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SEMIANNUAL REPORT FOR THE PERIOD
OCTOBER 1, 1979 TO MARCH 31, 1980 OF WORK ON:

- 1) SUPERCONDUCTING POWER TRANSMISSION SYSTEM DEVELOPMENT
- 2) CABLE INSULATION DEVELOPMENT

July 7, 1980

DIVISION OF ADVANCED TECHNOLOGY APPLICATIONS
ACCELERATOR DEPARTMENT

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.

UNDER CONTRACT NO. DE-AC02-76CH00016 WITH THE
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July 7, 1980

**POWER TRANSMISSION PROJECT
TECHNICAL NOTE NO. 106**

**DIVISION OF ADVANCED TECHNOLOGY APPLICATIONS
ACCELERATOR DEPARTMENT**

**BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973**

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1. General Objectives of the Program

1.1. Development of a Superconducting Power Transmission System

The objective of the program is to develop an underground superconducting power transmission system which is economical and technically attractive to the utility industry. The system would be capable of carrying very large blocks of electric power, thus enabling it to supplant overhead lines in urban and suburban areas and regions of natural beauty. The program consisted initially of work in the laboratory to develop suitable materials, cryostats, and cable concepts. The materials work covers the development and testing of suitable superconductors and dielectric insulation. The laboratory work has now been extended to an outside test facility which represents an intermediate step between the laboratory scale and a full-scale system. The facility will allow cables several hundred feet long to be tested under realistic conditions. In addition, the refrigerator has been designed for optimum service for utility applications.

The long-range design goals of the project are constantly refined by means of a deep involvement with electric utility company engineers during systems studies. These studies started with a design for a transmission corridor under construction by Long Island Lighting Company. The BNL design attempted to meet the same technical criteria as the system under construction and permitted an economic comparison. After the study several important changes were made in the project direction in order to reduce the cost of the overall system. Since then, other studies were carried out in cooperation with several utility companies in Pennsylvania. The original LILCO study was also updated as part of the continuous review of the work.

1.2. Development of Cable Insulation Using Polymeric Tapes

The development of a cable insulation using gas-impregnated lapped polymeric tapes commenced several years ago at BNL as a direct consequence of the program to design a flexible ac superconducting power transmission cable. During these years a better understanding was gained of the problems of lapping film plastic tapes and the associated properties and characteristics required of the tape material. In addition, a great deal of both room temperature and low temperature high-voltage testing was performed. It is now apparent that much of this work is applicable to design of superior high-voltage power transmission cables specifically designed for operation at room temperature. The lower dielectric constant and loss tangents of some polymers compared to kraft paper are important advantages and will permit the capacity of conventional underground or submarine cables to be raised. These cables will benefit from the reduced dielectric loss associated with polymeric tapes. One of the limitations of paper-oil cables designed for voltages above 345 kV is the heat generated within the electric insulation. Another advantage of polymers is the reduction in dielectric constant compared with paper-oil insulation. Impregnants other than helium are being investigated, especially hydrocarbon oils, as potential room-temperature components.

Staff members also monitor projects placed with commercial companies and other institutions by DOE. These projects are in the field of cable insulation and our activity provides DOE contract managers with an independent assessment of progress and problems.

1.3. Personnel

During this reporting period, Dr. V. Kovachev finished his visiting appointment and returned to Bulgaria. Professor K. Horii also finished his temporary appointment and returned to Japan. Dr. F. Schauer took up a visiting appointment; he joins the Laboratory after working on the superconducting cable project in Austria lead by Professor Klaudy. Dr. J. Bussiere left the Laboratory and returned to Canada. Mr. A. Ernst joined the permanent staff, he is an expert on paper taped cables and will work on the polymeric insulation program at BNL and also assist DOE HQ by monitoring other DOE contractors.

2. Cable Conductor Development

2.1. Commercial Production of Superconducting Tape

2.1.1. Intermagnetics General Corporation (IGC)

Production of superconducting tape for the 100 m test cable is continuing at IGC. An order was placed to prepare 48 ea., 600 ft. long strips of Nb_3Sn substrate.

Delivery was made on 19 tapes which ranged in length from 621 ft. to 736 ft. with most lengths about 700 ft. Quality control measurements made at IGC on samples from both ends of the tape show the thickness of the Nb_3Sn layers, dc critical currents and ac losses to be within the BNL specifications. Samples taken from one end of each length evaluated at BNL for Nb_3Sn layer thickness and ac losses confirm the IGC results.

An order was placed for laminating the Nb_3Sn tapes with 0.001" thick type 316 stainless steel on one side and 0.002" thick copper on the other and then slitting to size. These are the final operations required to complete the superconductor for the 100 m cables.

2.2. Contract Management

2.2.1. Intermagnetics General Corporation (IGC)

Experimental work during the period was addressed to Task VIII (lamination) and Task IX (hot dip tinning of stainless steel) as authorized under Amendment 10 of Contract 404101-S. In addition, the final report (IGC 1079-9) covering all of the earlier process development of the primary manufacturing processes for transmission line tape was completed and transmitted to BNL on December 13, 1979. Progress in the experimental phases is summarized under the following sections:

Lamination - A complete set of running gear for the laminator machine was designed, fabricated and installed in order to adapt the equipment for operation with 0.875 inch wide Nb_3Sn strip in place of the usual 0.750 inch wide superconductor. Performance was evaluated in a series of trial operations, which included a continuous cladding run approximately 800 feet long. The results demonstrated fully satisfactory operation in terms of both mechanical function and properties of the solder bonded laminates produced. This work is complete and the machine is ready for use on transmission line tape product. The deliverable item included in this task, i.e., 1200 feet of clad conductor, will be produced as soon as the required stainless steel is received from BNL.

Hot Dip Tinning of Stainless Steel - This work comprised an exploratory study of hot dip tinning as a method for making the stainless steel cladding foil solderable for lamination. The work was concerned with type 316 stainless steel strip (0.875 in. wide x 0.001 in. thick) provided by BNL. All experiments were performed by continuous mode processing using a 100% Sn melt.

Initial work investigated the effect of melt temperature on the tinning process with the following results.

700°C	Nonwetting
750°C	Marginal Wetting
8-900°C	Effective Wetting

Other experiments found that a tape speed of 2-4 ft./min. (corresponding to a residence time of about 15-30 sec.) produced good tin coats. Higher tape speed resulted in very heavy and rough coatings; slower speeds were not of interest.

On the basis of these results, a 1000 foot length of stainless steel was hot dipped with operating conditions set as follows:

Melt	:	7 lbs. Sn
Temperature	:	800°C
Tape Speed	:	4 ft./min.

An apparently good quality tin coat was observed on the full length of foil. Laminates were fabricated using 100 foot lengths from the "start" and "finish" ends of the stainless steel; these laminates included low loss superconductor and 0.002 in. thick copper in the standard PTP 21B configuration. The clad product was found to be of good physical quality. However, evaluation of peel strength in these laminates observed surprising and disappointing results. Although the peel strength for the stainless steel to superconductor bond in the "start" end sample was found to be unusually high, the bond in the "finish" end sample was observed to be unacceptably weak. The peel strength for the copper-superconductor bond was uniformly high in both samples. Subsequently, the 800 foot central length of stainless steel was laminated directly to copper foil; delamination of this material determined that the weak peel strength trait appeared relatively abruptly about 150 feet into the hot dip run and persisted throughout the balance of the length.

These laminates were submitted to BNL for more detailed evaluation. Microprobe analysis found extensive formation of Sn-Fe-Cr compounds at the stainless steel surface in the "finish" end/weak bond sample; only slight compound formation was observed in the "start" end/strong bond sample. In addition, a degraded ac loss characteristic accompanied the degraded peel strength; ac losses were found to be $3.3 \mu\text{W}/\text{cm}^2$ for the "start" sample and $39.4 \mu\text{W}/\text{cm}^2$ for the "finish" end laminate (measurements at 500 rms A/cm). Photomicrographs of the compounds on the stainless steel surfaces are shown in Fig. 2.1. The microprobe analysis results are shown in Table 2.1.

The microstructure observed in the Sn-Fe-Cr compound at the surface of the stainless steel suggested a dissolution-redeposition mechanism of formation, i.e., Fe and Cr dissolving in the melt during the initial operating period would lead to a saturation condition after which redeposition would occur on the surface of the stainless steel substrate. The compound formation condition

Table 2-1

Microprobe Analysis of Surface Compounds

DRIFT FACTOR 1.000

ITER 2

----	K	(Z)	(A)	(F)	(ZAF)	CONC	ATOMIC
FE-K	0.314	0.905	1.193	0.999	1.081	0.343	0.480
MN-K	0.000	0.921	1.232	0.999	1.136	0.000	0.000
NI-K	0.000	0.893	1.190	1.000	1.063	0.000	0.000
CR-K	0.043	0.903	1.305	0.966	1.140	0.050	0.076
SN-L	0.636	1.071	0.990	0.991	1.052	0.670	0.444

CONC TOTAL = 1.060

Etch: NH_4OH , H_2O , H_2O_2 Sample IGC 800/4

1000X

Start End

Etch: NH_4OH , H_2O , H_2O_2 Sample IGC 800/4

1000X

Finished End

Fig. 2-1. Surface Compound Deposits on Hot Tinned
Stainless Steel Strip

was considered to be causal with respect to both the poor bond (weak structure) and high losses (ferromagnetic property). Several subsequent experiments attempted to provide a preferential deposition sink in the form of a reduced temperature zone at the bottom of the melt. No significant improvement was obtained. In addition, instability in the wetting process was observed; initially good wetting would degrade on one or both sides of the stainless steel after 200-400 feet of processing.

Work on the high temperature hot dip process has been discontinued. Some exploratory work is presently in progress on solder tinning at 250-300°C with the use of flux. Apparently effective wetting has been observed on some initial samples. This work is in the nature of a backup investigation, however. Parallel work using electroplated stainless steel furnished by BNL has produced good quality clad conductor. The schedule work for the production of 100 m line conductor is planned using electroplated stainless steel.

Next Period - The principal work scheduled for the balance of this contract (terminating June 30, 1980) comprises:

Completion of the solder/flux tinning experiments.
Preparation and delivery of 1200 feet of finished product.

2.3. Other Cable Materials

2.3.1. Stainless Steel Coating

Results of solder bond strength tests reported in the previous semiannual report showed that electroplating could produce a coating on 0.001" thick type 316 stainless steel which would provide a bond strength acceptable for use in the superconducting tape composite. These tests were made on samples prepared by several commercial electroplaters. In all cases a gold strike was used to obtain good adhesion between the stainless steel and copper plate. Normally, nickel is used but the presence of nickel in the tape leads to unacceptable high ac losses.

Based on these results from the commercial laboratory-prepared samples orders were placed with two electroplaters to produce approximately 2-3000 ft. of strip. One of the vendors was unsuccessful in adapting the laboratory process to production equipment. The gold strike appeared to be adherent initially, but when the copper was applied, the entire plate separated from the stainless steel. The problem was attributed to the inability to get adequate current through the 0.0001" thick stainless steel.

Material was received from the second electroplater in two spools of approximately 1000 ft. and 2000 ft.

Sections of 100 ft. were taken from each spool and put through the laminator at Intermagnetics General Corp. An actual PTP tape configuration: 0.002" copper, Nb₃Sn, 0.001" stainless steel was fabricated. The tape was slit into 6 mm widths and evaluated. IGC reported they had no problems laminating the

material and that an acceptable product was obtained. Samples from the various tapes were evaluated at BNL for microstructure and bond strength. The microscopic examination showed the solder layers to be clean, free of voids and of thicknesses normal for IGC tapes. Bond strengths ranged between 0.25 to 0.40 lbs/6 mm width. These strengths were slightly lower than the 0.5 to 0.7 lbs/6 mm obtained from hand soldered samples but higher than the 0.2 lbs/6 mm strength obtained with commercial tinned type 302 stainless steel used in all BNL test cables. These results show that the electroplating would provide solderable stainless steel for the superconducting tapes.

2.4. Cable Conductor Design and Testing

2.4.1. Cable 103

Cable 103 was fabricated during the report period. This cable is the last 10 m sample to be tested for current-carrying ability before proceeding with the construction of 100 m cables. The major design features to be investigated with cable 103 are:

- (1) Conductor loss measurement with a full wall insulation between inner and outer conductor.
- (2) Operation of the cable with gas-cooled leads connected to a warm transformer.
- (3) Use of superconducting tape with the surface tin etched away.

The details of the cable construction are given in Table 2.2. A general layout of the radial dimension of the cable is shown in Fig. 2.2. During construction this was the first time a superconducting cable had been made on the Trafalgar machine. Two breaks in superconducting tape occurred which were repaired in situ.

Testing of cable 103 commenced after the end of this reporting period and a full account of the performance will be given in the next semiannual report. However, it may be said the cable performed very well; a current of twice-rated value, 8000 A, was carried and rated current (4000 A) was carried up to a temperature of 11 K. The losses appear to be somewhat less than cable 102 and results are still being analyzed.

The leads used in the test were identical to a pair tested separately, these results are given in section 4.3.4.

2.4.2. Cryogenic Stability of the 5th Avenue Cable

Calculations of the cryogenic stability of the 100 m, Fifth Avenue cable were carried out using the procedure described in PTP 88 (semiannual report for the period 1 Oct., 1978 to 31 Mar. 31, 1979) with a minor modification: a linear dependence of critical current on temperature was used in place of the quadratic dependence used earlier. The purpose of the calculations was to ascertain whether the high purity aluminum stabilizer used in the 10 m tests could be replaced with copper of RRR = 200. Two thicknesses of copper were used, 0.030 inch and 0.015 inch. Very little improvement was found using 0.30 copper instead of 0.015 copper, the total loss is decreased only 6% in the quenched state using the thicker copper.

