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**SEMIANNUAL REPORT FOR THE PERIOD
APRIL 1 TO SEPTEMBER 30, 1979 OF WORK ON:**

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

January 15, 1980

**DIVISION OF ADVANCED TECHNOLOGY APPLICATIONS
ACCELERATOR DEPARTMENT**

**BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.**

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January 15, 1980

POWER TRANSMISSION PROJECT TECHNICAL NOTE NO. 99

**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.

2. Cable Conductor Development

2.1. Commercial Production of Superconducting Tape

Production of superconducting tape for the 100 m test cable was started at IGC. An order was placed to prepare 24 ea, 600 ft long strips of Nb₃Sn substrate.

Delivery was made on 13 tapes which ranged in length from 621 ft to 736 ft. Quality control measurements made at IGC on samples from both ends of the tape show the thickness of Nb₃Sn 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 Nb₃Sn layer thickness and ac losses confirm the IGC results.

In a joint effort with IGC a task was undertaken to remove the tin on the superconductor tape surface. Superconducting tape with the surface tin removed was needed for a 10 m cable test. Conditions for etching i.e., acid-concentration and time in bath were established at BNL under static test conditions. The objective was to remove all the surface tin but still keep the attack at the edges to a minimum. The optimum conditions determined statically were then evaluated with longer strips on the IGC etch line. It was determined that the best results and control were obtained with a solution of (H₂O):1(HNO₃) with a 40 second bath residence time. Maximum edge penetration was approximately 0.003 inches. A total of about 2,800 ft of 6 mm wide SS/Cu clad superconductor tape was processed in this manner.

Several samples of superconducting tape which were made using knurled Nb-1Zr strip as the starting material were submitted to BNL for evaluation. IGC prefers to use the knurled material since it is the standard for their tape processing; providing them with better handling material and better solderability. The tape samples were fabricated to BNL specifications having stainless steel on one side and copper in the other.

Metallographic examination and ac loss measurements were performed on the samples. The metallographic sections showed the Nb₃Sn layers to have thicknesses, uniformity and surface roughness essentially the same as tapes supplied previously processed with unknurled Nb₃Sn. Solder layers were essentially the same as observed previously so no advantage to knurled material over unknurled material for soldering was obvious from our examination. AC loss measurements showed the losses to be about 11 μ W/cm² @ 500 A/cm @ 4.2 with the copper removed but the stainless steel still on the tape. In general, our tests showed there essentially was no difference between tapes made with knurled or unknurled Nb-1Zr starting materials.

2.2. Contract Management

2.2.1. Airco

The final task in the Airco superconducting tape development contract was to process to a finished tape the rectangular-shaped extrusion prepared by BNL. Procedures and results of successfully rolling the extrusion to final thickness were described in the previous progress report.

Final processing to be done by Airco was to slit the excess bronze from the edges, heat treat to form the Nb_3Sn , etch off the bronze, sputter-coat the Nb_3Sn with a thin layer of copper for soldering, laminate with copper and stainless steel and then slit to final width.

After slitting the as-rolled strip to about 2" wide, which removes the excess bronze from the edges which would cause kinks due to differential thermal stress, the strip was given a heat treatment at 700°C for 250 h to form Nb_3Sn layers 7 microns thick. In removing the bronze in 45% HNO_3 , 5% HCl , 50% H_2O bath several breaks occurred which reduced the yield to three pieces each approximately 200 ft long. A thin copper layer was sputtered onto the Nb_3Sn surface and the tape processed in the laminator. AC losses of the bare tape were about $2 \mu W/cm^2$ at 500 A/cm at 4.2 K, dc critical currents ranged between 70 and 147 A/6 mm at 10 T.

In the lamination process severe wrinkling of the tape was encountered, Fig. 2.1. Metallographic examination showed nonuniformity and voids in the solder layers and kinks and cracks in the Nb_3Sn substrate, see Fig. 2.2. The cracks were probably the cause of the wide variation in the dc critical currents. The poor quality of this tape made it unusable for a 10 m test cable.

At this time Airco has attributed the laminating problem to:

1. Stainless steel coating problems.
2. Nb/Nb_3Sn strip nonuniformity.
3. Laminating inexperience.

A final report RE-79-317-CRE-99 of the work done by Airco on superconducting tape development contract 404100S was received.

2.2.2. IGC

All work on the IGC superconducting tape development contract has been completed. During this report period the final 3200 ft order of 3/4" wide tape was delivered. Modifications to the process lines to go from 3/4" wide to 7/8" wide tape was completed and tested. The final report of work done under this contract is undergoing final editing.

2.3. Other Cable Materials

2.3.1. Copper Clad Aluminum

Approximately 27 lbs of high resistivity ratio ($\frac{R_{RT}}{R_{4.2K}}$) aluminum were cold roll clad with copper by Polymetallurgical Corp. of Attleboro, MA.

Figure 2.1. Surface Appearance of Laminated Extrusion #3,
Copper Side.

