experimental test cable.

Also it has been found that helium has a lower breakdown strength when bare metal electrodes are present than with insulating electrodes.[14,15] This phenomenon is usually explained by the fact that helium breakdown is initiated by field emission of electrons from the electrodes, but emission from polymer surfaces appears inhibited. Thus a screen should ensure that in the region of high-voltage there are no metal-helium interfaces. Figure 4 provides a comparison of the results obtained from samples with different screen designs.

Tape Thickness and Butt-Gap Breakdown

Since gap breakdown voltage is purely a function of gas density and gap depth it would be expected that butt-gap depth would have a major effect on discharge inception stress. This has been found to be true; discharge inception stress increasing with decreasing tape thickness. Embossing tapes to improve their mechanical performance appears to be detrimental to dielectric performance as can be seen from Table V. It is apparent this work must be repeated using thinner tapes.

HIGH VOLTAGE CABLE TESTING

A test cable was fabricated at the Anaconda Wire and Cable Company. This cable is a first step in ex-

Figure 4. Partial discharge inception versus helium density.

- A - Sample without screens; lapped between plastic covered electrodes
- B - 4 mil (102 μ m) aluminized P.E. screen
- C - 3 mil (76 μ m) aluminum - 25.4 μ m Kapton laminate screen
- D - 2 mil (51 μ m) aluminized Kapton screen

tending the results from short sample tests to the design of a 138 kV cable. Figure 6 shows the construction of this cable.

With this commercially built cable we expected to accomplish the following:

- a) Familiarity with manufacturers production requirements and limitations.
- b) Winding performance of selected plastic tapes on commercial winding machines.
- c) Bending performance of these tapes on a cable.
- d) Test of accessory designs to anchor cable ends and feed voltage to cable.
- e) Correlation of short sample data with a "real" cable, i.e., measurements of partial discharge inception, impulse strength and loss angle.

Cable Insulation Design

Three different polymers were used for the dielectric on the test cable. Based on a compromise between mechanical strength, electric strength, dielectric loss and cost, polyethylene, polycarbonate and polysulfone are among the most promising for a superconducting cable and were used on the test cable.

The cable employs several new experimental polymeric tapes. Included in this group is an aluminized tape that served as a voltage screen for the cable. This tape has as its conducting member a 1 micron thick vapor deposited aluminum strip down its center. This strip is deposited along the center of the tape, leaving on either side a 3/32 inch wide nonconducting border. The purpose of these borders is to minimize the field intensity at the edge of the tape. Another new material used in the construction of the Anaconda Cable is an 0.025 inch (0.64 mm) thick porous-Teflon bedding material. The bedding material located beneath the polyethylene section of the test cable helps to absorb a portion of the compressive forces produced by the differential

Figure 5. Diagram of small sample construction.

Table V. Short Sample Results

Insulation	Tape Thickness	No. of Layers	Sample Const.	Discharge Inception (He Density 115 kg/m ³)	Impulse Withstand (He Density 100 kg/m ³)
Oriented Polypropylene (Mobil Bicolor)	1.5 mil (38 μ m)	11	Fig. 5	21.4 MV/m	> 167 MV/m
Biaxially Oriented XLPE (Cryovac D-330-SW)	2 mil (51 μ m)	7	Fig. 5	18.6 MV/m	> 141 MV/m
Biaxially Oriented XLPE (Cryovac D-330-DW)	3 mil (76 μ m)	5	Fig. 5	14.8 MV/m	> 177 MV/m
Ethyl-vinyl-acetate (Cryovac Dykes Silica)	4 mil (102 μ m)	4	Fig. 5	17.4 MV/m	> 135 MV/m
Ethyl-vinyl-acetate (Cryovac Dykes Silica)	8 mil (203 μ m)	2	Fig. 5	21.4 MV/m	> 129 MV/m
Biaxially Oriented XLPE Valeron 4096	4 mil (102 μ m)	4	No Screens, Insul'd Elect- rode	18.0 MV/m	> 206.5 MV/m
Biaxially Oriented XLPE Valeron 4096	4 mil (102 μ m)	4	51 μ m Aluminized Kapton Screens	15.0 MV/m	> 191.3 MV/m
Biaxially Oriented XLPE Valeron 4096	4 mil (102 μ m)	4	Aluminized Kapton Laminate	11 MV/m	> 153.2 MV/m
Embossed Polycarbonate	10.5 mil (268 μ m)	3	Fig. 5	5.5 MV/m	> 55 MV/m

contraction between the inner conductor and polyethylene insulation. The bedding layer was also extended under half the polysulfone section to assess its effect on this relatively brittle insulation.