Table 2.2
Construction of Cable 103

CURRENT TEST CABLE NO: 103-INNER											
CORE DIAMETER = 0.918". No Tension @ 29 lbs											
Layer No.	Material	Thick Mils	Width Mils	No. of Segment N	DIA. - MILS			PITCH		Gap Mils	Tension Lbs
					Final O.D. ins.	Die	Length Inches	Angle Q	Hand		
1	Alum	11.6	236	9	0.042	-	3.47	39.76°	RH	0.010	2-3
2	Alum	11.6	236	9	0.966	-	3.33	41.58°	LH	0.010	2-3
3	SC ss towards dielectric	4.3	236	9	0.075	-	3.23	43.19°	RH	0.010	1 3/4-2
4	SC ss towards dielectric	4.3	236	9	0.984	-	3.21	43.70°	LH	0.010	1 3/4-2
MEASURED						QUANTITIES					
Layer	DIA.	PITCH		LENGTHS							Average
Alum 1	0.945	3.49	3.47	3.47		3.48	3.47	3.47	3.47	3.47	3.47
Alum 2	0.986	3.43	3.44	3.42		3.41	3.40	3.39	3.40	3.40	3.41
SC 3	0.998	3.35	3.27	3.23		3.23	3.22	3.23	3.23	3.25	3.25
SC 4	1.006	3.21	3.24	3.23		3.23	3.21	3.21	3.23	3.33	3.22

Table 2.2 (Continued)

CURRENT TEST CABLE NO: 103-OUTER											
CORE MATERIAL (Hand tape avg. high pts = 1.585) used 1.583" avg. CORE DIAMETER CABLE LENGTH 36'-3"											
Layer No.	Material	Thick Mils	Width Mils	No. of Segment N	Dia.		Pitch			Gap Mils	Tension Lbs
					Final O.D. Ins.	Die	Length Inches	Angle °	Hand		
5	SC ss towards dielectric	4.3	236	14	1.593	-	4.75	46.3 ⁰	LH	0.009	1 3/4-2
6	SC ss towards dielectric	4.3	236	14	1.603	-	4.75	46.48 ⁰	RH	0.010	1 3/4-2
7	Alum	11.6	236	14	1.633	-	4.75	46.67 ⁰	LH	0.011	
8	Alum	11.6	236	14	1.663	-	4.75	47.2 ⁰	RH	0.013	
MEASURED QUANTITIES											
	DIA. AVG.	PITCH		LENGTHS						Average	
5	1.595	4.75	4.76	4.76		4.76	4.74	4.77	4.75	4.75	
6	1.605	4.78	4.75	4.74		4.73	4.73	4.76	4.73	4.75	
7	1.634	4.75	4.78	4.75		4.76	4.75	4.76	4.76	4.76	
8	1.666	4.71	4.67	4.67		4.57	4.67	4.65	4.66	4.66

Figure 2-2. Radial Build-up of Cable 103

With the 0.015 inch thick copper the maximum stable current density was found to be 697 A/cm with a stream temperature of 8 K and 673 A/cm with a stream temperature of 8.5 K. The largest single contribution to the temperature rise is in the helium boundary layer; it contributes 30% of the total radial temperature rise.

Since 673 A/cm corresponds to a cable current of 6460 A, which is more than 50% higher than the nominal cable current of 4 kA, the use of 0.015 inch copper is considered adequate.

3. Cable Insulation Development

3.1. Cable Bending

3.1.1. Introduction

In our previous semiannual report (April - October 1979) it was reported that the bend-test cable built with material # 4 suffered severe collapse damage subsequent to bending over the 50 inch diameter mandrel ($D/d = 31.7$). This material is a two ply polypropylene laminate without slip additive and it is our favored candidate for superconducting cable use. Subsequent calculations by Morgan,* using a computer program modified for synthetic lapped insulation, indicated a possible reason for this result (see Table 3-1).

Table 3-1							
<u>Calculated Radial Pressure Values, Psi</u>							
		<u>Bend Diameter, Inch</u>					
		<u>100</u>		<u>75</u>		<u>50</u>	
<u>R, Inch</u>	<u>PHIR</u>	<u>PMAx</u>	<u>PMIN</u>	<u>PMAx</u>	<u>PMIN</u>	<u>PMAx</u>	<u>PMIN</u>
0.540	24.0	30.3	4.1	30.0	5.8	29.4	9.1
0.572	15.3	28.7	4.1	28.4	5.5	27.9	8.6
0.603	14.3	27.3	3.7	27.0	5.1	26.5	7.8
0.634	14.2	26.0	3.4	25.7	4.6	25.3	7.1
0.665	13.9	24.8	3.1	24.6	4.2	24.2	6.5
0.697	13.1	23.7	2.9	23.5	3.9	23.2	6.0
0.728	11.0	22.7	2.7	22.5	3.6	22.3	5.5
0.759	5.8	21.8	2.5	21.6	3.4	21.4	5.2
0.791	0.0	20.9	2.4	20.8	3.2	20.6	4.9

Bending performance is a function of both bend radius and insulation radius, and cables should bend without damage as long as the radial pressure PHIR, developed by lapping, remains between two limits: PMIN and PMAx. The points to be noted in Table 3-1 are that PMAx changes very little with bend radius, a few percent at most. PMIN, on the other hand, increases steadily with decreasing bend radius. The value at $R = 0.759$ inch and bend diameter 100 inch is 2.5 psi, which changes to 5.0 psi with a 50 inch bend diameter, a 100% increase. PHIR at the 0.759 inch radius is 5.9 psi. This implies that the winding was on the verge of collapse wrinkling at the smallest bend radius, as was indeed observed experimentally. The calculations also imply, since PHIR is less than PMAx, a lack of butt-gap creases: on dissection of the test cable only minor creasing was observed.

*"Bending Behavior of Lapped Plastic EHV Cables," G. H. Morgan and A. C. Muller, Presented at the 1980 International Symposium on Electrical Insulation, Boston, Massachusetts, June 9-11, 1980.

Subsequent calculations using a modified method of calculating the compression modulus E_3 , gave results for PHIR about 50% higher than the above. The new method is described in detail below; unfortunately, the correlation between observed and predicted collapse wrinkling is now not so marked, although the trend towards higher PMIN at smaller bend radii remains.

In addition to this formalized method of treating bending related cable damage, an empirical relation between bending stability and taping angle is well known by the cable industry. According to available data, paper lapped cables can become "mechanically unstable" when the taping angle, α , is greater than 81° or 82° . Since the tensile moduli of plastic dielectric tapes are significantly lower than those associated with paper tapes, it may follow that plastic lapped cables become unstable to bending for values of α that are several degrees smaller than the critical values reported above.

Cable # 5 was built to test this assumption. In this cable the $1/8$ inch wide tapes used in the two outer sections of cable # 4 (layers 33-64 inclusive) were replaced by one inch wide tapes. This change was calculated to reduce α by approximately three degrees on these sections, from 78° to 75° . The bend results with cable # 5 were significantly improved. No collapse damage was present.

Cable # 6 was made with the identical material used in # 5, but with all tapes one inch wide; this reduces α in the two inner section as well and hence decreases the minimum lay angle to that of cable # 4. No collapse damage was observed, but the butt gap creasing was worse. A detailed comparison of the computed and observed bend test results of all six cables is given below.

3.1.2. Theory of Critical Pressure During Bending

The generally poor correlation of bend test results with computer program predictions reported for the previous semester indicated the need for a re-examination of the Pirelli theory* and the computer program based upon it. Two items were found to require modification. The first of these is the critical axial pressure for collapse of a simply-supported thin-walled circular cylinder. This quantity is used in calculating PMAX; typically PMAX is proportional to the critical axial pressure. The second item is the way in which the compressive modulus is computed from stack height vs pressure data.

The critical pressure P for collapse of a cylinder was derived by Gazzana-Priaroggia et al*. It was shown that, provided that l/r , the ratio of cylinder length to cylinder radius is not too small, the critical pressure is independent of l/r and given by

$$P_0 = s^2(4G^2E_1E_2/9)^{1/4}/r \quad (3.1)$$

where s is the cylinder thickness and G , E_1 and E_2 are the elastic moduli. This value of P is used in the computer program to compute PMAX, the radial pressure at which the axial pressure developed by bending is equal to P_0 , and hence the pressure at which butt-space creases can be expected. However, if l/r is less than about 0.1, the many-waved mode of wrinkling which results in P_0

* P. Gazzana-Priaraggia, E. Occhini, N. Palmieri, Fundamentals of the Theory of Paper Lapping of a Single-Core High Voltage Cable, Pirelli, Spa. publ. Milan 1961.

degenerates into a symmetrical collapse which requires a substantially higher pressure to initiate. For the symmetrical collapse, the critical pressure is

$$P = E_2 s^2 \lambda^2 / 12 r^2 + E_1 s / \lambda^2 \quad (3.2)$$

where $\lambda = \pi r / l$. In the case of butt-space creases, l is a length comparable to the butt gap, typically 1.2 mm, so for a radius of 15 mm, $1/r = 0.08$ and the latter formula applies. For typical BNL cable parameters the ratio P/P_0 is 1.625, so that P_{MAX} should be increased by this ratio for butt space creases. Use of P_0 for a new design is a conservative approach, but in analyzing experimental results, P is perhaps more realistic.

3.1.3. Measurement of Compression Modulus

The compressive modulus, E_3 , cannot be measured without ambiguity. The method used, described by Pirelli, requires measurement of a stack of typically 100 circular discs of 1.05 inch diameter cut from a sheet. The height of such a stack is a non-linear function of the applied pressure, and the zero pressure height, H_0 , is poorly defined. These measurements are performed for BNL by NBS, Gaithersburg, and to avoid the ambiguity in the linear modulus (Eq. 3-1) based on

$$E_3 = H_0 p / (H_0 - H) \quad (3.3)$$

the zero-pressure, height, NBS has been reporting the differential or tangent modulus, defined by Eq. (3.4)

$$dE_3 = H dp/dH \quad (3.4)$$

where p is the pressure H the stack height at p and dp/dH the slope of the p vs H curve at p , hence the term "tangent modulus". Most of the mathematical development of the Pirelli theory is formulated using the linear modulus, and the computer program follows this formulation. The computer program has been modified to accept a pressure-dependent non-linear modulus by iteration. The basic difficulty with the linear modulus - the poorly defined H_0 - has been dealt with by a modification of a method suggested by Pirelli. Their approach was to find a fitting function for the H vs p data which "does not take into account the initial thickness but practically coincides with the usual definition throughout the range in which the strain may be considered small." In essence, the strain (compression of the stack of discs) begins at a small initial pressure p_0 which is one of the three parameters of the fitting function. The function suggested by Pirelli for paper tapes is

$$H = a_1 + a_2 \log (p + p_0) \quad (3.5)$$

At $p = p_0$, $H = H_0 = a_1 + \log (p_0)$, and the (pressure-dependent) linear modulus is defined as in Eq. 3.3, but with the significant difference that H_0 is now in essence a result of the fitting function, rather than the actual zero-pressure stack height. The raw data for four of the materials measured by NBS was obtained from them and were fitted to this function by a non-linear least squares procedure. In contrast to the Pirelli results with paper, negative values for p_0 were found for the present plastic materials. After

some experimentation, an extension of the Pirelli fitting function was found which gave a positive p_0 for all materials for which data was available. The form is given⁰ in Eq. (3.6).

$$H = a_1 p + a_2 + a_3 \log (p + p_0) + a_4 / (p + p_0) \quad (3.6)$$

This is an integral of a truncated real Laurent series about the point p_0 as is the Pirelli function. No significance is attached to this empirical function - in fact, the signs of the coefficients vary from one material to another. Some attention is given to the use of the differential modulus in the Pirelli reference, but mainly to prove the existence of a "plateau" pressure in cables taped with non-linear materials.

Using this five-parameter fitting function for H, the NBS data for four materials were fitted. Three of the four materials were used in the four bend test cables reported in the previous semiannual report. The coefficients are given in Table 3-2. The fourth material was used in a fifth bend test cable not previously reported; the material is very similar to that used in bend test cable No. 4, a 2-ply polypropylene without slip additive. The data for the material in cable No. 4 were lost at NBS, and none of the material is available for retesting.

3.1.4. Comparison of Computed and Observed Bend Test Results

A comparison of the computed and observed bend test results is given in Table 3-2.

Cable No.	Material	a_1	a_2	a_3	a_4	p_0
1	PP-U-PPB	-3.9779E-5	0.25822	5.2750-E	0.37353	13.566
2	3PP-2U-C	-2.0821E-5	0.27690	3.5405E-3	0.21562	14.094
3	Polycarb.G	7.7449E-8	0.33582	-1.6781E-3	0.25268	3.2232
4	9-1955	-	-	-	-	-
5	0-3495	-3.82-9E-5	0.25377	6.5162E-3	0.38732	14.990

The quantity A given in Table 3.3 is the percentage P_{MAX} is greater than PHIR and B is the percentage P_{MIN} is less than PHIR, i.e., $A = 100 (P_{MAX} - PHIR) / PHIR$ and $B = 100 (PHIR - P_{MIN}) / PHIR$; (loc) A is the radial section in which A is a minimum (section 1 is nearest the center and 4 is the last). The angle θ is the largest taping angle for the whole cable (at the outermost tape if all^m tapes have the same width). Three lengths from each of the 6 cable types were bent over mandrels of three diameters, 2.54, 1.90 and 1.27 meters. Except for cable No. 1, which had a somewhat smaller diameter, the 3 values of D/d (bend diameter divided by cable diameter) are about the same for all the test cables.

The experimental observations on the test specimens are of four types:

- 1) creases at butt gaps
- 2) wrinkles not at butt gaps
- 3) collapse creases involving a number of contiguous tape layers
- 4) axial tape migration

Table 3-3

Comparison of Computed and Observed Bend Test Results

CALCULATED						OBSERVED				
Cable No.	A	loc A	B	loc B	θ_m	Bend Dia./ Cable Dia.	Butt Gap Creases	Non-BG Wrinkles	Collapse Creases	Butt Gap, mm or Migration
1	-54.3	1	82.6	4	77.99	70.8	no	no	no	yes
1	-55.3	1	75.8	4	77.99	53.1	slight	no	no	yes
1	-57.3	1	62.4	4	77.99	35.4	slight/3*	slight	no	yes
2	-14.5	1	80.4	4	79.23	63.3	no	no	no	slight
2	-15.7	1	73.3	4	79.23	47.5	small	no	no	yes
2	-27.5	1	59.1	4	79.23	31.6	many	no	no	yes
3	-12.8	2/3**	73.7	4	79.39	62.5	no	no	no	no
3	-13.7	2/3	63.9	4	79.39	46.9	no	no	no	no
3	-15.5	2/3	44.3	4	79.39	31.3	one/3	no	no	yes
4	28.3	2/3	79.0	4	79.27	63.3	no	no	no	no
4	27.2	2/3	63.4	4	79.27	47.5	no	no	no	yes
4	24.9	2/3	53.5 & 44.4	1/2-4	79.27	31.7	no	no	yes/3	yes
5	21.7	1	59.8	4	77.93	62.7	no	no	no	no
5	20.3	1	45.6	4	77.93	47.0	two/2*	no	no	0.5-2.0
5	17.6	1	52.8 & 17.1	1/2-4	77.93	31.4	four/3	faint/2	no	0-2.0
6	23.3	3	148.2	4	77.93	62.7	no	no	no	no
6	21.7	3	45.5	4	77.93	47.0	yes/2	no	no	0.8-3.0
6	18.3	2/3	17.0	4	77.93	31.4	yes/2	yes/1	no	0-4.7

* The notation "four/3", etc., means four creases were observed in section 3.