Cu Etch

125X

Nb Etch

1000X

Figure 2.2. Metallographic Sections of Laminated Extrusion #3

Starting aluminum was received in three pieces, each 0.187" thick x 2" wide x 20 ft long. These are the maximum size pieces the manufacturer (Indium Corp.) could supply at present. One section was processed immediately using parameters previously established by Polymetallurgical and the other two sections were electron beam welded at BNL in an attempt to establish this as a possible method of producing long single lengths. All sections were processed as follows: 0.062" thick Al and 0.004" thick copper were cold bonded and rolled to 0.011" thickness in three reductions with 475°F anneals between reductions. There was no anneal after the final reduction. The single section length was designated Run A and the welded section as Run B. The E. B. weld was strong enough to withstand the rolling forces.

Visual examination showed the surface quality of Run B to be much better than Run A in that there was not aluminum showing through the copper in the Run B material. The Run A type material is undesirable because pieces of copper tend to flake from the surface when the material is bent with a small diameter. These copper flakes could cause problems in the dielectric insulation when the cable is taped. The difference in processing between Runs A and B which could account for this behavior is that the cleaning of the Run B aluminum was done with much greater care and supervision.

Although Polymetallurgical claims the cleaning to be the only difference in processing, the results of resistivity ratio measurements would indicate otherwise. Results of the measurements are shown in Table 2.1. It can be seen that the R/R of Run A was higher than Run B in the as-received condition. A heat treatment of 350°C for 1 h reduced somewhat the R/R of the Run A material while the Run B material showed a marked increase. It is suspected that the heat treatments performed by the Polymetallurgical subcontractors are responsible for the observed differences.

2.3.2. Stainless Steel Coating

The problems encountered in mechanical spooling of stainless steel in the Airco sputter coater has led to the evaluation of electroplating as a means of coating to provide a solderable surface. Samples of electroplated stainless steel prepared previously and more recently were peel-tested to evaluate their adhesion for comparison with sputter coated material. The peel test consists of soldering together two pieces of the sample, thermal cycling between room temperature and 4.2 K and then peeling the two pieces apart with a measured tensile force. Recently electroplated samples differ from previous samples in that a gold acid bath rather than a nickel chloride bath is used to activate the stainless steel surface. Presence of nickel on the surface of the stainless leads to unacceptable high ac losses. Results of the peel tests are shown in Table 2.2. These results show that some of the electroplated samples are almost as good as the sputtered material and are within the BNL specification of 0.4 lbs/6 mm wide strip. Arrangements are being made to have long strips of type 316 stainless steel electroplated with the gold/copper solutions.

Table 2.1

Resistivity Ratio Measurements on Roll
Bonded Copper Coated Aluminum

Run A	$\frac{R_{RT}}{R_{4.2\text{ K}}}$	Condition
Spool #1	3010	As received
Spool #1	2280	Ann 350°C-1 h
Spool #2	2704	As received
Spool #3	2417	Ann 350°C-1 h
<u>Run B</u>		
Spool #6	4087	Ann 350°C-1 h
Spool #8 (inside)	1647	As received
Spool #8	3690	Ann 350°C-1 h
Spool #12	1656	As received
Spool #12	1359	As received
Spool #12 (inside)	1543	As received
Spool #12	3625	Ann 350°C-1 h
Spool #12	3767	Ann 350°C-1 h

Table 2.2

Peel Test Results on Stainless Steels
Coated with Copper or Tin

<u>Sample Description</u>	<u>Min. Measured Force to Peel (lbs)</u>
1. Electroplated Copper on 21-6-9 Nickel Strike	1.0 0.8 0.8
2. Tinned Type 302 SS	0.3 0.3 0.4
3. Electroplated 21-6-9 Gold Strike Only	0.3 0.2 0.1
4. Copper Sputtered 21-6-9	1.2 1.5 1.5
5. Copper Electroplated Type 316 Gold Strike + 0.0001" Copper	1.5 1.4 1.4

2.4. Cable Conductor Design and Testing

2.4.1. Electrical Resistance Between SS/Cu Clad Superconducting Tapes

2.4.1.1. Conductors in Physical Contact

As discussed in the previous semiannual report (BNL 51035) resistive contact between superconducting tapes comprising a two-layer conductor can lead to appreciable losses. This mechanism may in fact be responsible for some of the losses observed in cables 101 and 102. A study of contact resistance between SS/Cu clad superconducting tapes was therefore initiated. Tapes 6 mm wide, were placed at right angles to each other and subjected to a mechanical force of up to ~ 3 kg. Measurements were made with copper facing either copper or stainless steel in the as-received condition (i.e., tinned surfaces) and after etching away the tin from the SS and Cu surfaces. Results are shown in Fig. 2.3. Although there is considerable scatter, it is seen that contacts of etched copper to copper, tinned copper to copper and tinned stainless steel to copper lead to similar low resistances. With the tin etched away the resistance of copper to SS contacts increases by about an order of magnitude and is roughly equal to the resistance of SS to SS contacts.