Conductor Configuration

It is only necessary for the inner and outer conductors to carry the capacitive charging current during ac tests and the 1.5 x 50 μ s lighting wave surge current during impulse tests.

The cable core used was a solid segmental Pirelli core. Whilst the thermal contraction performance and surface roughness were less than ideal for the test cable, it was readily available. This serves as the inner conductor under the polycarbonate section of the insulation and part of the polysulfone section. Where Teflon bedding was used, an aluminum-mylar laminated tape served as the inner conductor. The metallized mylar tape with insulated margins provides the inner and outer dielectric screen for all insulation sections.

Tape Winding

Problems peculiar to cable winding with smooth plastic tapes were immediately apparent when work commenced at the Anaconda plant. The low coefficient of friction of polyethylene and Teflon caused the electronic tensioning systems on the Pirelli machines to slip and winding tensions less than two pounds could not be maintained. Switching to heads with a mechanical tensioning system proved satisfactory. Tensions as low as 0.7 lbs could be maintained with the mechanical system.

The plastic tape pads telescoped at the normal head rotational speed. Running the machine at half speed eliminated this problem. The polysulfone tapes had a high surface charge and easily collected dust and other air-borne debris. A commercial static eliminator proved an effective remedy.

Figure 6. Construction of Anaconda Cable.

Bending Performance

At the start of each cable section and after tension adjustments, overlays and butt spacing were deemed satisfactory, a 12 foot sample bend section was cut from the cable and bend-tested as shown in Fig. 7. Each sample section was then dissected to check for bending stresses on the tapes. All cable sections appeared to bend satisfactorily, except section B (polysulfone without bedding) which exhibited stretch marks on the insulation tapes which corresponded with the spiraled segment edges of the center conductor.

High Voltage Test Arrangement

Sections of the cable containing each type of insulation were tested in a cryogenic enclosure about 75 ft (22.5 m) long. The high-voltage was fed to the cable sample through a room-temperature to helium-temperature transition bushing and the far-end was terminated in the helium space, see Fig. 8 and 9. The photograph in Fig. 10 shows the high-voltage feedthrough termination for the test cable. The epoxy high-voltage feedthrough bushing serves a dual role in providing both high-voltage insulation and a temperature transition from room temperature to 6 Kelvin. High pressure helium is fed via the epoxy cable terminal down the center conductor of the test cable to the far-end terminations. Stress control of the ground shield (outer dielectric screen) of the cable is produced by a build-up of hand-applied insulation, which allows the shield electrode to end in a large radius on the epoxy terminal. Field control of the termination of the cable center conductor is implemented with an embedded aluminum shield in the epoxy terminal.

The test cable is a three electrode device; the armor is terminated before the stress cone and the shield electrode is brought out for loss measurements through a guard tube at the stress cone. The room-temperature end of the high voltage termination is completed with a ceramic bushing impregnated with SF₆ to reduce surface discharges. Figure 9 is a schematic of the cable dead-end termination in the helium space. The details of its construction are similar to the feed-end with the exception that the high pressure helium exits from the epoxy cable terminal.

ELECTRICAL TEST RESULTS

Table VI and VII list the test results obtained to date in comparison with the short sample data. The room temperature data gave a check of hardware and instrumentation before cooldown and a valuable cross check with work done at CERL, England^[16,17] and by other workers.^[19] This performance is also an effective means for evaluating cable screens, stress cones, termination design and general cable construction.