** 2/3 means at the junction of sections 2 and 3.

Items 1 and 2 should correlate with A, but non-butt gap wrinkling is lessened by the support that contiguous layers give one another. In fact, the tendency to non-butt gap wrinkling should increase as B decreases (PMIN increases) i.e., non-butt gap wrinkling can be regarded as a precursor to collapse creases in the Pirelli formulation. As discussed earlier, when correlating item (1) and A, A should be increased by perhaps 60%. Item (3) should correlate with B. In fact, the correlation in general is only fair in the case of item (1) and poor in the case of item (3). For example, cable 1 should have the most butt gap creasing, and cable 6 relatively little, yet cable 1 has relatively little and 6 a great deal. On the other hand, cable 4 should have the least and it has none. It is possible that with the thin tapes of cable 1, creasing occurs during bending, but "irons-out" when the cable is straightened for dissection. This is in contrast to paper, which retains creases. As for item (3), the prediction for collapse creases is greater for cable 5 than for 4, but the observation is the reverse.

There are two possible explanations for the poor correlations - either the Pirelli theory is inadequate or the input data are in error. The Pirelli theory does not address the axial migration of tapes mentioned earlier. Under repeated bending migration may cause butt gaps to close. In the two most recent bend tests, quantitative observations of the butt gap distribution were made and are given in the final column of Table 3-1.1. The two numbers in each entry are the minimum and maximum butt gap, in mm. The largest variations in butt gap were observed in cable 6 and this cable also had the greatest butt gap creasing. It is plausible that such migration is related to taping angle, yet cable 6 and cable 5 had the smallest taping angles and should be most resistant to migration. Industry sources attach considerable significance to control of the taping angle in paper-lapped cables; one source calls for taping angle variations of 1.5 degree or less. Another source calls for tape width increments of 3 to 5 mm, which is about equivalent.

The difficulty described above with the compression modulus is also a possible explanation for the poor correlations. We hope to resolve this question by radial pressure measurements similar to those made two years back using pull-tabs.

Dielectric tapes similar to those used in the above tests were obtained for construction of test cable # 104. This cable will have for insulation approximately 100 layers of polypropylene tape and the total insulation thickness will be 0.406 inches. To best satisfy both bending and dielectric requirements, tapes of three thicknesses were obtained: 80, 100, and 120 μ m. In order to restrict θ to values of 78° or less, tapes were slit into three widths: 7/8, 1 1/8 and 1 3/8 inches.

3.2. Materials Development

3.2.1. High Modulus Tape Development

The 1979 portion of the high modulus tape development program was completed and the results are summarized below. After initial runs were made in 1978 using a hydrostatic extrusion technique, modulus enhancement is now obtained by a rolling technique at Battelle Columbus Laboratory (BCL), using a "four high" rolling mill. The major advantages to the rolling method over the previous technique are that wider tapes can be fabricated and throughput rates of at least 30 meters/min are possible. Also, modulus enhancement by rolling has eliminated the tendency towards fibrillation that was normally present with other methods. Approximately seventy tapes were produced at BCL during 1979 using the rolling method. Tapes were evaluated for mechanical strength, oil compatibility, dielectric loss, and thermal conductivity.

The processing conditions are summarized in Table 3-4. Included are the variables of polymer type, molecular weight, processing temperature, thickness reduction ratio (TRR), and the resulting tensile modulus, E_1 , in the longitudinal direction. Also, Co^{60} gamma ray doses of 50×10^6 rads were given to duplicate samples to determine the effects of radiation cross-linking on oil compatibility and thermal conductivity. Cross-linking is known to reduce the solubility of amorphous regions of a polymer and could reduce dissolution. Total gamma ray doses are also listed in Table 3-4.

Compatibility evaluations are simple "soak" tests in which a tape specimen approximately 1 cm x 2 cm is immersed in the 100°C test oil under nitrogen gas pressure for a period of 5000 hr. Samples are removed from the oils periodically and the weight, thickness, length, and width are measured. Dimensional and weight changes following soak tests are given in Table 3-5 for the nineteen samples evaluated at the writing of this report. Also, loss tangent and thermal conductivities are included for two TRR values for most samples. For reference purposes the pertinent data are also included for a tape oriented by the hydrostatic extrusion method (see sample BNL # 1). The effects of varying the various processing conditions on oil compatibility, thermal conductivity and dielectric loss are summarized below.

3.2.1.1. Oil to Polymer Compatibility

a) Effect of Polymer Type

Polyethylene (PE) samples have less weight gain (oil absorption) than the polypropylene (PP) specimens. Weight changes of 2% or less, are present with those PE samples identified as BNL # 1, # 4, and # 7. Length change (shrinkage) appears to be independent of both polymer type and oil type and may be primarily a heat shrink effect. However, the length of sample BNL # 1 changed less than 1%. This PE sample was subjected to a draw ratio of 11.8 and processed at 130°C.

Table 3-4

PROCESSING CONDITIONS FOR HIGH MODULUS POLYOLEFIN TAPES PREPARED BY BATTELLE DURING 1979

BNL I.D.	BCL I.D.	Polymer Type*	Molecular Weight		Processing Temp, C°	Thickness Reduction Ratio	Crosslinking Dose, Megarads Co ⁶⁰	Tensile Modulus, E ₁ GPa
			Mn	Mw				
Polyethylene Samples								
BNL # 1	BCL # 1	PE # 4	9,000	150,000	130	11.8	None	16.8
BNL # 2	BCL # 28	PE # 1	14,000	72,000	20-30	5.9	None	--
BNL # 3	BCL # 28	PE # 1	14,000	72,000	20-30	5.9	50	--
BNL # 4	BCL # 63	PE # 1	14,000	72,000	75	8.3	None	--
BNL # 5	BCL # 30	PE # 2	13,000	78,000	20-30	6.8	None	2.2
BNL # 6	BCL # 30	PE # 2	13,000	78,000	20-30	6.8	50	--
BNL # 7	BCL # 58	PE # 2	13,000	78,000	75	8.3	None	3.7
BNL # 8	BCL # 32	PE # 3	16,000	70,000	20-30	6.1	None	2.0
BNL # 9	BCL # 32	PE # 3	16,000	70,000	20-30	6.1	50	--
BNL # 10	BCL # 69	PE # 3	16,000	70,000	75	8.3	None	3.4
Polypropylene Samples								
BNL # 11	BCL # 8	PP # 1	28,000	160,000	20-30	3.8	None	--
BNL # 12	BCL # 8	PP # 1	28,000	160,000	20-30	3.8	50	--
BNL # 13	BCL # 72	PP # 1	28,000	160,000	100	5.8	None	3.0
BNL # 14	BCL # 10	PE # 2	32,000	266,000	20-30	4.0	None	1.4
BNL # 15	BCL # 10	PE # 2	32,000	266,000	20-30	4.0	50	--
BNL # 16	BCL # 71	PP # 2	32,000	266,000	100	5.8	None	2.4
BNL # 17	BCL # 17	PP # 3	24,000	180,000	20-30	3.8	None	1.8
BNL # 18	BCL # 17	PP # 3	24,000	180,000	20-30	3.8	50	--
BNL # 19	BCL # 25	PE # 3	24,000	180,000	20-30	4.8	None	2.2

*Polymer Vendor and Stock No.

PP # 1: Phillips Marlex HSV-040-01

PP # 2: Rexene EP-54H5

PP # 3: Hercules PA-954

PE # 1: Chemplex 6060

PE # 2: Phillips Marlex EMN 6030

PE # 3: Union Carbide DMDJ 7006

PE # 4: Phillips Marlex 6009

Table 3-5
PHYSICAL PROPERTIES OF HIGH MODULUS POLYOLEFIN TAPES

Oil Compatibility at 100°C (5,000 hrs)										
BNL I.D.	Loss Tangent at 80°C and 100°C (at 100 Hz)		Thermal Conductivity at 80°C and 100°C (Watts/cm-K)		Length Change, %		Thickness Change, %		Weight Change, %	
					Amoco L-50	Sunoco XX	Amoco L-50	Sunoco XX	Amoco L-50	Sunoco XX
Polyethylene Samples										
BNL #1*	--	--	--	--	-0.4	+0.4	--	--	-1.2	+0.2
BNL #2	50	74	6.7x10 ⁻⁴	2.9x10 ⁻⁴	-22.8	-9.4	+11.4	+13.0	+2.2	+4.0
BNL #3	--	--	--	--	-12.4	-12.4	+15.0	+13.0	+2.6	+4.0
BNL #4	30	37	4.8x10 ⁻⁴	4.7x10 ⁻⁴	-9.2	-9.2	+9.8	+10.2	+0.5	+2.0
BNL #5	39	60	7.2x10 ⁻⁵	2.7x10 ⁻⁵	+13.2	-2.6	+3.0	+4.0	+1.2	+2.2
BNL #6	--	--	--	--	-2.4	-4.6	+0.5	+4.4	+1.0	+2.6
BNL #7	94	143	1.6x10 ⁻⁴	1.5x10 ⁻⁴	-1.4	-1.6	-1.0	+0.4	+0.6	+2.0
BNL #8	14	16	4.8x10 ⁻⁴	4.7x10 ⁻⁴	-5.2	-3.2	+13.2	+11.8	+6.0	+7.0
BNL #9	--	--	--	--	Cracked in both oils following irradiation				+1.3	+2.3
BNL #10	14	20	2.5x10 ⁻⁴	2.6x10 ⁻⁴	-0.8	-1.8	-1.6	+1.2		
Polypropylene Samples										
BNL #11	65	186	1.19x10 ⁻³	1.07x10 ⁻³	-11.6	-8.8	+12.3	+11.2	+7.6	+8.8
BNL #12	--	--	--	--	-9.2	-16.0	+12.0	+12.0	+8.0	+10.0
BNL #13	--	--	4.9x10 ⁻⁴	4x10 ⁻⁴	-8.0	-7.0	+10.8	+9.6	+5.6	+6.0
BNL #14	22	44	1.17x10 ⁻³	1.25x10 ⁻³	-4.0	-11.2	+24.0	+32.0	+25.2	+25.2
BNL #15	--	--	--	--	-9.4	-4.0	+12.0	+16.0	+9.6	+16.0
BNL #16	--	--	8.1x10 ⁻⁴	7.6x10 ⁻⁴	-12.8	-11.0	+29.6	+38.8	+20.0	+28.8
BNL #17	111	161	9.2x10 ⁻⁴	8.5x10 ⁻⁴	-7.0	-7.6	+10.4	+9.6	+7.2	+8.0
BNL #18	--	--	--	--	-9.8	-8.0	+12.0	+9.6	+5.2	+8.0
BNL #19	--	--	--	--	-9.2	-9.0	+14.2	+13.2	+6.4	+7.2

*Prepared by hydroextrusion process.

b) Effect of Oil Type

Weight changes are usually larger for those samples immersed in the Sunoco naphthenic oil than those duplicate samples tested in the Amoco polybutene oil. This effect was expected since the Sunoco product has an aromatic content of approximately 20%; the polybutene has no aromatic content. Aromatic species tend to react more strongly with polymers than do the more inert polybutenes.

c) Effect of Degree of Orientation (TRR)

In general, dimensional stability tended to improve as the draw ratio was increased. The mean weight increase dropped from 3.7% to 1.2% for the polyethylenes as the mean TRR was increased from 6.3 to 8.3%. The effect was similar but smaller for the polypropylene resins. Sample BNL # 1 which was subjected to a thickness reduction ratio of 11.8 was found to experience dimensional changes less than 1% following immersion. Part of the stability associated with this polymer, however, may be due to the higher processing temperature used.

d) Effect of Radiation Crosslinking

Although polypropylene undergoes some chain scission at a dose of 50 Mr, this dose was chosen since cross-linked gel is not present at smaller doses. Thickness and weight changes of one polypropylene, BCL # 10 (BNL # 15), were reduced appreciably following radiation cross-linking. BCL # 32 (BNL # 9) a polyethylene, became brittle and cracked in both oils following irradiation. More significant were the improvements in thermal conductivity following cross-linking (see below).

3.2.1.2. Thermal Conductivity

Thermal conductivities measured at BCL at 80 and 100°C appear in columns # 4 and # 5 of Table 3-5. Although the conductivity of a stacked disc geometry has not yet been related to the thermal conductivity of a lapped impregnated cable, the interim goal for the stacked disc measurement is $\lambda \geq 1 \times 10^{-3}$ W/cm-K. Inspection of the data reveals several trends as follows:

- 1) For approximately equal orientation, the PP conductivities are slightly higher than PE conductivities.
- 2) Orientation tends to reduce the conductivities of polypropylene polymers.
- 3) Orientation significantly increased the conductivity of PE # 2 and decreased the conductivity of PE # 3. The conductivity of PE # 1 remained almost constant with draw ratio.
- 4) Radiation cross-linking was found to cause a significant increase in the thermal conductivity of PP # 2 (see Table 3-6 below).

Table 3-6				
Thermal Conductivity vs. Gamma Ray Dose for Oriented Rexene Polypropylene (PP #2)				
Temp, °K	Dose, Megarads			
	0	50	75	100
273	1.25×10^{-3}	3.00×10^{-3}	3.25×10^{-3}	1.90×10^{-3}
300	1.35×10^{-3}	3.61×10^{-3}	4.11×10^{-3}	4.08×10^{-3}
330	1.39×10^{-3}	4.31×10^{-3}	4.82×10^{-3}	4.23×10^{-3}
360	1.54×10^{-3}	4.70×10^{-3}	5.17×10^{-3}	5.01×10^{-3}
373	1.71×10^{-3}	5.02×10^{-3}	5.13×10^{-3}	5.87×10^{-3}

This sample of PP # 2 was identified as BCL # 11 by Battelle. It has a TRR of 4.4. Oil compatibility tests will be performed on these three specimens to determine if compatibility was jeopardized by the radiation treatment.