Using a computer simulation of the loss mechanism^{*}, a resistance of $\sim 5 \times 10^{-3} \Omega/\text{contact}$ would appear sufficient to explain the high losses observed in cables 101 and 102 at 60 Hz. However, from these calculations one would also expect a loss nearly independent of temperature and increasing faster than linearly with frequency, in disagreement with observations. Because of the partial agreement with theory, and the results of Fig. 2.3, it was decided that cable 103 would be wound with etched tapes (no surface tin) and stainless steel facing copper. The much higher contact resistance should result in lower cable losses.

2.4.1.2. Electrical Resistance of a Soldered Joint

The resistance of soldered joints between superconducting tapes is of interest to estimate losses at the shorted end of 1 m and 10 m cables and also to estimate losses of splices in future longer cables. Solder joints studied were between 6 mm wide tapes clad on one side with 1 mil stainless steel and 2 mils copper on the other. Using indium solder, joints of hairpin geometry 1, 2, and 5 cm long were made with copper facing either copper or stainless steel. The resistance was measured with dc and also with ac (using the wattmeter) between 30 and 250 Hz. Results are shown in Fig. 2.4. Note that when stainless steel faces copper the resistance is much higher, as expected. Also the optimum length for such joints is probably greater than 5 cm. For Cu to Cu joints the optimum length is approximately 2 cm.

Using the data of Fig. 2.4, one can estimate losses at the shorted end of a cable. It is assumed that the joint is made from short lengths of superconductor soldered to the cable at one end and shorted together at the other end. This is shown schematically in Fig. 2.5 where the cross-hatched areas represent solder joints. Assuming equal currents, $I/2$, in each layer of the cable and a resistance R for each solder joint, the loss of the entire joint is

$$P_{\text{joint}} \approx \frac{9I^2}{4n} R \quad (2.1)$$

^{*}PTP Tech. Note # 85.

Figure 2.3. Resistance of Pressure Contacts Between 6 mm Wide ss/Cu Clad IGC Tapes.

Figure 2.4. Frequency Dependence of Resistance of Solder Contacts Between Superconductive Composite Tapes Clad With Stainless Steel and Copper.

Figure 2.5. Schematic of Shorted End of a Typical Cable.

where I is the cable current and n is the number of tapes per layer. For a typical cable made with nine 6 mm wide tapes and a cable current of ~ 3850 A (~ 500 rms A/cm), using $R = 5 \times 10^{-8} \Omega$ (from Fig. 2.4) leads to a joint loss of ~ 200 mW.

2.4.2. Summary of Total and Joint Loss Measurements in 1 m and 10 m Cables

A summary of total cable losses (measured with a "AB" probe) and joint losses ("CD" probe) at 500 rms A/cm for 1 m and 10 m cables is given in Table 2.3. Measured joint losses are between 150 and 350 MW, in good agreement with the estimate given above (200 MW). Total losses vary between 500 and ~ 100 MW for 10 cables. The loss per unit length for each cable is also listed in Table 2.3. The lowest losses were observed in the 10 m cables (~ 0.2 W/m) and the insulated 1 meter cable (11) (0.3 - 0.6 W/m). The non-insulated 1 m cables led to rather high losses, ~ 0.9 W/m. One interpretation of these results is that 1 m tests measure "end losses" and that cables of ~ 100 m and longer will exhibit much lower losses.

2.4.3. Cable 102 Test Results

Measurements of ac losses, critical current, quench recovery and other electrical characteristics were performed on cable 102, the second "10 meter" cable. The construction of cable 102 was very similar to that of cable 101. The main difference was in the orientation of the copper/stainless steel cladding of the superconducting layers. In cable 102 the copper layers are in contact with each other whereas in cable 101 the contact was between stainless steel and copper. Because of the tin present on both surfaces, however, the contact resistance should be the same in each case (see Fig. 2.3). The constructional details of cable 102 were given in the previous semiannual report. Instrumentation was similar to that used in cable 101, including an "AB" probe used to measure the total loss of the cable, an axial probe measuring losses of the inner conductor and two "spiral probes" measuring losses of individual tapes on the inner conductors. Two heaters were also used to initiate quenches in the cable, allowing measurements of quench propagation and recovery. Two new current sensing coils (Rogowski loops) were also installed, one near the transformer, the other near the shorted end. These new coils, made of #40 copper wire, gave loss results in good agreement with each other, but a factor of two larger than the previously installed Rogowski coil (made of #36 copper wire) which was used for testing cable 101. This difference is probably due to eddy currents in the old coil which was made of much thicker copper wire.