During the cold runs it was not possible to maintain the helium at a uniform density throughout the test cable. The minimum helium density in regions of electric stress occurred in the cold end of the high-voltage feedthrough bushing. During all tests this region was maintained at a minimum density of 60 kg/m³. A typical helium density variation in the electric field regions during a test was between 86 and 123 kg/m³.

Loss Measurements

Loss measurements were performed using a transformer ratio-arm bridge. Both the standard capacitor and bridge were calibrated by NBS and the working accuracy of the bridge was estimated to be better than 10 PPM.

In general the test cable loss measurements were greater than the small sample data provided from single

sheet measurements by NBS.^[20,21] The exception to this trend is the room temperature loss of polysulfone. The loss tangent values given for the cable were measured at a 10 MV/m center conductor stress. We did not observe the precipitous rise in $\tan \delta$ as measured in small coaxial samples by French workers.^[22] Further work needs to be done on the loss mechanism in a practical cable construction with special attention to screen design.

Discharge Inception

The discharge inception performance of the test cable is well below expected levels. Examination of the tested sections showed wrinkles in the insulation screens and deformation of insulation tapes from improper cable armoring. X-ray analysis revealed insulation tape registration and separation of the insulation from the center conductor, see Fig. 2. The system sensitivity for the partial discharge measurements was 0.8 pC with a typical cable capacitance of 16,000 pF.

Impulse Tests

Impulse tests were carried out using a 1.5 x 50 μ s wave. When scheduling permitted, impulse tests were done at room temperature as well as helium temperature. The impulse strength recorded is the highest level at which the cable survived 10 pulses. Most failures occurred on the first or second pulse on the next impulse level. The location of the impulse failures was usually an insulation wrinkle. The results of "cold run" on the polyethylene section are very poor in comparison with the small sample data, and as it is the first 22 meter cable sample tested it reflected our inexperience in stress cone design. The cable impulse withstand levels compared favorably with the ac breakdown strengths of coaxial samples tested by Bobo and Thoris.^[23]

DISCUSSION OF CABLE RESULTS

Although the Anaconda Cable has not yielded impressive results it has been an important step in our progress toward a workable 138 kV design. Worthwhile experience has been gained in taping plastics, taping machine performance, and accessory design. The difficulties of running a large cryogenic experiment and the importance of easy assembly of bushing and cable accessories have been made manifest. The value of pretesting

Figure 7. Bend Test on the Anaconda Cable.

Figure 8. High-voltage feedthrough termination for Anaconda cable test.

whenever possible, i.e., room-temperature runs, has been firmly established. In our experience to date if the dielectric does not perform well "warm" it will not improve when it is "cold".

A 100 mil (2.54 mm) wall cable makes mechanical bending problems trivial but makes stress cone design difficult. At a 10 MV/m center conductor stress the 100 mil cable has a stress of 8.2 MV/m at the outer conductor while a 300 (7.62 mm) mil cable (for next cable) has a stress of only 6.2 MV/m at the outer conductor.

DESIGN OF NEXT HIGH VOLTAGE TEST CABLE

A high-voltage test cable based on our present state-of-the-art in conductor and dielectric design is now being built by the General Cable Company. Figure 11 shows an isometric view of these BNL designs. The cable being manufactured differs slightly from that shown in that copper instead of superconducting tapes will be used. In all other respects the cable will very closely model the design of a complete cable.

This cable is similar to the one built by Anaconda as it also has three different dielectrics but it incorporates the following changes and improvements:

- 1) Cable core and conductor have thermal contraction in the radial direction that matches that of the dielectric.

- 2) Improved dielectric screen construction so that the depth of the butt spaces in the highest field regions is less than 1 mil (25.4 μ m).
- 3) Dielectric wall thickness of 300 mil (7.62 mm) designed so that where the double butt space depth occurs at lay direction reversals it shall be less than 2 mils (51 μ m).
- 4) The plastic insulation tapes shall be applied with individual tension derived from recent taping studies.
- 5) The cable will be sheathed such that the "go" and "return" helium streams shall be separated by a lead jacket on the cable.