3.2.1.3. Dielectric Loss

Loss tangent values measured at NBS are given in columns # 2 and # 3 of Table 3-5. $\tan \delta$ was taken at 80° and 100°C at a frequency of 100 Hz. The values given in the table are taken following a thermal cycling technique developed at NBS, whereby the resulting values are usually lower than those associated with untreated samples. A complete report of loss tangent versus temperature over the temperature range of 303 to 383 K for the three polyethylene resins is summarized in Table 3-7. Values are given for two thickness reduction ratios for each polymer. PE # 3 has the lowest values of loss tangent of the three materials. No correlation between TRR and loss tangent is evident.

3.3. Parametric Study of Polymeric Insulation for Pipe Type Cables

As an aid to determination of target values for power factor and thermal conductivity of candidate polymeric insulating tapes for room temperature application a parametric study was undertaken. Current ratings and losses were calculated for high pressure oil filled pipe-type cable circuits of voltage ratings 138 through 1100 kV. For comparison purposes ratings of a cellulose insulated system were also computed. Thermal conductivity was varied from 0.83×10^{-3} to 1.7×10^{-3} W/°C-cm for the polymeric insulation. A value of 1.7×10^{-3} W/°C-cm was taken for the cellulose insulation. Power factor was varied from 100×10^{-6} to 300×10^{-6} (0.01 to 0.03%) with a dielectric constant of 2.4 for polymeric system. For the cellulose system the power factor was assumed to 2300×10^{-6} (0.23%) with a dielectric constant of 3.8.

The results plotted in Figures 3-1 and 3-2 indicate that in relation to properties measured on candidate polymeric materials the critical parameter is thermal conductivity. At operating voltages of 345 kV and below much of the rating advantage of the lower dielectric loss polymeric material would be lost for conductivities below 10^{-3} W/°C-cm. In contrast the highest power factors measured on candidate materials would result in negligible effect on current

Table 3-7

Effect of Thermal Cycling on the Dielectric Loss (Tan δ) of Polyethylene Tapes

BCLPE # 27 (Ave. 2 Samples)
(PE-1, TRR=4.7, Roll Temp.=293/303K)

Tan $\delta \times 10^6$ at
100 Hz (1kHz)

T(K)	1st Htg. Cycle	2nd Htg. Cycle	3rd Htg. Cycle
303	54(40)	43(31)	33(22)
303	-	41(32)*	-
313	58(44)	46(34)	38(24)
323	65(50)	45(36)	40(26)
323	51(42)*	45(35)*	38(19)
333	51(43)	40(37)	38(23)
343	54(43)	41(36)	42(32)
353	54(41)	47(39)	53(42)
353	-	43(40)	30(39)
363	-	68(50)	60(42)
373	-	88(62)	74(46)
373	-	77(47)	-
383	-	-	88(45)

BCLPE #29 Ave(Ave. 2 Samples)
(PE-2, TRR=6.8, Roll Temp.=293/303K)

Tan $\delta \times 10^6$ at
100 Hz (1kHz)

1st Htg. Cycle	2nd Htg. Cycle	3rd Htg. Cycle
82(73)	54(30)	24(10)
-	62(31)*	-
85(76)	78(45)	31(15)
93(82)	88(60)	35(19)
98(84)*	88(63)*	35(10)*
107(90)	92(74)	33(16)
122(96)	99(81)	34(20)
128(91)	108(82)	39(22)
-	95(70)	41(23)*
-	106(70)	50(23)
-	112(70)	60(27)
-	80(45)*	-
-	-	67(35)

BCLPE #32 (Ave. 2 Samples)
(PE-3, TRR=6.1, Roll Temp.=293/303K)

Tan $\delta \times 10^6$ at
100 Hz (1kHz)

1st Htg. Cycle	2nd Htg. Cycle	3rd Htg. Cycle
16(11)	14(10)	12(10)
-	-	-
16(15)	16(12)	17(10)
17(17)	16(15)	16(13)
17(17)*	15(15)*	17(14)*
16(17)	12(16)	14(16)
15(15)	12(14)	12(17)
16(15)	13(13)	13(15)
-	14(13)*	13(15)*
-	15(15)	14(13)
-	16(13)	14(13)
-	-	-
-	-	17(12)

BCLPE #63 (Ave. 2 Samples)
(PE-1, TRR=8.3, Roll Temp.=348K)

Tan $\delta \times 10^6$ at
100 Hz (1kHz)

T(K)	1st Htg. Cycle	2nd Htg. Cycle	3rd Htg. Cycle
303	49(34)	40(29)	34(26)
313	58(43)	47(34)	39(28)
323	56(48)	48(39)	40(31)
323	51(44)*	46(39)	38(30)*
333	49(47)	43(42)	34(34)
343	52(46)	43(41)	29(32)
353	54(44)	45(39)	31(29)
353*	-	38(34)*	30(30)*
363	-	44(36)	34(28)
373	-	43(36)	37(30)
383	-	-	44(33)

BCLPE #58 (Ave. 2 Samples)
(PE-2, TRR=8.3, Roll Temp.=348K)

Tan $\delta \times 10^6$ at
100 Hz (1kHz)

1st Htg. Cycle	2nd Htg. Cycle	3rd Htg. Cycle
79(82)	42(24)	43(25)
85(82)	59(33)	59(35)
91(83)	78(44)	74(44)
97(93)	81(47)*	75(45)*
96(93)	90(62)	83(57)
98(103)	94(76)	88(68)
102(103)	96(82)	98(76)
-	91(77)*	94(72)*
-	107(84)	110(86)
-	148(97)	143(90)
-	-	165(93)

BCLPE #69 (Ave. 2 Samples)
(PE-3, TRR=8.3, Roll Temp.=348K)

Tan $\delta \times 10^6$ at
100 Hz (1kHz)

1st Htg. Cycle	2nd Htg. Cycle	3rd Htg. Cycle
13(9)	16(8)	14(9)
24(13)	19(11)	17(11)
27(17)	19(15)	18(14)
24(16)	20(15)*	18(14)*
23(20)	18(17)	16(17)
28(22)	19(18)	14(16)
29(22)	21(18)	16(15)
-	19(16)*	14(15)
-	22(16)	16(14)
-	24(17)	20(16)
-	-	31(23)

*Measurement made after samples were stored overnight at indicated temperature.

Figure 3-1.

Figure 3-2

rating due to dielectric loss up to 1100 kV. Since cellulose insulated cables have little or no load capability without forced-cooling above 550 kV there is no question as to the economic advantage of the polymeric system at these voltages, particularly as the cost of energy rises. A comparison study of the installed costs of a typical 345 kV pipe type cable circuit utilizing either cellulose or polymeric insulation was performed, see Table 3-8. On a dollars per MVA-mile basis the polymeric system is 20% less costly than the cellulosic system. It is planned to expand this study for the full range of voltages.

3.4. Life Tests on Short Cable Samples

3.4.1. Experimental Set-Up

In order to predict the life of superconducting cable insulation under expected working electric stress at 60 Hz, accelerated life tests were carried out with short cable samples at elevated frequencies and stresses.

Coaxial samples were lapped with 4 or 5 layers of 100 μ m thick tapes of polyurethane-bonded 2-plypropylene. An intercalated stress screen was lapped with aluminized polyethylene or polypropylene tapes on the outer surface of the insulation. The density of helium was controlled at approximately 110 kg/m³ (8-10 K, 15 atmospheres). Partial discharges and dissipation factor were measured at 60 Hz before and during the life tests. The high frequency test circuits used are shown in Fig. 3-3. At the highest test stresses, lower frequencies were used to avoid excessive heating. In Fig. 3-3a, a frequency between 7 and 8 kHz was resonated with the sample capacitance (about 2 nF) and a ferrite-core inductance (about 0.2H). As shown in Fig. 3-3b, the 330 Hz supply was implemented by resonating the sample capacitance and the self-inductance of a high voltage transformer. The charging current was compensated with 10 mhy inductor in parallel with the primary winding of the transformer. Samples were dissected after the life tests and tape surfaces were observed with electron and optical microscopes.

3.4.2. Experimental Results

The details of the construction of the insulation, test conditions, and test results are summarized in Table 3-9. Samples # 1, 4, 5, 6 were stressed with high frequency voltage and samples # 1, 4, 6 survived without breakdown. Samples # 1 and 2 were tested last year and are included for completeness.

3.4.3. Discussion

The life of cable insulation depends on the behavior of partial discharges in the butt gaps of the taped insulation. Partial discharge inception stress is a function of the product of helium density and butt gap depth. This hypothesis is supported by recent experiments on both short cable samples and gaps between insulation coated electrodes.* The inception stress for

* Semiannual Report 1 October 1979 - 31 March 1980, BNL 51150. (Figures 3.6 and 3.7).

Table 3-8

Installed Costs of 345 kV Underground Transmission Line
Single 5 - Mile Circuit - 3250 kcmil Aluminum Conductor

	Cellulose	Polymeric
(1) Insulation Type		
(2) Maximum AC Stress (kV/in.)	310	500
(3) Thickness (in.)	0.90	0.49
(4) Cable Diameter (in.)	4.10	3.26
(5) Pipe Inner Dia. (in.)	10.25	8.125
(6) MVA Rating	660	834
(7) Dielectric Loss (kW/mile)	54	2.4
(8) Peak Ohmic Loss (kW/mile)	194	293
(9) Cost of Losses (\$/ct. ft.)		
Loss factor = 0.5	80	86
Loss factor = 0.2	63	62
Material Costs (\$/ct. ft.)		
(10) Cable	51	77
(11) Oil	6	4
(12) Pipe	10	8
(13) Terminations	6	6
(14) Oil Pressurization	3	3
(15) Total Material Cost (\$/ct. ft.)	76	98
(16) Installation-Urban Area	300	300
(17) Total Installed Cost (\$/ct. ft.)		
- Loss factor = 0.5	456	484
- Loss factor = 0.2	439	460
(18) Unit Cost (\$/MVA/mile)		
- Loss factor = 0.5	3648	3064
- Loss factor = 0.2	3512	2912

NOTES:

- (1) Maximum rated temperature: Cellulose 85C, Polymer 90C. Thermal Conductivity (Cellulose or Polymer): $1.7 \times 10^{-3} \text{ W-}^\circ\text{C}^{-1} \text{ cm}^{-1}$, Power Factor: Cellulose 0.23% Polymer 0.01%, Dielectric Constant: Cellulose 3.8, Polymer 2.4.
- (2) Rating Based On: Daily Load Factor 75%, Earth Ambient Temperature: 25°C; Soil Thermal Resistivity: 75°C-cm/Watt; Burial Depth: 36 in.
- (9) Energy Cost: \$0.03 per kW-Hr; Carrying Charge Rate: 18%, Demand Charge: 800 per kW.

$$\text{Loss Factor Defined as } \sum_{n=1}^n \frac{I_n^2 t_n}{I_{pk}^2 24}$$

n = segments of 1 hr.

- (10) Cost of Materials (Jan. 1980): Aluminum \$0.66/lb.; Paper \$0.75/lb.; Oil \$2.50/gal; Polymer \$2.50/lb.

Figure 3-3. High Frequency Life Test Circuits

Table 3-9

SUMMARY OF TEST SAMPLES, TEST CONDITIONS AND TEST RESULTS

SAMPLE NO.	# 1	# 2	# 3	# 4	# 5	# 6
Date of Test	5/9-5/10, 9/8-9/15 (1978)	10/26 (1978)	10/23 (1979)	11/1-11/4 (1979)	11/19 (1979)	11/29-11/30 (1979)
Insulation Construction						
Inner screen	4 mil Al PE	4 mil Al PE	None	None	None	
Insulation	5x4 mil PP	5x4 mil PP	5x4 mil PP	5x4 mil PP	4x4 mil PP	"
Outer Screen	1.5 mil PE, 4 mil Al PE	1.5 mil PE, 4 mil Al PE	1.5 mil PE, 4 mil Al PE	1.5 mil PE, 4 mil Al PP	1.5 mil PE, 4 mil Al PP	
Insulation Thickness	29.5 mil (0.75mm)	28 mil (0.71mm)	25.5 mil (0.65mm)	25.5 mil (0.65mm)	21.5 mil (0.55mm)	"
Inception Stress of P.D.	5-10 MV/m (5 pC) 12-17 MV/m (10 pC)	13.6 MV/m (8-12pC)	14.5-15.7 MV/m (0.4-1pC)	8.4 MV/m (1pC) 12-18 MV/m (5-10pC)	4.2 MV/m (0.5-1pC) 16.5-17.0 MV/m (0.5-1pC)	10.2-13.3 MV/m (0.5-1.0pC)
Test Stress	10 MV/m	25.6 MV/m 28 MV/m	26 MV/m	17 MV/m	20 MV/m	20 MV/m
Test Frequency	7.8-7.9 kHz	60 Hz 60 Hz	60 Hz	6.6-7.3 kHz	8 kHz	330 Hz
Discharge Magnitude	5-10 pC	8.8pC 25.6pC	500-1000pC	10 pC	3 pC	3-5 pC
Life (Equivalent life at 60 Hz)	>5,785 min ($>7.64 \times 10^5$ min)	>80 min 50 min	33 min	>1,458 min ($>1.80 \times 10^5$ min)	1-2 min (130-260 min)	>1,623 min ($>8.93 \times 10^3$ min)
Breakdown	None	None B.D.	B.D.	None	B.D.	None
Deterioration of Tape	None	None except breakdown point	Many cracks on butt gap surface	Deposit of decomposed materials on gap surface	None except breakdown point	Many cracks on butt gap surface
Erosion of Al Layer	Eroded	-	Eroded	None	Eroded	None
Dissipation Factor at 10 MV/m	-	-	2.8×10^{-5}	2.1×10^{-5}	2.9×10^{-5}	2.5×10^{-5}

for a 4 mil butt gap discharge is calculated to be about 18 MV/m across the insulation of a cable sample at a helium density of 110 kg/m³.