2.4.3.1. Losses

Total cable losses expressed in W/m are given in Fig. 2.6 at 7.4 and 9.7 K as a function of the current density, σ , in the inner conductor. Losses of the joint ($\sim 15\%$ of total) were subtracted from the total to deduce the loss per unit length of cable. Losses increase roughly as σ^2 at both temperatures. At 500 rms A/cm losses are 0.21 W/m at 7.4 K and 0.29 W/m at 9.7 K. These losses are comparable to values reported for cable 101. However, because of a phase shift in the old Rogowski coil, the actual losses of cable 101 were probably twice as high. Also shown in Fig. 2.6 are losses deduced from a helical voltage probe on the inner conductor.

Table 2.3

TOTAL (AB) AND JOINT LOSSES OF 1 m AND 10 m CABLES

No.	Single or Double Helix	Angle		Stabilizer		Superconductor		Loss @500 rms A/cm			Remarks
		Inner	Outer	Inner	Outer	Inner	Outer	Total (AB) (mW)	Joint (CD) (mW)	Loss** Length (W/m)	
9	Double	43.3°	38°	Al .008"	Al .008"	KB 15A	KB 30	1010		0.8***	Short made with Cu end rings
10	Double	30°	38°	Al .008"	Al .008"	KB 15A	KB 30	1122		0.9	Joint on Cu end rings
11A	Double	45°	44°	No	No	IGC with SS/Cu	KB 30	2020	151	1.9	Insulated conductors; A lead suspect joint made with RCA links
11B	Double	45°	44°	No	No	"	KB 30	722	294	0.4	A*B leads moved; toroid moved
11C	Double	45°	44°	No	No	"	KB 30	504		0.3***	Shorted end region slit
12	Double	45°	44°	No	No	"	KB 30	764	155	0.6	Same cable as 11C, except shorted end consists of 2 separate joints
101	Double			Al	Al	IGC SS/Cu	IGC SS/Cu	2400* @7-9K	~300	0.2	10 m cable; SS facing Cu
102	Double	~42°	46°	Al	Al	IGC SS/Cu	IGC SS/Cu	2650 @7.3K	350	0.2	10 m cable; Cu facing Cu

Note: Losses were measured at 4.2K unless otherwise indicated.

* Due to phase shift in current pickup coil, losses were probably twice this value.

** Joint loss subtracted.

***Joint loss of 200 mW assumed.

As was the case for cable 101 these losses are much lower than the cable losses and are similar to short sample measurements.

The frequency dependence of losses was measured at 7.0 ± 0.3 K for current densities of up to 350 rms A/cm (see Fig. 2.7). As shown in Fig. 2.3 losses increase roughly linearly with frequency between 20 and 150 Hz. Losses of the joint were also found to increase linearly with frequency, in good agreement with short sample measurements on solder contacts (Fig. 2.4).

In conclusion, the loss behavior of cable 102 is very similar to that of cable 101. Losses are higher than short sample measurements would imply and the loss waveform is nearly sinusoidal, a characteristic of normal metal losses. The origin of these losses remains uncertain. There is a strong possibility that they are dominated by end effects. A significant loss contribution may also come from the rather small contact resistance between tapes.

2.4.3.2. Critical Current and Quench Recovery

Critical current measurements under continuous ac conditions could not be made because of the limited power rating of the superconducting transformer. However, using a capacitance discharge circuit resonating at ~ 60 Hz the cable was found to carry peak currents of up to ~ 32 kA at ~ 6 K.

Recovery from heat pulses was studied in a rather qualitative way. It was found that heat pulses of ~ 70 W applied for ~ 1.7 s did not drive the cable normal at 550 rms A/cm and ~ 6 K. Slightly longer pulses however drove the cable irreversibly normal. Once the cable is driven locally normal with a heat pulse at current densities of ~ 500 rms A/cm, a normal region of ~ 1 m length develops but remains localized (does not expand) or expands very slowly. During an experiment such a region was inadvertently left normal for ~ 1 minute at the rated current (~ 3850 A). Although this produced a considerable local temperature rise (up to ~ 300 K) the normal region probably never expanded to more than ~ 2 meters. Also the cable suffered no observable damage from this ordeal.

2.4.4. Conductor Loss Measurement of Long Cables

The conductor loss in a test cable is determined by measuring the differences between the incident and transmitted powers of the inner and of the outer conductors. The losses attributable individually to the inner and the outer conductors current cannot be experimentally separated. The conductor loss is the algebraic sum of the two measured power levels. A network representing the cable and power sources that is useful in discussing conductor loss measurements is given in Fig. 2.8. This figure also indicates the current leads and identifies branch voltages and currents. A tabulation of branch voltages, currents and power factor angles is given in Table 2.4. This table also includes incident and transmitted powers for the inner and for the outer conductors, which are calculated from the power flow equations:

Figure 2.6. Losses of Cable #102 as a Function of Current Density.

Figure 2.7. Frequency Dependence of Total Cable Losses (Joint Loss Subtracted).

Figure 2.8. Network Useful in Discussing Conductor Loss.