CONCLUSION

The reasons for the basic design criteria for the dielectric insulation under development have been presented. No single material is able to meet these criteria at present, however, significant improvements in the mechanical properties of some polymeric film tapes have been made. There seems to be an excellent chance that cable lapped with solid film tape will be made in the near future that can be reeled and bent in a satisfactory manner. The results of small sample tests have demonstrated that screen design is a crucial design factor in achieving the highest-possible partial discharge inception stress. Although the same levels were not

Figure 9. Far-end cable termination for Anaconda cable test.

Table VI. Comparison of Anaconda Cable Results with Small Samples. Room Temperature with SF₆ at 200 Psia

	Loss Measurements		Discharge Inception		Impulse Withstand
	Small Sample*	22 Meter Cable	Small Sample	22 Meter Cable	22 Meter Cable
P'eth.	36.5×10^{-5}	59.5×10^{-5}	18.5 MV/m	8.7 MV/m	83.5 MV/m
P'carb.	117×10^{-5}	288×10^{-5}	19.1 MV/m	20 MV/m	78.2 MV/m
P'sul.	75×10^{-5}	66×10^{-5}	26.8 MV/m	12.2 MV/m	-

* Single sheet value, NBS (Ref. 20,21).

Table VII. Comparison of Anaconda Cable Results with Small Samples at Helium Temperature

	Loss Measurements		Discharge Inception		Impulse Withstand	
	Small Sample*	22 Meter Cable†	Small Sample	22 Meter Cable	Small Sample	22 Meter Cable
P ^{eth.}	0.8×10^{-5}	2.4×10^{-5}	16.5 MV/m	8.2 MV/m	150 MV/m	43 MV/m ^{††}
P ^{carb.}	8.5×10^{-5}	17.5×10^{-5}	15 MV/m	7.4 MV/m	95 MV/m	82.4 MV/m
P ^{su1.}	9.5×10^{-5}	11.5×10^{-5}	13.4 MV/m	9.6 MV/m	131 MV/m	78.7 MV/m

* Single sheet values, NBS, (Refs. 20,21)

† Corrected for stress cones

†† Stress cone failure

measured in an actual cable sample there were obvious defects in the insulation construction. Nevertheless, this cable was a useful step which greatly improved the design of much of the auxiliary equipment such as stress cones and feedthrough bushings. Despite the defects in the cable the impulse withstand voltage was satisfactory. The experience gained has been applied to the design of a new cable with a rated line-ground voltage of 60 kV. The high-voltage laboratory apparatus is now being re-built to accommodate this cable. The results of these tests are awaited with great interest.

ACKNOWLEDGEMENT

We gratefully acknowledge the cooperation of many people in the cable industry and at other research institutions. In particular, E.M. Allam and W.H. Cortelyou of Phelps Dodge Wire and Cable Company assisted with the study of taping problems. E. D. Eich of Power Technologies Inc. has consulted with us for several years. J. A. M. Gibbons of CERN has been of great assistance during his visits to BNL. The manufacture of the test cable at Anaconda was supervised by S.J. Englehardt. Finally the invaluable technical assistance in the laboratories of J. Bunicci, A. L. Minardi and J. Scrofani must be mentioned.

REFERENCES

- [1] E. B. Forsyth, et al. "Flexible Superconducting Power Cables," IEEE Trans., PAS 92, No.2, 494, 1973.
- [2] E. B. Forsyth, G. A. Mulligan, J. W. Beck and J. A. Williams, "The Technical and Economic Feasibility of Superconducting Power Transmission: A Case Study," IEEE Trans., PAS 94, 161, 1975.
- [3] E. B. Forsyth, R. B. Britton, J. Dean, J. E. Jensen and K. F. Minati, "A Supercritical Helium Facility for Measuring High-Voltage Breakdown," Advances in Cryogenic Engineering 19, Plenum Press, 1974.
- [4] P. Gazzana-Priaroggia, E. Occhini and N. Palmieri "A Brief Review of the Theory of Paper Lapping of a Single-Core High-Voltage Cable," Proc IEE, 108, Part C, 25, 1961.

Figure 10. Voltage terminal end of cable test cryostat with vacuum housing and high voltage bushing installed.