In sample # 1, the small discharges observed at low stress (5-10 MV/m) may not be butt gap discharges but other disturbances such as contact noise between the aluminized screen tapes and the inner or outer conductors. It is assumed that butt gap discharges did not occur during the life test at a stress of 10 MV/m. Sample # 2 endured for 80 minutes at 25.8 MV/m. Then the stress was raised to 28 MV/m and breakdown occurred after 50 minutes. The discharge magnitude was 26 pC at 28 MV/m. No deterioration of the sample # 3 originated at a butt gap just above the inner conductor. A microscopic observation of the sample tapes showed many cracks along the butt gap surfaces as seen in Fig. 3-4. The cracks were not observed along the entire butt gap length. Typical damage sites were a few inches in length. The discharge magnitudes were 500-1000 pC at 26 MV/m. It appears that severe discharges occurred at some places in the butt gaps due to the dilution of helium density owing to heating caused by discharge activity. It is not clear in the test of sample # 4 whether butt gap discharges did occur during the life test. Small discharges were observed at a low stress of 8.4 MV/m and large discharges appeared at 12-18 MV/m. The dissipation factor increased a little between 18 and 20 MV/m. This observation corresponds to the 18 MV/m inception stress predicted for butt gap discharge. Deterioration was observed on the tape surfaces, but microscopic photographs showed that the deterioration was actually the deposit of chemically decomposed materials and there were no cracks as seen in Fig. 3-5. Therefore it can be assumed that the discharges were too small to damage the tapes.

The results of the test of sample # 5 indicate that butt gap discharges under high frequency stress are very harmful. At 20 MV/m with 60 Hz, the discharge magnitudes were about 3 pC, but breakdown occurred after a few minutes with the application of 20 MV/m at 8 kHz.

The pertinent energy relationship for a butt gap discharge can be summarized as follows:*

Butt gap depth - 0.1 mm
Area of discharge - $0.1 \times 0.1 \text{ mm}^2$
Discharge magnitude - 2 pC
Energy loss per discharge - 1×10^{-8} Joules
Temperature rise per discharge in a 10^{-3} mm^3 volume - 10^{-2} K

The above results assume all of the energy loss contributes to the temperature rise and neglects the heat loss through the insulation. With an applied frequency of 8 kHz, the discharge rate would be 16 kHz with a resulting temperature rise of 100 K a second. Although the theoretical rate is reduced by heat transfer to the surroundings, the temperature rise is very dangerous in high frequency tests at appreciable discharge levels.

* Semiannual Report 1 October 1979 - 31 March 1980, BNL 51150, p. 33

Figure 3-4. Microscopic Photographs of Deterioration on Tape Along Butt Gap for Sample #3

Magnification
x 55

Optical Microscope

x 500

Optical Microscope

x 1000

Electron Microscope

Figure 3-4. Microscopic Photographs of Deterioration on Tape
Along Butt Gap for Sample #3

← 1 mm →
Magnification $\times 55$

Magnification $\times 500$

Figure 3-5. Microscopic Photographs of Deterioration on Tape
Along Butt Gap for Sample #4

Sample # 6 showed the excellent resistivity of this insulation system to butt gap discharge damage at low frequency stresses. A very faint deterioration was detected with visual examination along a butt gap just above the inner conductor for a few inches. Examination with a microscope showed many cracks; see Fig. 3-6a. The thin cryovac (polyethylene) tape lapped over the polypropylene tapes were also deteriorated at a butt gap interface as shown in Fig. 3-6b. The pattern of damage was a little different from the cracks on the polypropylene tapes.

Figure 3-7 shows the relation between applied stress and equivalent life at 60 Hz. Usually life L is expressed as follows:

$$L = C G^{-n} \quad (3.7)$$

where

L = Life
 C = Constant
 n = Constant
 G = Electric Stress

Since the deterioration by partial discharges is accelerated approximately in proportion to the frequency of applied stress, equivalent life at 60 Hz is prolonged by the ratio of test frequency to 60 Hz.* The life of sample # 5 was too short because of local heating by high frequency discharges as described above. Because of the survival of samples # 4 and # 6 the life is longer than the solid line prediction represented by $L = C G^{-19}$.

For a liquid nitrogen impregnated model cable the n value is determined as shown in Table 3-10. A value of n equal to 19 is quite reasonable when based upon the results for polyethylene and polyethylene-terephthalate taped model cables by Weedy and Swingler.[†] From the curve of Fig. 3-7 it is confirmed that the life of this insulation system is longer than 30 years for an operating stress of 10 MV/m at an operating frequency of 60 Hz and a helium density of 110 kg/m³. The effect of area and length of the insulation has still to be determined.

3.5. Evaluation of Conductive Bedding

A conductive bedding layer between the metal conductors and the insulation screens will be required for the 5th Ave 138 kV superconducting cable. It is desirable that the effect of the bedding layers on the cable losses is negligible. The maximum contribution of the bedding to the dielectric loss sets a maximum value for ρ , the resistivity constant of the bedding material.

Using a series RC circuit model the cable losses can be expressed as:

$$\tan \delta = \omega RC \quad (3-8)$$

* PTP Technical Note # 84.

[†]B. M. Weedy, S. G. Swingler, Life Expectancy of Liquid-Nitrogen Taped Cable Insulation, IEEE Trans. Elec. Insulation, Vol. EI-14, No. 4 pp. 222-228 (1979).

Figure 3-6. Microscopic Photographs of Deterioration on Tape Along Butt Gap for Sample #6

Material (Trade name)	Life Expectancy (Years)	Material (Trade name)	Life Expectancy (Years)
Calendered polyethylene paper	11	Polyethylene terephthalate (Melinex)	14
Cable paper	16	"	16
Poly 2,6 diphenyl paraphenylene	18	"	17
Aromatic polyamide (Nomex)	17	"	17
Polyimide (Kapton)	11

Figure 3-7. Equivalent Life at 60 Hz Versus Operating Stress

Table 3-10

LIFE EXPONENT n FOR LAPPED TAPE SYSTEMS

Material (trade name)	No. of Layers	Thickness (μm)	Pressure (kPa)	n
Calendered polyethylene paper	9	126	600	22
Cable paper	6	90	100	72
Poly 2,6 diphenyl paraphenylene oxide (Tenax)	6	157	100	80
Aromatic polyamide (Nomex)	6	80	100	100
Polyimide (Kapton H)	6	50	400	11
Polyethylene terephthalate (Melinex)	12	23	400	14
" " "	6	75	400	16
" " "	6	125	400	18
Polyethylene	6	75	400	17
"	6	125	400	17

where R = equivalent resistor/unit length
 C = equivalent capacitance/unit length

The component R due to the bedding material can be found from the relation

$$R_1 = \frac{0.144\rho}{L} \left[\ln \frac{d_i}{d_o} + \ln \frac{D_o}{D_i} \right] \text{ ohms} \quad (3.9)$$

and

$$C = 0.614L\epsilon \frac{1}{\ln \frac{D_o}{D_i}} \times 10^{-12} \text{ Farads} \quad (3.10)$$

where

L = length in inches
 ρ = resistivity in ohm-inches
 ϵ = relative dielectric constant
 d_i = inner diameter of inner conductor bedding
 D_i = outer diameter of inner conductor bedding
 d_o = inner diameter of outer conductor bedding
 D_o = outer diameter of outer conductor bedding

The component of $\tan \delta$ due to the bedding layers is:

$$\tan \delta = 0.0884\omega\epsilon\rho \left[\frac{\ln \frac{D_i}{d_i} + \ln \frac{D_o}{d_o}}{\ln \frac{D_o}{D_i}} \right] \times 10^{-12} \quad (3.11)$$

for the 138 kV 5th Ave cable:

d_i = 1.265 inches
 D_i = 1.351
 d_o = 2.171
 D_o = 2.257
 ω = 377
 ϵ = 2.2

$$\tan \delta = 1 \times 10^{-6} \text{ (5\% of } 2 \times 10^{-5}\text{)}$$

solving Eq. 3.11 for ρ and substituting gives

$$\rho_{\max} = 61.8 \text{ K } \Omega \text{ inches}$$

This value for ρ gives a bedding loss which is 5% of the total expected dielectric loss (2×10^{-5}).

3.5.1. Measurements on Bedding Materials

Three carbon-loaded materials were evaluated and the measured values for ρ are tabulated in Table 3-11. Clearly the carbon paper is unacceptable.

where $R = \text{equivalent resistor/unit length}$
 $C = \text{equivalent capacitance/unit length}$

The component R due to the bedding material can be found from the relation

Table 3-11

Bedding Resistivity (ρ)

Material	5 mil (nominal) Carbon Paper	25 mil (nominal) carbon loaded Teflon # 102	25 mil (nominal) carbon loaded Teflon # 103
Room Temp.	1.22M Ω -in	1.29 K Ω -in	0.9 K Ω -in
Liquid Nitrogen	2.79 M Ω -in		
Liquid Helium	20.4 M Ω -in	10.9 K Ω -in	3.45K Ω -in

Table 3-12

Calculated Loss Due to Bedding Resistivity

Material	ρ at 4.2 K	Increase in short sample tan δ	Increase in 138 kv cable tan δ
Carbon paper	20.4M Ω -in	662 x 10 ⁻⁶	86.1 x 10 ⁻⁶
Carbon teflon 102	10.9K Ω -in	1.3 x 10 ⁻⁶	0.18 x 10 ⁻⁶
Carbon teflon 103	3.45K Ω -in	0.4 x 10 ⁻⁶	0.06 x 10 ⁻⁶

Measurements on Bedding Materials

Three carbon-loaded materials were evaluated and the measured values for ρ are tabulated in Table 3-11. Clearly the carbon paper is unacceptable.

Using the values of ρ measured at 4 K the predicted $\tan \delta$ values for a coaxial short sample and the 5th Ave 138 kV design were calculated. The results are listed in Table 3-12. The short sample calculations are based on 25 mils of insulation and two layers of bedding at the center conductor only. A short sample using carbon paper bedding was tested and the losses were measured to be 420×10^{-6} radians. The discrepancy with the calculated value may be due to heating of the carbon paper. The ρ value use for the calculation was measured at 4.2 K and there may be a substantial variation with temperature above 4.2 K.

3.6. Contract Monitoring

In support of DOE power transmission cable research the Power Transmission Project reviewed the work in progress at Simplex Wire & Cable Company to develop a conceptual design of a riser cable system and a 100 MW riser cable for an OTEC generating station. In particular, the review focused on design of an oil impregnated paper insulated cable of the self-contained oil filled type and the test requirements for prototype cables. This cable has the following principle design conditions:

Nominal System Voltage	138 kV
Switching Surge Withstand Level	550 kV
Depth to Bottom Cable Interconnection	4000-6000 ft
Distance to Shore	15 nm
Load Max	100 MVA
Ambient Temperatures	
Sea-Bottom	5°C
Sea-Surface	30°C
Air (Inside Ship)	40°C
Thermal Resistivity of Bottom Silt	200°C-cm/watt
Depth of Imbedment - on Bottom	8 ft
Wave Motion	
Frequency	0.076 to 0.24 Hz
Total No. of Cycles (10 Years)	10^8
Wave Height	2 ft to 36 ft*

* 36 ft is Hurricane Condition

Maximum Weight (Based on Installation in Sea Water)	22 lbs/ft
Maximum Diameter (Based on Installation Requirements)	6 in.

The cable is to be supported by its armor suspended from the floating OTEC plant either directly to the bottom or from the plant to an intermediate sub-surface buoy and then to the bottom. The cable is to have an arsenical alloy lead sheath and armor wires of a special stainless steel alloy (AL6X) chosen

for its resistance to crevice corrosion in sea water. Due to the motions of the plant in seas of varying amplitude the fatigue resistance of the sheath and the armor are critical design problems. The fatigue resistance of the armor decreases with increasing average tension. Therefore for heavier cable designs as the cable weight increases the static and the dynamic tensions both increase and the fatigue resistance decreases. Sheath fatigue considerations limit the allowable bending of the cable to a minimum radius of close to 300 ft subject to confirmation by testing of a prototype cable. The mechanical terminations must restrict the bending at the support point to within allowable limits.

A preliminary thermal analysis based on expected bottom conditions (i.e., cable assumed to be buried in 8 ft or silt) indicates that a minimum conductor size of 1250 kcmil copper is required. The paper tapes have been chosen for mechanical strength to allow the highest possible taping tensions. The result should be a "hard" insulation structure which will survive repeated bending in a vertical configuration. The electrical strength of the insulation is lower than for designs which have been electrically rather than mechanically optimized and a heavier than normal insulation thickness is required; compounding the weight problem.

4. Mechanical Engineering and Facilities

4.1. BNL Taping Line

The manufacture of cable 103 was completed, using the original Wardwell machine for the metal tapes. The dielectric tapes, however, were installed using the Trafalagar machine for the first time on a test cable.

The modified Pirelli machine was successfully operated applying metal tapes to sections of the Mark II cable core. Tape thicknesses of 0.030" and 0.015" were wound and tested for manufacturing techniques to be used on 5th Ave. cables.

Two more bend samples were manufactured on aluminum core, using both 7/8" and 1" wide tapes during the same run. Roller parts have subsequently been ordered which will enable the Trafalagar machine to apply 7/8", 1", 1 1/8", 1 1/4" and 1 3/8" wide tapes in devices, as well as all their custom mounting hardware, have been received during this period.

The extension to the winding room and Building 820 (new wing) is now under construction with completion of contract work scheduled for mid-July 1980. Parts received for machinery in the new wing include the 2nd Gatto core tension puller and the roll-up guard doors for the next Trafalagar sections.

4.2. Cable Tests

4.2.1. H.V. Dielectric Cable Tests

During this reporting period four cooldowns of the H.V. test cable have been attempted. None of these tests were successful since the proper operating temperature and pressure was not reached although some electrical data were taken on the last test. The results of these tests are summarized in the following sections.

4.2.1.1. Second Cooldown

The test setup and equipment was the same as for the first cooldown, reported in the previous semiannual report.* The previously mentioned leaks were repaired and the expansion engines overhauled. The test started on 11 December and by late afternoon on the 12th the vacuum in the west box deteriorated into the micron region and the cable was still above 80 K. On the 13th the vacuum was up to 100 μ and the cable was 20 K at the coldest point. The test was aborted since there was no possibility of cooling to a lower level.

An analysis of the cooling system showed the refrigerator was producing 250 watts of refrigeration at this temperature level but the west end was using up to 150 W of this capacity. Since the refrigerator capacity decreases with lower temperatures, there was no reason to continue.

* Semiannual Report for the Period April 1 - Sept. 30, 1979, BNL 51150.