Table 2.4

Current, Voltage and Power Levels Calculated for 100 m Cable Test*

<u>Position</u>	<u>Branch Voltage</u>	<u>Branch Current</u>	<u>Power Factor Angle</u>	<u>Power Flow (watts)</u>
<u>Inner Conductor</u>				
$(V_A - V_B)$	$86.98 \angle -21.312^0$	$5972 \angle -110.566^0$	89.254^0	+6763
$(V_1 - V_2)$	$86.98 \angle -21.178$	"	89.388	5547
$(V_3 - V_4)$	$42.834 \angle -21.727$	"	88.839	5183
$(V_C - V_D)$	$42.830 \angle -21.545$	"	89.112	3959
<u>Outer Conductor</u>				
$(V_E - V_F)$	$3.91 \angle -26.551^0$	$5970 \angle -11.528$	83.977^0	2450
$(V_5 - V_6)$	$3.90 \angle -23.565$	"	86.963	1232
$V_7 - V_8)$	$3.92 \angle -24.19$	"	86.338	1495
$(V_G - V_H)$	$3.92 \angle -21.21$	"	89.318	278

* See Fig. 2.8 for explanation of symbols.

Table 2.5

Current, Voltage and Power Levels: Direct Reading Method

<u>Conductor</u>	<u>Voltage</u>	<u>Current</u>	<u>Power Factor Angle</u>	<u>Power (watts)</u>
Inner	$44.158 \angle -20.617^0$	$5972 \angle -110.557^0$	89.92^0	364
Outer	$0.050163 \angle 97.289$	$5970 \angle -110.517$	152.192	-263

$$P_1 - P_2 = \text{Re} (V_1 - V_2) I_1^* - (V_3 - V_4) I_1^* \quad (2.2)$$

$$P_3 - P_4 = \text{Re} (V_5 - V_6) I_2^* - (V_7 - V_8) I_2 \quad (2.3)$$

where P_i is the power flow at the i th port.

Voltage-pairs ($V_1 - V_2$, $V_5 - V_6$,) are required for power measurements. All voltages must be processed differentially using difference amplifiers with excellent common mode rejection ratio capabilities; the reference is established for accommodation of the electronics. The differential pairs also establish the ports of the model of Fig. 2.8, a four-port electrical network. The power flow at each port is measured using a four-quadrant multiplier. The signs of power flow are arbitrarily assigned, however, they must be consistent. The signs used for this discussion are

positive sign - power flow into the port
negative sign - power flow out of the port

The algebraic sum of the complete set of power flow at the ports is the net power absorbed or delivered by the network. If their sum is positive the network is a sink of power (I^2R heating loss); if their sum is negative the network is a source of electrical power. Within the network power transferred between branches cannot be identified from external measurements.*

Knowing that the inner and outer conductor loops are magnetically coupled the network of Fig. 2.8 is modelled as is shown in Fig. 2.9. This model is useful for considering the power balance. Power losses (P_{inner} , P_{outer}) within the loops are shown as flowing into a heat sink. Power transferred between the loops is indicated by P_x . The power balance is:

$$P_{\text{inner}} = (P_1 - P_2) - P_x \quad (2.4)$$

$$P_{\text{outer}} = (P_3 - P_4) + P_x \quad (2.5)$$

Terminal electrical measurements yield information as to the total power dissipated within the cable:

$$P_{\text{dissipation}} = P_{\text{inner}} + P_{\text{outer}} = (P_1 - P_2) + (P_3 - P_4) \quad (2.6)$$

corresponding to a law of mass action. Analytic development (such as performed by the routine ECAP) allows the component power to be separated into dissipation and transferred components:

$$P_{\text{dissipation}} = P_{\text{inner}} + P_{\text{outer}} = (P_1 - P_2 - P_x) + (P_3 - P_4 + P_x) \quad (2.7)$$

corresponding to a law of detailed balance.

* See Thevenin's Network Theorem.

From the data of Table 2.4 the power dissipation of the test cable is:

$$P_1 - P_2 = (5547 - 5183) = 364 \text{ watts}$$

$$P_3 - P_4 = (1232 - 1495) = - 263 \text{ watts}$$

$$P_{\text{loss}} = P_{\text{inner}} + P_{\text{inner}} + P_{\text{outer}} = 101 \text{ watts}$$

Similar calculations from the data of Table 2.4 gives the dissipation of each current lead as approximately 608 watts.