Figure 11. Composition of the latest BNL cable design now under construction.

- [5] E. W. Greenfield, "Taping of Paper Cable: Theory and Practice," Washington State Institute of Technology Bulletin 268, 1963.
- [6] E. B. Forsyth, A. C. Muller and S. J. Rigby, "Some Theoretical Considerations Affecting the Design of Lapped Plastic Insulation for Superconducting Power Transmission Cables," EPRI Pub. # EL-269, September, 1976.
- [7] E. P. G. Thornton and D. H. Booth, "The Design and Performance of the Gas-Filled Cable System," Proc. IEE, 106, Part A, 207, 1959.
- [8] J. A. M. Gibbons and A. W. Stannett, "Plastics in Transmission Cables," Presented at the International Electrical Insulation Conference, BEAMA, Brighton, U. K., May, 1974.
- [9] J. R. Juchniewicz, A. T. Balinski and W. Zak, "Susceptibility of Liquid Nitrogen Impregnated Electrical Insulation to Partial Discharges," Cryogenics, 15, 519, 1975.
- [10] A. C. Muller, "Mechanical Properties of Insulating Tapes at Cryogenic Temperatures," Revue Generale de l'Electricite 94, 568-72, 1975.
- [11] F. Jelinek and A. C. Muller, "The Study of the Dimensional Behavior of Various Thin-Film Polymers in the Temperature Range 4.2 to 300 K, Joint ICMC-CEC Meeting," Queens University, Kingston, Ontario, July 22-25, 1975.
- [12] A. C. Muller, "An X-Ray Method for Studying Butt Gap Distribution and Spliced Joints in Lapped Paper and Plastic Cables," Paper A 77 108-3, presented at the 1977 Winter Meeting of the IEEE Power Engineering Society, New York City, N.Y., January, 1977.
- [13] E. B. Forsyth, A. J. McNerney and A. C. Muller, "Dielectric Design Considerations for a Flexible Superconducting Power Transmission Cable," presented at the Cryogenic Engineering Conf., Kingston, Canada, July, 1975 (BNL 19839).
- [14] R. J. Meats, "Pressurized-Helium Breakdown at Very Low Temperatures," Proc. IEE 119, 760, 1972.
- [15] R. J. Meats, "Butt-Gap Discharges in Laminated Polyethylene Insulation Impregnated with Very Cold Helium Gas," Third International Conf. on Gas Discharge, IEE Conf. Publ. #118 pp. 419-425, 1974.
- [16] J. A. M. Gibbons and A. W. Stannett, "Present State of Development of a Gas-Pressurized Lapped Polythene Cable for E.H.V. Transmission," Proc. IEE, 120, No. 4, 433, April, 1973.
- [17] J. A. M. Gibbons, R. P. Howard and D. J. Skipper, "Gas Pressurized Lapped Polythene dielectric for Extra High-Voltage Power Cable Systems," Proc. IEE 112, 89, 1965.
- [18] S. J. Rosch, U. S. Patent 2 102 129, 1973.
- [19] A. A. Cookson, "Electrical Breakdown for Uniform Fields in Compressed Gases," Proc. IEE 117, 269, 1970.
- [20] W. E. Anderson and R. S. Davis, "Measurement of AC Insulation Losses at Cryogenic Temperatures" IEEE International Symposium on Electrical Insulation, June 14, 1976, Montreal, Canada.
- [21] F. I. Mopsik, "Dielectric Loss of Polymer Films at Cryogenic Temperatures," 1975 Conf. on Electrical Insulation and Dielectric Phenomena, Nov., 1975, NBS, Washington, D.C.
- [22] B. Fallou et J. P. Breteau, "Comportment Dielectrique sous Haute Tension des Structures Rubanees Impregnees de Fluides Cryogeniques," Revue Generale de l'Electricite 94, 748-57, 1975.
- [23] J. C. Bobo et J. Thoris, "Proprietes Dielectriques de Structures Isolantes Aux Basses Temperatures," Revue Generale de l'Electricite 94, 758-63, 1975.