4.2.1.2. Third Cooldown

The Westinghouse bushing had always been a source of trouble with vacuum leaks that disappeared at ambient temperature, and as a new Alto bushing had arrived (# A6) which checked out well in ambient temperature tests in SF₆, it was decided to install the new bushing. The installation was completed and the cooldown started on 14 January 1980. The vacuum of the west box was 3×10^{-5} torr at ambient temperature. By 2100 hours on the 15th the cable was near 11 K and all systems were running well. At 0730 on the 16th the low pressure side was subatmospheric because all the helium in storage had been transferred to the cold line. When new helium gas was added and the system was returning to normal operating pressures, both the high and low pressure sides experienced a rapid pressure rise sufficient to cause the safety relief valves to vent. The exact pressure the high pressure side reached is unknown since all of the 300 psi pressure gauges were off scale. At this time the vacuum in the west box failed, rising to $> 1000 \mu$. When the pressures had returned to normal the vacuum remained in the 100-200 μ region and the run was aborted.

As the system was warmed up the leak gradually disappeared and at ambient temperature all efforts to find it were negative. The various flanges and joints were re-torqued preparatory to another cooldown attempt.

4.2.1.3. Forth Cooldown

The cooldown started on 21 January 1980 with acceptable vacua which deteriorated to the 5 μ level in the west box on the 22nd with the maximum line temperature approximately 20 K. Varying the high pressure had an effect but as the line cooled further the pressure had to be continually reduced. On the 23rd the refrigerator cooling rate was 180 W with the losses in the west box approximately 120 W and it was not possible to cooldown below 10 K. Since the density was too low for electrical tests the run was discontinued.

When the Alto # 6 bushing was removed and checked with dye penetrant, a number of cracks showed in the epoxy flange. These cracks account for the vacuum failure but do not explain why it does not leak warm. Problems of this nature lead to the development of epoxy bushings with metal flanges, these are described in section 4.3.

4.3. Cable Terminations

4.3.1. H.V. Feedthrough Bushings

Tests were conducted on several Alto bushings and one Westinghouse bushing during this report period. The results are summarized in Table 4-1. The 150 kJ impulse generator was used for the first time at the 5th Ave Test Site. A prototype Alto bushing (A-3) was tested to failure to evaluate the epoxy casting design. This bushing failed at 680 kV ($1.2 \times 50 \mu$ s). The failure site is shown in Fig. 4-1. The breakdown originated at a rubber seal which had been improperly placed in the prototype bushing. As can be seen from Table 4-1 a later Alto design (A-7) withstood 808 kV with no apparent damage. This is more than adequate for the planned testing program for the 138 kV superconducting cable.

Table 4-1
Bushing Test Results

BUSHING	TEST RESULTS	COMMENTS
Alto # A6	SF ₆ P.D. Inception - 42 kV P.D. at 150 kV L-G - 15 pc Cooled down successfully.	No defects
Alto # A7	SF ₆ P.D. Inception - 28 kV P.D. at 150 kV L-G - 40 pc Impulse withstand - 808 kV 1.5 x 50 s	Epoxy Chipped on bolt circle on SF ₆ end - cooldown not attempted
Alto # A103	SF ₆ P.D. Inception - 66 kV P.D. at 150 kV L-G - 50 pc Cooled down successfully.	- No defects, first of new series of bushings with metal flanges
Westinghouse # W-2	SF ₆ P.D. Inception - 8 kV P.D. at 150 kV L-G - 60 pc	Crack on warm end taper - if installed in cryogenic set-up, SF ₆ would leak into vacuum space

Figure 4-1. Impulse Breakdown of Alto A-2

4.3.2. The Development of Laminar Feedthrough Bushings

The cast and Al_2O_3 - or SiO_2 -filled bulk epoxy bushings for the BNL superconducting cable project made by Westinghouse and Alto have suffered from several different problems such as cracking and low partial discharge inception voltage. The capability to withstand the impulse voltage of 820 kV is probably close to the limit for a bushing without capacitive screens. Thus the design of a laminar bushing has been put in hand in which voltage division is controlled by internal screens.

The electrical performance requirements of the bushing are as follows:

impulse voltage	:	825 kV
partial discharge inception	:	> 160 kV rms
ac test voltage for two hours	:	240 kV rms

Further, the bushing should be compatible with the previous constructed (cast) bushings and therefore fit in the mechanical components of the termination which are already design.

Conventional, capacitive controlled epoxy bushings are constructed by wrapping a special paper together with the control layers (consisting mainly of aluminum foils) around a shaft (which may also be the inner conductor). This assembly is then dried in vacuum and impregnated by a special high viscous hot ($\sim 300^\circ\text{F}$) epoxy also under vacuum. In cooling down and curing, this epoxy might shrink either in the soft or solid state (different information supplied by different companies) by up to about 2% by volume.

This special impregnation-epoxy does not match the thermal contraction of aluminum which forms the inner and outer conductor. Under working conditions the bushing is cooled to 6 K at one end with the other end remaining at room temperature. No open space between the inner or outer conductor and the epoxy-body of the bushing is allowed because of the possibility of large heat leaks due to He convection in these spaces. Therefore, the epoxy body of the bushing and the aluminum conductors have to be decoupled mechanically by providing a reasonable helium seal between the epoxy and the aluminum along all the length of the bushing to prevent or at least reduce dramatically the He convection. This seal has to be compressible or expandable even at low temperatures.

4.3.2.1. Design of the Bushing

The installation assembly is shown in Fig. 4-2. The bushing is built horizontally into the termination of the cryogenic cable. It connects the ambient temperature SF_6 -pressure vessel with the cold (about 6 K) helium-pressure vessel. The intention is to provide both the electrical insulation between the inner and outer conductors and thermal insulation in axial direction with a seal between the SF_6 and the helium-space. The capacitive control layers force the electrical field into a linear or almost linear distribution, both radially inside the bushing body as also along the surface creepage paths in the SF_6 and He.

Figure 4-2. General Assembly of Termination with Laminar Bushing

4.3.2.2. Heat Losses Due to the Helium in the Outer Compensation Layer

On cooldown the bushing moves relative to the aluminum as indicated in Fig. 4-3, and the space between the layers is increased by a small amount. The helium can flow in this space in circumferential direction around the bushing. The temperature gradient is mainly in axial direction. At the steady state after cooldown, the helium in the space between the layers conducts heat in two directions:

- (1) In radial direction (due to dielectric losses inside the epoxy and heat conduction from the warm end) from the bushing to the outer cooled conductor.
- (2) In axial direction from the warm to the cold end of the annular gap.

This heat transfer occurs either by simple conduction through the static helium or by convection. To decide which possibility is more likely, the following rough worst-case estimations are performed.

To estimate the heat conduction by convection in gases or liquids we require:

The Prandtl numbers

$$Pr = \frac{C_p \mu}{K}, \quad (4.1)$$

the Grashof number

$$Gr = \frac{\beta g \Delta T L^3}{\nu^2} \quad (4.2)$$

and the Rayleigh number

$$Ra = GR \cdot Pr \quad (4.3)$$

with

C_p = specific heat at constant pressure
 μ = absolute viscosity
 K = thermal conductivity

and

$$\beta = \rho \left[\frac{\partial (1/\rho)}{\partial T} \right]_{\rho}, \text{ volumetric expansion coefficient at constant pressure } (\rho = \text{density, } T = \text{Temperature})$$

also

$$g \approx 10 \frac{m}{s^2}, \text{ gravitational acceleration}$$

ΔT = temperature difference

L = reference length

ν = kinematic viscosity coefficient

The average heat flow either by conduction only or by conduction and convection can be related to an equivalent heat conductivity K_e . The ratio K_e/K indicates the contribution of convection to the heat flow. It is noted by different authors*, that the ratio of K_e/K is to a first approximation only a function of Ra , and almost independent of the geometry. This holds true especially for $Pr > 1$ and is shown graphically in the paper by Eckert et al. Since the Prandtl number in our case varies from 0.77 (at 10 K) to 0.67 (at 300 K), the graphical forms indicates the order of magnitude. Experiments with air (with similar Prandtl number $0.7 < Pr < 0.71$) convecting in spaces with different geometries show that the deviations from the graph are negligible for our purposes. The problem is to determine the Grashof and with that the Rayleigh number.

First the maximum possible temperature difference within one space between two convolutions of Kapton shall be estimated. Based on calculations on the present cast Al_2O_3 - or SiO_2 - filled bushings, the heat flux between the bushing and the outer conductor is about 10 W. Assuming the radial opening between the bushing and the outer conductor is 20 mils and this space is filled with cold gaseous helium with a thermal conductivity of 0.15 mW/cmK (at 10 K) taking into account the surface area of the bushing of about 576 square inches, then the maximum ΔT across the He layer is 1 K for a surface area of 576 in².

Since the maximum axial extension of one space between two convolutions of Kapton stages is about 1 inch (see Fig. 4-3), the temperature difference in axial direction, assuming a linear temperature distribution between the cold end and the warm end of the bushing, is about 300/24 or 12.5 K.

The expansion coefficient β decreases from 0.1 K^{-1} at 10 K to 0.003 K^{-1} at 300 K. The kinematic viscosity $\nu = \frac{\mu}{\rho}$ at the cold end is $\nu_{10 \text{ K}} = 3.7 \cdot 10^{-8} \text{ m}^2/\text{s}$, and at the warm end $\nu_{300 \text{ K}} = 6.3 \cdot 10^{-6} \text{ m}^2/\text{s}$. A consideration of the geometry shown in Fig. 4-2 leads to a reference length, L , of 320 μm . Thus we have:

$$\begin{aligned} Gr &= 3.6 \times 10^5 \\ Ra &= 2.8 \times 10^5 \end{aligned}$$

based on the graphical form given by Eckert et al we find:

$$K_e/K \approx 4$$

Thus is $K \approx 1 \times 10^{-3} \text{ W/cm-K}$ then $K_e \approx 4 \times 10^{-3} \text{ W/cm-K}$.

This leads to a computed heat loss by conduction in the He of $6 \times 10^{-2} \text{ W}$, a negligibly low value.

* Eckert, E. R. G., Drake, R. M., Analysis of Heat and Mass Transfer, McGraw Hill, 1972, pp. 522.

Raithby, G. D., Hollands, K. G. T., Laminar and Turbulent Free Convection, Adv. Heat Transfer, Vol. 11, 1975, pp. 266.

Ostrach, S., Laminar Flows with Body Forces, High Speed Aerodynamics and Jet Propulsion, Vol. IV, 1964, pp. 528

4.3.2.3. Summary

The design developed for an alternative bushing to those supplied by Westinghouse and Alto promises lower heat leak and better control of stress distribution. Two companies are qualified to make a trial bushing and negotiations for an experimental unit are under way. The companies are:

- 1) Lapp Insulator Company
Leroy, NY
- 2) Dielektra
Koln, W. Germany

Based on experience with similar bushings evaluated in Europe the likelihood of cracking on cool-down is very low.

4.3.3. High Current Voltage Bushing With Metal Flanges

Two high current high voltage bushings have now been cast and delivered by Alto Development Corp. These bushings have the 4 kA coaxial current leads cast in place. Dimensionally the high current bushing is the same as the voltage bushing with the cast epoxy flanges replaced by the metal flanges of the outer conductor. The new bushings can therefore be tested with the same equipment used for the voltage bushings. The electrical tests described in section 4.3.1. were performed prior to cool-down. Number 103 bushing was then installed in the low temperature voltage test apparatus and attached to a G.C. cable. The bushing was successfully cooled to about 9 Kelvin without cracking or gas leakage. At 9 Kelvin the bushing withstood 100 kV impulse. Corona inception began at a very low value because the helium density was only 40 kg/m³.

The low temperature voltage test will be repeated with the cable removed and a bail attached to the cold end of the bushing. The final test planned for this bushing is a low temperature current test.

4.3.4. Horizontal Current Leads

Two complete pairs of coaxial leads were assembled and a series of four tests made on the first pair. The second pair were used with cable 103, see section 2.4. These leads are nominally optimized for 4 kA and are intended to be operated in a horizontal position using supercritical helium with an inlet pressure of 12 atm. abs. During the initial testing, the inlet pressure was typically 1.2 atm, resulting in excessive pressure drop owing to the high volume flow rate. The inner lead is about 64 mm in diameter and is constructed by close-winding a custom-made 1100 alloy aluminum extrusion to form a long cylinder and then brazing the turns together. The extrusion is made in 15 m lengths and has three lengthwise internal channels in which helium gas can flow. The finished inner lead thus conducts helium spirally and current axially or laterally across the extrusion. The cross section area is 3.13 cm². The tested outer has the same 1100 aluminum extrusion wound wide spaced on a 6061 alloy tube of 89 mm o.d. and cross sectional area 12.6 cm². The 8 mm radial gap between the leads contains alumina-filled epoxy. The overall length is 0.91 of which 0.89 m is heat exchanger. To simplify the task of connecting the superconducting cable to the coaxial leads, the connection consists of bolted flanges, covered with superconductor on all current-carrying surfaces except the mating faces.

The connection is thus resistive. In the first trials, one mating face was machined copper and the other was gold-plated aluminum. The tests were carried out in a vertical cryostat containing boiling helium. In the first test difficulties were experienced in filling with helium in part because pressurizing the cryostat sufficiently to obtain a high gas flow thru the leads prevented a high helium transfer rate, and in part because of improper venting of the cryostat. Current was applied only briefly at 3 kA because of rapid helium boil-off. Pressurization of the cryostat during lead testing was improved for the second test permitting higher lead flow rates with reduced heat leak down the lead. This test indicated a very high heat input with the leads powered, and it was suspected that the cold-end electrical short circuit of the coaxial assembly was the cause of this. The third test included voltage taps across the various parts of the short, which consisted of the two bolted joints mentioned above, a soldered superconducting link and a massive short copper connection. The instrumentation for the third test showed that the bolted joints were indeed the problem, with a dissipation in the outer joint alone of 23 watts at 3990 A. For the fourth test, the joints were fitted with thin indium gaskets and a massive copper rod present during the three earlier tests was removed. The two-inch diameter 60lb rod was intended as a thermal link to the boiling helium below, but since no such "heat sink" is present for operation with a cable, it was removed. The improved joints reduced the dissipation of the entire short to 0.55 watt at 4 kA, 1.03 W at 5 kA and 2.8 W at 6 kA; at the latter current the lead temperature was rising slowly because of inadequate helium flow, limited by pressure drop. The apparent joint resistance was 34, 41, and 77 n Ω at 4, 5 and 6 kA respectively.