The computer program gives the details of the above power flow as:

$$(P_1 - P_2) = P_{\text{inner}} + P_x$$

$$P_{\text{inner}} = 70 \text{ watts (power dissipated)}$$

$$P_x = 294 \text{ watts (power transferred), } (P_1 - P_2 = 364 \text{ W}$$

$$(P_3 - P_4) = P_{\text{outer}} - P_x$$

$$(P_3 - P_4) = P_{\text{outer}} - P_x$$

$$P_{\text{outer}} = 31 \text{ watts (power dissipated)}$$

$$P_x = - 294 \text{ watts (power absorbed), } (P_3 - P_4 = - 263 \text{ W}$$

Equations 2.2 and 2.3 can be reinterpreted to directly calculate (read) the net power in the inner and the outer conductors:

$$P_{\text{inner}} + P_x = \text{Re } (V_1 - V_2) - (V_3 - V_4) I_1^* \quad (2.8)$$

$$P_{\text{outer}} - P_x = \text{Re } (V_5 - V_6) - (V_7 - V_8) I_2 \quad (2.9)$$

A schematic for implementing the direct reading method is given in Fig. 2.10 and Table 2.5 gives the current, voltage and power for this method.

The direct reading method is preferred over the power flow method, in that a difference amplifier replaces a wattmeter. Basically, difference amplifiers are linear components and can be built with greater linearity and bandwidth than wattmeters; a product device.

The value of power transmitted between the two conductors due to magnetic coupling is strongly dependent on the adjustment of the compensating voltage. Conductor loss depends on line current and is almost independent of the value of compensating voltage. The individual wattmeter readings ($P_{\text{inner}} + P_x$) and ($P_{\text{outer}} - P_x$) are near their minimum value with the compensating voltage set for an unbalance current of zero. At this setting the transferred power is zero and the measured dissipation is most accurate. Figure 2.11 illustrates the effect of unbalance on wattmeter readings and is a plot of the individual wattmeter readings as a function of the amplitude of the $- 120^\circ$ phase compensating voltage.

Figure 2.9. Model Useful in Discussing Power Balance.

$$P_{\text{INNER}} + P_x = \text{Re} \left\{ [(V_1 - V_2) - (V_3 - V_4)] I_1^* \right\}$$

Figure 2.10. Power Measurement Direct Reading Method.

Figure 2.11. Wattmeter Readings as a Function of Compensation.

3. Cable Insulation Development

3.1. Cable Bending

The series of twelve bend tests was completed on the four synthetic tapes developed for use on BNL experimental cables. The purpose of this experiment was twofold. First, the bending behavior of solid, synthetic tapes would be evaluated and second, the BNL computer program could be tested against four materials having a range of mechanical properties. See Table 3.1. The bend specimens were wound at the BNL taping facility on a 2.74 cm diameter stranded aluminum core with 64 layers of tape. The specimens were x-rayed before and after standard bend tests which were performed on one of three semicircular mandrels having diameters of 1.27, 1.90 and 2.54 meters, respectively.

The results of cable dissections following bending are summarized in Table 3.2. In general, no wrinkles, creases, or other major tape disturbance occurred as long as D/d , the ratio of the bend diameter to the cable diameter, was greater than about 35:1. Cable # 4 developed pronounced creases after bending over the 1.27 m mandrel ($D/d = 31.6:1$). A regular pattern of "diamond shaped creases" was found along the entire length of the bend section. The internal structure of the insulation of cable No. 4 is illustrated radiographically in Fig. 3.1. The creases extended radially through the entire insulation thickness and they were accompanied by frequent voids.

Bending tests at 1.90 m ($D/d \approx 50:1$) suggest that tape migration precedes actual wrinkling. Evidence of tape movement was seen in three cables following bends at this diameter. The pattern of tape migration is qualitatively illustrated in Fig. 3.2.; a radiograph of cable no. 4 taken after bending. Dissection of this cable revealed the presence of annular regions of enlarged butt gaps ($= 0.080$ to 0.100 ") adjacent to regions of very small butt gaps (≈ 0.000 to 0.020 ").

The results of the bend tests are in rather poor agreement with the predictions of the computer program. Of the twelve bend tests (4 tapes and 3 diameters), two at the smallest bend diameter showed substantial collapse damage, a result not predicted. The program predicted severe butt-space wrinkles in two of the four designs but one of these had none and the other had only minor wrinkles. The program predicted minor butt-space wrinkling in the other two designs, and little or none was observed.

One very interesting fact revealed by dissection of the cables was that the damage found in cables # 1, 3 and 4 was usually most pronounced in the third tape section (tape layers 33 to 48 inclusive). The computer program may have shown one probable reason for this: the taping angle, α , reached 78° in the third section of these specimens. Since high modulus, paper lapped cables are known to become unstable when α reaches 82 or 83° , it may be possible that lower modulus plastic lapped cables become unstable to bending at taping angles a few degrees smaller. In future bend tests will be controlled by using the appropriate wider tapes as cable diameters increase.