In these tests the temperatures were monitored with Chromel-Au (0.07 atomic % Fe) thermocouples along the colder, bottom part of the current lead and type E thermocouples along the upper portion. The thermocouples were spaced about 140 mm apart and in thermal contact with the outer conductor only of the coaxial current lead. Type E thermocouples were also used to monitor the temperatures at the center and the outer flange at the top of the lead, and additionally, to monitor the temperature of the helium gas at the flow meters. The temperatures obtained using the Chromel-Au (0.07 % Fe) thermocouples are estimated to have an accuracy of about ± 5 kelvin while the type E thermocouples give results accurate to about ± 3 kelvin. Liquid nitrogen was used as the reference bath for the type E thermocouples and liquid helium for the Chromel-Au (0.07 % Fe) thermocouples.

The temperature profile obtained experimentally did not match exactly the profile predicted by the computer program. Various hypothesis were proposed to account for this disagreement:

- 1) The computer model treats the inner and outer conductor of the coaxial lead independently and assumes no thermal interaction between the two, but they are in thermal contact through 8 mm of filled epoxy.
- 2) The program assumes the power dissipation in the superconducting region of the lead to be zero while the actual loss in this region could be as much as 1/8 that of non-superconducting regions due to gaps between the superconducting strips.

- 3) The superconducting transition temperature was assumed to be 16.5 K while it might actually be lower (~ 14 K) owing to compression by differential contraction.
- 4) The program assumes the lead to be in a vacuum as it will be in actual use while in these tests it was in low density helium gas.
- 5) The model fails to incorporate some important material properties of the actual lead, and some of the materials properties are poorly known.
- 6) The experimental data have large systematic errors.

In order to examine this problem in more detail the program was modified to allow it to automatically vary the assumed value of conductor area and the conductor resistivity ratio to achieve the best agreement with the experimental results. Originally, values of 17.5 cm^2 for the area and 3.43 for the resistivities ratio had been thought to be the expected values for the aluminum outer conductor as determined from ac resistance measurements at room temperature. The computer program, however, found a resistivity ratio of about 9.5 was required to give the best fit to the data. Area values did not differ significantly from the assumed value of 17.5. The results indicate that the lead has a much higher thermal conductivity at low temperatures than had been expected. The reason for this discrepancy may be due to inaccurate thermal conductivity values and is being investigated. At the design rating of 4000 amperes the helium mass flows were 0.27 g/s and 0.32 g/sec through the inner and outer conductors respectively. The limited helium reservoir capacity prevented prolonged testing to optimize these flow rates, which should be compared with computer predictions of about 0.18 g/sec for an optimized lead. The voltage drops in the inner and outer leads at 4 kA were 66.6 mV and 36.8 mV, respectively, compared to 64.5 mV predicted by the computer program. This indicates the outer lead area is excessive, as do the temperature profile fit and the effective area deduced from room temperature resistance measurements. A measurement in Nov. 1979 gave an RRR of 3.427 ($\rho(273)/\rho(4.2)$) for 6061 T6. For this material the lead program gives an optimum area of about 11.5 cm^2 . This is not much smaller than the nominal area of 12.6 cm^2 . It is not clear why the effective area is so much greater than nominal. Part of this area increase arises from the 1100 alloy heat exchanger brazed to the 6061 tube. Based on the known geometry and resistivity ratios for the 6061 T6 tube and 1100 extrusion, an effective area and resistivity ratio can be computed. The result for the area is 14.7 cm^2 , a 17% increase. This is a significant increase, but still 19% short of the effective area of 17.5 cm^2 from the ac resistance. The computed RRR is 3.985, much lower than the apparent resistivity ratio of 9.5 from the temperature profile.

The second pair of the two coaxial leads constructed is identical to the first except that the extrusion on the outer is 3003 alloy which has a higher resistivity than 1100. This should verify the result above that the extrusion is not responsible for the observed large effective area of the outer conductor.

Because the inner conductor cannot be instrumented except at top and bottom temperature profiles for it were not obtained. As mentioned above, the nominal cross section area is 3.13 cm^2 , but the effective area from room temperature resistance measurements is 4.67 cm^2 ; 49% greater. This result is in disagreement with the observed voltage drop during the cold tests given above: 66.6 mV vs a computer prediction of 64.5 mV, which would indicate the inner lead area is substantially correct.

4.4. Cable Cores

4.4.1. Metallic Cable Core Mark II

The Pirelli Cable Co. has now delivered the first 1200 feet of the new core. This flexible cable core is the structural base upon which the inner conductor segments will be wound and will be used to fabricate the two 100 meter cables.

The Mark II core is a modification of the first metallic cable core fabricated by the General Cable Corp., to BNL specifications. The major differences between the first core and the Mark II core are as follows:

1. The outer diameter was increased from 0.910 inches to 1.10 inches for use with the 138 kV design, a summary of the dimensions is given in Table 4-2.
2. The specified thermal contraction of the core diameter during cooldown from 273 to 4 K was reduced from 1.0% to 0.65% assuming the length is held constant. To accomplish this, the helix angle of the core segments was changed from 30° to 45°.
3. The specified axial spring constant of the core was increased from 77 pounds 1% elongation to 100 pounds 1% elongation. To accomplish this, the segment thickness was changed from 0.040" to 0.60".
4. The copper alloy of the core was changed from a silicon bronze (alloy # 651) to red brass (alloy # 230) in order to increase the thermal conductivity of the core by a factor of approximately 3.

A second shipment of 1200 feet of core is expected in the Spring of 1980.

No low temperature measurements have yet been made on this core. At ambient temperature, the mechanical properties of a 45.5 inch long test section were measured using the Instron testing machine. Discrete loads of 20, 40, 60, 80, 100 and 120 pounds were applied and changes in length and diameter were measured at each tensile load level. Axial spring constants and the ratio of $\Delta D/D = \Delta L/L$ were calculated from the measurements.

The measured $\Delta D/D = \Delta L/L$ ranged from a low of 0.970 to 1.143 and averaged 1.10.

Table 4-2		
<u>Summary of Core Dimensions</u>		
	Inner Layer	Outer Layer
Direction of Lay	Right Hand	Left Hand
Number of segments	5	
Segment width - inches	0.433	0.453
Segment thickness - inches	0.060	0.060
Lay length - inches	3.444	3.267
Lay angle - degrees	40.0°	45.0°
Gap spacing - inches	0.010	0.010

The theoretical value of this ratio can be calculated from the helix angle of the core segments $\Delta D/D \cdot \Delta L/L = \frac{1}{(\tan \theta)^2}$. This ratio is 1.0 for a 45° angle.

The measured axial spring constant varied more than expected over this load range. It increased from a low of 15.2 pounds/1% elongation at 20 pound load to 222 pound 1% elongation at 100 pound load.

Further measurements, at low temperature and at ambient, will be made on this core before constructing the 100 m cables.

4.5. 1000 MVA Test Facility

At the end of the last reporting period the cryogenic system had been extended to include the 100 m cable enclosure. The performance of the system had not been evaluated at that time. A major effort in this report period was to determine the performance of the system, a goal that was frustrated by equipment failures. The failures were rectified after the end of the reporting period and thus the performance of the system, which has now been measured, will be given in the next semiannual report. It is not expected that the delay of about five months will significantly affect the date of the electrical tests.

4.5.1. Summary of Cryogenic Operation and Problems

A test of the cable enclosure started on October 29, 1979. Equipment involved in the test included the helium refrigerator, helium gas management system, helium transfer lines and the cable enclosure. System startup was smooth and uneventful except for some periodic noises from the # 1 turbine. This noise had concerned us previously, and had been discussed with Helix and Sulzer. They assured us that this noise did not come from the turbine or the turbine bearing, and we should continue operations. At about mid-afternoon on October 29, the # 1 turbine speed dropped to about 500 rps. The refrigerator system was shut down, and turbine # 1 process valves were configured to warm-up the turbine system. On October 30, 1979, turbine # 1 was removed. During removal it was noticed that the threaded ring, used to hold the impeller cover and nozzle ring in place, was loose. In addition, there was clear evidence of rubbing between the turbine blades and impeller cover. Examination of the turbine brake filter housing showed a black colored film. At the time, this film gave us concern because it appeared like an oil deposit. Samples taken from the filter were given to BNL Chemistry Department for analysis. Since they were unable to analyze for the presence of oil or glycol, the analysis was confined to solid material which turned out to be numerous metallic element mostly associated with dip brazing. After cleaning all components, the spare # 1 turbine was installed. On November 1, 1979, the system was re-started. The start-up went well with no apparent turbine problems.

Operations continued on November 2, 1979. After operating a few hours, a noise developed in the turbine coldbox. Turbine # 3 was shut down, and the noise continued. Following additional tests, it was determined that the noise was coming from turbine # 2, and the system was shut down. It was decided to warm-up the # 2 turbine piping and install the # 2 turbine spare. Helium gas was

circulated through the turbine circuit for warm-up and on the morning of November 3, 1979, turbine # 2 was removed. The turbine nozzles and impeller cover were cleaned and the turbine polymer insulator was found to be cracked; it was replaced. The turbine compressor filter assembly was very dirty, all components were cleaned and samples taken for analysis.

On November 3, 1979, turbine # 2 circuit was pumped and purged in accordance with recommended procedures. The valves were configured as required and the screw compressor was started. When the helium process reached operation conditions turbine # 1, # 2 and # 3 were started. At 10:00 hours, a noise developed in the turbine coldbox which seemed to come from either turbine # 1 or # 2. All turbines speeds were reduced to 250 rps which caused the noise to disappear. The system appeared to be operating normally and cooldown continued until the system was secured as scheduled at midnight.

On November 4, 1979, the system was re-started without problems. Temperatures for turbine # 1 and # 2 were near design values. Return temperature to the load was about 70°K. At 1300 hours, turbine # 1 made a loud noise and the speed indicator oscillated around 500 rps and then turbine # 1 stopped. A re-start was attempted without success and the decision was made to secure the refrigerator until the failure mode had been analyzed.

4.5.2. Failure Analysis

Since Sulzer prohibits all users from examining the turbine bearing cartridges, the turbines were packaged and returned to Helix Technology Inc., Westborough, Massachusetts, who are the United States representative of the Sulzer, they handled shipping and repair arrangements with Sulzer. Our first report from Sulzer, through Helix Technology, regarding the turbines repair came about 10 days after shipment. Sulzer first indicated that the # 1 turbine bearing cartridge was loaded with oil. A cursory inspection of the turbine cartridges and mating surfaces with black light at Brookhaven had not revealed the presence of oil. A few days after receiving the first report, Sulzer modified the analysis to indicate the contaminant with ethylene glycol, not oil. Infra-red spectrophotometry was used to determine the presence of glycol. The reason for Sulzer's revision of the contaminant identification is still not clear.

The only possible fluid contaminants of the system are either ethylene glycol/water mixture or compressor oil. About 60 GPM of oil is continuously injected into the helium screw compressor. All oil down to 5 ppb is removed from the helium gas process system by various stages of oil separators, coalescers demisters and absorber beds. If this removal system failed, oil would be present in the helium gas that supplies the refrigerator, turbine bearings and turbine brake circuits. The helium process stream is monitored by two full flow laser aerosol detectors and two hygrometers. During operation, neither of these instruments indicated levels that were different from previous refrigerator tests. Ethylene glycol could reach the turbines if one of the following components failed:

- 1) The helium aftercooler could leak
- 2) The turbine brake heat exchangers could leak
- 3) The turbine cartridge O-ring seals could leak

A failure in the helium aftercooler would be detected by the laser aerosol detectors and the hygrometers. The oil removal system also provides a line of defense for aftercooler seal failure since ethylene glycol would be removed by the purification system. A coolant leak in the turbine brake heat exchangers or the turbine bearing cartridges would have a direct path to the turbine low temperature region. Moreover, seal failures in the turbine cartridges of the brake heat exchangers have no lines of defense against failures. If one seal fails, ethylene glycol enters the helium process directly.

4.5.3. Testing Program and Results

Following a detailed examination of the strength and weakness of the various components that could contribute to the turbine failure, a testing program was developed to determine how the ethylene glycol entered the turbine bearing cartridge. First, the H₂O/ethylene glycol mixture was drained from the turbine brake heat exchangers. Helium mass spectrometer tests were performed on the brake heat exchanger by pressurizing the process side with helium and using a sniffer test on the shell side. No leaks were found in the brake heat exchanger. All helium process piping connected to the refrigerator inlet was examined for soil deposits with black light. No evidence of oil or glycol was found. All piping was washed with ethyl alcohol then dried and reinstalled. Turbine inlet filters were also examined with black light. Neither oil nor glycol was found in the filters and filter housings. To investigate the effectiveness of the oil removal system and the presence of oil or glycol at the refrigerator inlet, a large LN₂ cold trap was constructed and installed at the discharge side of the last three purifier components. First, the trap was located downstream of the charcoal adsorber. The screw compressor was operated to circulate approximately 390 SCFM of helium at 10 and 15 atmospheres for 6 hours/day for 6 days. Each day the trap was warmed to room temperature. Samples were taken to determine if glycol or oil had been trapped. A portion of the sample was discharged onto a silvered mirror surface for visual inspection. The remaining sample was discharged onto a white napkin and examined with black light. After completing the test at this position, the trap was disassembled and examined with black light. The trap was washed with ethyl alcohol. Samples of the alcohol wash and glass wool were sent to an outside testing laboratory for analysis. Testing techniques included flame ionization and infra-red spectrophotometry. Test results showed no evidence of oil or glycol at refrigerator inlet. The LN₂ trap was then relocated to the downstream side of the Helix demister, and the test was repeated. Again, tests results showed no evidence of oil or glycol. Next the trap was located on the downstream side of the coalescer. It was expected that results from here would include oil. Tests procedures were repeated at this location and after operating two days approximately 5 cc of oil was collected. Tests results still did not indicate any glycol in the samples.

Only the helium aftercooler mass spectrometer test remained to complete the testing program of the main process system. H₂O/glycol was drained from the shell side and the tube side was pressured to 225 psig. A mass spectrometer test was done using the sniffer technique. Tests were repeated several times over a 4 day period with no evidence of leaks.

All tests and test results conducted on the helium process system up to this point did not indicate any component failures, system design weaknesses, or incorrect operating procedures that would allow ethylene glycol to enter the turbine cartridges. Consequently, our efforts were re-directed to a intensive examination of the turbine cooling circuit design. In the Sulzer design, the coolant is separated from the process stream by O-rings. Unlike the helium aftercooler that has several levels of defense against seal failures, the turbine coolant seals require only a single failure for glycol to enter the turbine bearing cartridge. Of course, this is a very weak design for such a critical seal. Because of its location, the turbine cartridge coolant seal must be absolutely leak tight under all possible start-up, operating and shut down conditions, the location of the suspect seal is shown in Fig. 4-4.

Helix Technology and Sulzer were contacted to determine if the coolant seals were leak checked on the turbine cartridges which were returned prior to disassembly for repairs. Sulzer informed us that the turbines were not leak tested before repair, thus the possibility of leaks in those assemblies could not be determined. Sulzer was questioned regarding the details of their test procedures for these seals. Briefly, they pressurize the coolant circuit to 7 atmospheres and then conduct a mass spectrometer sniffer test on the turbine and compressor ends. It is our opinion that a sniffer test is not sensitive enough to check for zero leakage and a vacuum mass spectrometer test would be more appropriate. It was agreed by all parties that on receipt of the repaired turbines by BNL, a vacuum mass spectrometer test would be conducted.

Early in January 1980, BNL received the repaired turbine cartridges number 1 and number 2. Mass spectrometer test was conducted on each turbine cartridge. The coolant circuit was pressurized to 7 atmospheres and a vacuum mass spectrometer was connected to the turbine and turbine brake ends. With full throttle on the leak detector, no leaks were found.

On January 25, 1980, turbine cartridge number 3 was delivered and it was mass spectrometer tested. When the cooling circuit was pressurized to 5 atmospheres, the leak detector background increased immediately and then decreased. Like turbines # 1 and 2, turbine # 3 appeared to be leak tight. However, when pressure was removed on the cooling circuit side, the leak detector leak rate increased noticeably and continued to rise. In 30 minutes the leak detector was reading 35 x 50 scale. This is a realistic test and under some operating conditions the differential pressure across the seal can vary from 0 to 8 atmospheres.

Having observed this leakage problem tests were repeated on all of our Sulzer turbine cartridges. The turbine brake side O-ring seal leaked in all assemblies. Tests were conducted using identical procedures to those developed for # 3. Turbine cartridge # 1 was since been tested under several different conditions and always leaked.

4.5.4. Identification of Failure Source

The 5th Avenue refrigerator helium gas purification system underwent extensive tests. Results of the tests pointed overwhelmingly to internal turbine cartridge seal(s) failure which allows the ethylene glycol to

SULZER CRYOGENIC TURBOEXPANDER
SELF-ACTING GAS BEARING SYSTEM

Figure 4-4. General Design of Sulzer Gas Bearing Turbine

enter the turbine bearings. These O-ring seal(s) must be re-designed to ensure zero leakage under all conditions. Anything short of satisfying the zero leakage requirement will be rejected by BNL.

4.5.5. Corrective Measures and Status

Helix Technology was notified of our suspicion of the cartridge coolant circuit leaks on January 28, 1980. Helix accepted the findings of the BNL tests and forwarded them to Sulzer. Sulzer in turn said they would investigate. By the middle of February, Sulzer apparently could not or did not verify the BNL findings and seemed to be making little progress. It was decided to send a BNL representative with the repaired but still-leaking turbine cartridges to Switzerland. Helix concurred with this idea, as the trip would permit a direct meeting of the builders and users.

This trip turned out to be not only frustrating but extremely unpleasant. Although most of the Sulzer representatives were pleasant and cordial, there was an obvious effort to keep our man away from the works area and at no time was he allowed to show them how the BNL tests were made or to observe their testing techniques. Sulzer would not (and has not since) admitted that the leak was due to a latent design defect. They did agree to look at new seal designs and when they had been successfully tested, then would be installed in our cartridges. In the next semiannual report the results of leak tests on cartridges with re-designed seals will be given. The operation of the complete system was successful, once the modified cartridge assemblies were installed.

4.5.6. Electrical Excitation Equipment

4.5.6.1. High Current Power Supply

The capacitor bank for the high current supply has been assembled. For ease in handling the bank has been constructed in two parts. The capacitance of the bank is adjustable and has a maximum capacitance of 0.161 Farads. The minimum adjustment step is 575 μ F. Figure 4-5 is a photograph of a section of the capacitor bank. The bank is part of the resonant circuit formed by the inductance of two cable inner conductors in series. The cables will be excited at 4000 A continuously and up to 6000 A on an intermittent basis.

4.5.6.2. High Voltage Interface Electronics

A fiber optic system has been developed and tested which enables temperature to be recorded on the 138 kV cable center conductor with high voltage applied. Initial tests indicate an accuracy better than 0.1% when measuring the resistance of germanium thermometers. The system was tested up to 150 kV line-to-ground.

Figure 4-6 is a block diagram which illustrated system operation. In the Ground Level Control Chassis fiber optic transmitters (Burr-Brown 3812T) provide the sensor position and polarity code. In the High Voltage Deck fiber optic receivers convert the light signals received to 5 volt logic levels to drive the multiplexer and select current source polarity. The multiplexer in conjunction with the current source permits a four terminal measurement at each

Figure 4-5. One-half of Capacitor Bank Assembly for High Current Power Supply

Figure 4-6. High Voltage Interface Electronics

position. The multiplexer connects individually selected sensors to the amplifier. After passing through the sign changer (+ / -) the amplifier output is converted to a frequency proportional to its magnitude in the V/F section. The frequency range is between 0 and 100 kHz. The fiber optic transmitter converts this frequency to light pulses which are sent via fiber optic cable to the Ground Level Control receiver. The receiver converts the light signals back to an electronic frequency. The Ground Level Station is computer controlled. The computer converts the received frequency to a resistance value which in turn can be scaled to a temperature value. Computer software instructs the H.V. Interface Electronics via the Select Inputs to take multiple readings of both polarities at each sensor position. The computer then computes an average value for the multiple readings. Before each cycle a known standard resistor is read with the same measurement procedure at the multiplexer position labeled STD. This position provides a self calibrating standard for the complete system.

4.6. Research at NBS, Boulder

During the past six months the primary effort at NBS has been on SPTL cool-down strategies using a computer program previously developed at NBS. The boundary conditions have been modified so that it is possible to consider the case of a far-end expander with liquid nitrogen precooling; this requires a change in boundary conditions at a specified stream condition using a modified Newton's method. Previously boundary conditions could be charged only to specified or desecrate times.

The effects of precooling the far-end expander with liquid nitrogen, pre-cooling temperature, line pressure drop, and line length have been investigated and the results are shown in Tables 4-3 and 4-4.

Table 4-3			
<u>Effect of Precooling and Line length</u>			
	<u>Go Stream Pressure</u>	<u>Return Stream Pressure</u>	
Inlet	15 atm	Approximately 8 atm, determined by mass flow rate	
Exit	10 atm	6 atm	
<u>Cool-Down Times</u>			
<u>Length</u>	<u>Far End Expander</u>	<u>Far End Expander With 80 K LN₂ Precooling</u>	<u>Far End Expander With 65 K LN₂ Precooling</u>
28 KM	104 Days	84 Days	78 Days
2/3x28 KM		26 Days	23 Days
1/2x28 KM		11 Days	10 Days

Table 4-4
Pressure Drop Effect

$P_{inlet} = 15 \text{ atm}$	65 K LN ₂ Precooling	$L = 28 \text{ km}$
Pressure drop in go stream		Cool-down time
6 atm		69 days
5 atm		78 days
4 atm		90 days
$P_1 = 15 \text{ atm}$	Far end expander only	
6 atm		131 days
5 atm		104 days
4 atm		170 days

The dependence of the cool-down time goes as the reciprocal of the length cubed (Table 4-3) for constant pressure drop, this agrees with previous analytical work which gave:

$$\text{Cool-down time} \sim (L/\dot{m})^2$$

since $\dot{m}^2 \sim \Delta P/L$ we obtain

$$\text{Cool-down time} \sim (L)^3$$

for constant pressure drop.

The advantage of using liquid nitrogen precooling for the far-end expander is clearly illustrated by the results. However, the complexity of 65 K precooling (requiring vacuum pumps to maintain about 0.15 atm over the LN₂ bath) is probably not justified for the small reduction in cool-down time obtained in going from 80 K to 65 K. NBS next plan to investigate the effect of going to a 20 atm refrigerator since Table 4-4 shows a nearly linear dependence of cool-down time of $1/\Delta P$. Single flow cool-down will also be studied in the near future.

NBS continue to monitor the heat flux meter field test. By algebraically summing the output of a pair of meters mounted on opposite sides of the pipe near the horizontal axis, the effects of stray soil heat fluxes are largely eliminated. Figure 4-7 shows the summed output of a horizontal pair of meters during late winter. The lowest heat flux, 28 W/cm², is the expected nominal enclosure heat flux, a 200 % shift in heat flux is easily detected. Moisture precolating through the soil can have a pronounced effect on local soil temperature gradients and heat fluxes as indicated by the snow melt on 2-19-80.

Figure 4-7. Combined Signal for Meters C_1 and C_2
During Late Winter

5. Visits, Meetings and Publications

5.1. Visits to BNL

<u>DATE</u>	<u>VISITOR(S)</u>	<u>AFFILIATION</u>	<u>PURPOSE</u>
Oct. 1, 1979	Physics Club	Hofstra U.	K. F. Minati gave tour of Power Transmission Project.
Oct. 24, 1979	Ed Heller Tom Dunn Marion Bennett	DOE HQ.	E. B. Forsyth gave tour of Power Transmission Project
Oct. 25, 1979	Physics Society	Fairleigh Dickerson U., NJ	R. A. Thomas gave tour of Power Transmission Project
Oct. 31, 1979	Maritime College	SUNY	A. J. McNerney gave tour of Power Transmission Project
Nov. 15, 1979	NATO Visit		E. B. Forsyth gave tour of Power Transmission Project
Dec. 14, 1979	Electrical Technology Students	Bronx Community College	R. A. Thomas gave tour of Power Transmission Project
Jan. 21, 1980	Ezra D. Heitowit R. B. Leachman	Staff Aides, House Subcommittee on Energy Res. & Production of the House Science & Tech. Committee	E. B. Forsyth gave tour of Power Transmission Project
Feb. 21, 1980	Carl Stange Carl Petersen E. Hersch	FMC	J. E. Jensen gave tour of Power Transmission Project
Mar. 3, 1980	Group attended Magnet Workshop at BNL		R. A. Thomas gave tour of Power Transmission Project
Mar. 10, 1980	Industrial Research Institute		E. B. Forsyth gave tour of Power Transmission Project
Mar. 11, 1980	P. Rohner H. Hofheimer	Cable Consultant Corporation Larchmont, NY	Discussion of Power Transmission Project
Mar. 14, 1980	Temple U Physics & Chem. Students	PA	R. A. Thomas gave tour of Power Transmission Project

5.2. Visits by BNL Personnel

<u>DATE</u>	<u>NAME</u>	<u>PLACE</u>	<u>PURPOSE</u>
Oct. 11, 1979	E. B. Forsyth A. J. McNerney	Washington, D.C.	Attended review meeting on GE Transformer Project
Oct. 21-25, 1979	K. Horii	Whitehaven, PA	Attended Conference on Electrical Insulation & Dielectric Phenomena
Nov. 6, 1979	E. B. Forsyth W. E. Harrison	Washington, D.C.	Visited DOE HQ to discuss Contract Management
Nov. 8, 1979	R. J. Gibbs	Boston, MA	Took Sulzer Turbines to CTI
Dec. 5-6, 1979	A. Ernst	Columbus, OH	Visited Battelle Columbus Lab relative to insulation development.
Dec. 6, 1979	A. Muller R. Porter	Columbus, OH	Reviewed progress of high modulus tape development program at Battelle
Jan. 23-24, 1980	J. E. Jensen	San Diego, CA	Attend Cryogenic Eng. Conf. Board Meeting & discussed plans for 1981 Conf.
Feb. 4-5, 1980	A. Ernst	NYC	Attended PES Meeting & attended meeting relative to OTEC Riser Cable Accessories
Feb. 25-Mar. 7, 1980	R. J. Gibbs	Winterthur, Switzerland	Hand carried gas bearing turbine cartridges to Sulzer Bros. Ltd.
Mar. 2-5, 1980	G. Morgan F. Schauer	Los Alamos, NM	Visited LASL for a review of their superconducting power transmission line
Mar. 3-4, 1980	A. Ernst	Portsmouth, NH	Visited Simplex Wire & Cable Co. to review OTEC Riser Cable Development
Mar. 18, 1980	E. B. Forsyth A. Ernst	Washington, D.C.	Visited DOE HQ.
Mar. 20, 1980	R. D. Schmidt F. Schauer A. J. McNerney	Leroy, NY	Visited Lapp Insulator Corp.

5.3. Publications

1. E. B. Forsyth, R. J. Gibbs, J. E. Jensen and A. J. McNerney, The Cooling and Electrical Excitation of 100 m Superconducting Power Transmission Cables, to be presented at ICEC 8, Genova, Italy, 3-6 June 1980.
2. A. J. Pearmain, E. B. Forsyth, M. Kosaki and R. A. Thomas, Preliminary Ageing Tests on a Superconducting Cable Dielectric, to be presented at the IEEE International Symposium on Electrical Insulation, Boston, MA, 9-11 June 1980.
3. V. T. Kovachev, Temperature Dependence of the Minimum in AC Power Losses of $(\text{Nb}_{0.99}\text{Zr}_{0.01})_3\text{Sn}$ in Parallel AC and DC Magnetic Fields, submitted to Journal of Applied Physics.
4. A. C. Muller, X-Ray Examination of Lapped Electrical Insulation, to be published in Proceedings of the Workshop on Experimental Techniques for Investigating the Degradation of Electrical Insulation, Whitehaven, PA, 1979.
5. G. H. Morgan and A. C. Muller, Bending Behavior of Lapped Plastic EHV Cables, to be presented at the 1980 International Symposium on Electrical Insulation, Boston, MA, 9-11, 1980.
6. A. C. Muller, X-Ray Examination of Insulation in Lapped High Voltage Underground Power Transmission Cables, held at the 39th Fall Conference of ASNT, St. Louis, MO., Oct. 18, 1979.

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