Table 3.1

MECHANICAL PROPERTIES OF PLASTIC TAPES FOR CABLE BEND TESTS

Mechanical Property	Tape #1 Polypropylene Two Ply (Slip Additive)	Tape #2 Polypropylene Three Ply (Slip Additive)	Tape #3 Polycarbonate "G" One Ply (No Slip Additive)	Tape #4 Polypropylene Two Ply (No Slip Additive)
Thickness, S	66 μm (2.60 mils)	100 μm (3.95 mils)	102 μm (4.00 mils)	104 μm (4.10 mils)
Tensile Modulus, E_1	$23.3 \times 10^3 \text{ kg/cm}^2$ ($3.33 \times 10^5 \text{ psi}$)	$19.1 \times 10^3 \text{ kg/cm}^2$ ($2.73 \times 10^5 \text{ psi}$)	$21.3 \times 10^3 \text{ kg/cm}^2$ ($3.04 \times 10^5 \text{ psi}$)	$22.0 \times 10^3 \text{ kg/cm}^2$ ($3.14 \times 10^5 \text{ psi}$)
Tensile Modulus, E_2	$19.5 \times 10^3 \text{ kg/cm}^2$ ($2.78 \times 10^5 \text{ psi}$)	$16.6 \times 10^3 \text{ kg/cm}^2$ ($2.37 \times 10^5 \text{ psi}$)	$20.5 \times 10^3 \text{ kg/cm}^2$ ($2.93 \times 10^5 \text{ psi}$)	$39.8 \times 10^3 \text{ kg/cm}^2$ ($5.68 \times 10^5 \text{ psi}$)
Shear Modulus, G	$10.6 \times 10^3 \text{ kg/cm}^2$ ($1.52 \times 10^5 \text{ psi}$)	$11.3 \times 10^3 \text{ kg/cm}^2$ ($1.62 \times 10^5 \text{ psi}$)	$8.05 \times 10^3 \text{ kg/cm}^2$ ($1.15 \times 10^5 \text{ psi}$)	$14.7 \times 10^3 \text{ kg/cm}^2$ ($2.1 \times 10^5 \text{ psi}$)
Compressive Modulus, E_3 (at 20 psi Load)	$1.32 \times 10^2 \text{ kg/cm}^2$ ($1.88 \times 10^3 \text{ psi}$)	$0.7 \times 10^2 \text{ kg/cm}^2$ ($1.00 \times 10^3 \text{ psi}$)	$1.82 \times 10^2 \text{ kg/cm}^2$ ($2.60 \times 10^3 \text{ psi}$)	$1.04 \times 10^2 \text{ kg/cm}^2$ ($1.49 \times 10^3 \text{ psi}$)
Anisotropy Factor, n ($n = E_1/E_3$)	177	273	117	211
Friction Coefficient, μ_s (CMD to CMD)	0.26	0.23	0.45	0.37

*Estimated

Table 3.2

RESULTS OF BEND TESTS ON FOUR PLASTIC LAPPED CABLES

Bend Diameter	Cable #1 Polypropylene Two Ply (Slip Additive)	Cable #2 Polypropylene Three Ply (Slip Additive)	Cable #3 Polycarbonate "G" One Ply (No Slip Additive)	Cable #4 Polypropylene Two Ply (No Slip Additive)
2.54 Meters (100 Inches)	Tape Migration, No Wrinkles or Ridges (D/d = 71.8)	Slight Tape Migration, No Wrinkles or Ridges (D/d = 63.3)	No Tape Disturbance (D/d = 62.6)	No Tape Disturbance (D/d = 63.2)
1.90 Meters (75 Inches)	Tape Migration Small Ridges Over (D/d = 53.8)	Tape Migration, Small Ridges Over Butt Gaps (D/d = 47.5)	No Tape Disturbance (D/d = 47.0)	Tape Migration No Wrinkles or Ridges (D/d = 47.4)
1.27 Meters (50 Inches)	Tape Migration, Many Small Ridges, Several Wrinkles Over Butt Gaps in Third Tape Section (D/d = 35.9)	Tape Migration, Many Small Ridges Over Butt Gaps (D/d = 31.6)	Tape Migration, One Wrinkle Over Butt Gap in Third Tape Section (D/d = 31.3)	Tape Migration Severe Diamond Pattern Creases (D/d = 31.6)

Figure 3.1. Radiograph of BNL Test Cable #4-BPPL-64-4-AL,
After Bend Test on 50" Diameter Reel. May 25, 1979.

Figure 3.2. Radiograph of BNL Test Cable #4-BPPL-64-4-AL,
After Bend Test on 75" Diameter Reel. 5" Left of Center
of Bend. July, 1979.

3.2. Materials Development

3.2.1. Tapes for Superconducting Cables

A new variety of laminated polypropylene (PP) tape is under consideration for use as dielectric insulation on BNL superconducting cables. This material, a two-ply PP laminate (Tape #4, Table 3.1), is supplied by the Bryce Corp. and has several advantages over the three-ply PP laminate that has been under evaluation previously. E_1 , E_2 , and G are higher, loss tangent and does not exceed 1.7×10^{-5} at a stress of 15 kV/mm, and no slip additive is used in this product. Tape type # 4 is available in thicknesses of 80, 100, and 120 μm should tape thickness grading be adopted in future EHV cable designs.

3.2.2. High Modulus Tape Development

A series of nineteen new fabrication trials was completed at Battelle Columbus Laboratories (BCL) in support of the BNL program to develop a high modulus polyolefin tape suitable for use on EHV ambient temperature oil or gas impregnated cable designs. The goal of this program is to develop a tape with a modulus of 4 GPa (600,000 psi) that will not fibrillate during processing and which will have long term stability in 100°C cable oils. It is expected that a thickness reduction ratio of approximately 8:1 will be required in order to meet design specifications. Two types of PP and three types of PE were processed using a new rolling technique in this first series of trials. Experimental fabrication data are summarized in Table 3.3.

In trials 20 through 23 Rexene PP54H5 was fluid rolled in single passes to a maximum reduction of 4:1 before melting began to occur. Another polypropylene, Hercules PA954, was fluid rolled in four successive passes in Trials 24 through 26 to a maximum cumulative reduction of 4.8:1. The reductions in these trials were not limited by melting but by the stiffness of the tape material which became progressively greater as the cumulative reduction increased.

Three types of polyethylene were cold rolled to high reductions in Trials 27 through 34. In Trials 27 and 28, Chemplex 6060 was fluid rolled to a reduction of 5.9:1. The maximum reduction in these trials was limited by both slippage of the tape on the rolls and the onset of melting. Somewhat higher reductions of 6.7:1 and 7.6:1 were achieved in subsequent trials for Marlex EMN6030 and DMBJ7006, respectively, by dry rolling before slipping and melting limitations were encountered. Some modulus values were approximately 2GPa (300,000 psi), which is approximately 50% of the target value for this program.

Future rolling experiments for polypropylene will be made using heated rolls in an effort to achieve higher reductions and produce thinner tape in these materials. The polyethylenes will also be processed with heated rolls to reduce the tendency of these materials to slip on the rolls. Multiple-pass reductions will be considered when longer single-pass reductions produce excessive heat and melting. The use of fluid with heated rolls will be considered only when dry rolling is found unsuitable.

Table 3.3

EXPERIMENTAL ROLLING DATA FOR POLYPROPYLENE AND POLYETHYLENE TAPE

Trial No.	Feed Stock		Rolling Parameters		Measured Tape Parameters				
	Mat ⁽¹⁾	Avg. Thick., min.	Roll Speed, m/min.	Roll Gap Setting, mm	Lub./Coolant System ⁽²⁾	Avg. Thickness, mm	Reduction Ratio	Modulus GPa	Tensile Strength, MPa
20	PP-2	1.02	12	0.38	F1	0.43	2.35:1	1.1	70
21	"	1.02	12	0.25	"	0.31	3.33:1	1.4	106
22	"	1.02	12	0.20	"	0.25	4.00:1	1.6	121
23	"	1.02	25	0.20	"	0.25	4.00:1	1.5	124
24	PP-3	0.97	12	0.51	"	0.51	1.90:1	1.8	113
25	"	0.64 ⁽⁴⁾	6	0.13	"	0.23	4.22:1 ⁽³⁾	2.2	171
26	"	0.64 ⁽⁴⁾	25	0.18	"	0.23	4.22:1 ⁽³⁾	2.0	155
27	PE-1	0.89	12	0.25	"	0.19	4.68:1	-	-
28	"	0.89	25	0.25	"	0.15	5.93:1	-	-
29	PE-2	1.02	6	0.25	None	0.15	6.67:1	2.1	128
30	"	1.02	25	0.25	"	0.15	6.67:1	2.2	167
31	PE-3	0.97	6	0.20	"	0.13	7.60:1	1.3	141
32	"	0.97	12	0.25	"	0.15	6.33:1	2.0	129
33	"	1.02	6.2	0.25	"	0.16	6.70:1	2.6	170
34	"	0.99	6.2	0.20	"	0.13	7.80:1	2.4	160
35	PP-1	0.76	12.4	0.10	F1	0.15	5.00:1	1.6	148
36	"	0.81	3.1	0.00	"	0.18	4.80:1	1.8	142
37	"	0.84	3.1	-0.05	"	0.18	4.70:1	-	-
38	"	0.81	5.1	0.00	"	0.16	5.30:1	1.9	161
39	PP-2	1.02	12.4	0.30	"	0.23	4.40:1	-	-

- (1) PP-1: Marlex HGV-040-01, PE-1: Chemplex 6060
 PP-2: Rexene PP54H5, PE-2: Marlex EMN 6030
 PP-3: Hercules PA954, PE-3: DMBJ 7006

(2) Water-soluble machining oil with rust inhibitor - applied to exit and entry sides of rolls.

(3) Cumulative value.

(4) Rolled from 0.97 mm thickness.

3.2.3. Structure and Dielectric Loss of Polymeric Tapes (NBS, Gaithersburg)

Synopsis. The dielectric loss of three experimental polypropylene tapes (BCLPP # 8, # 10 and # 17) as well as commercial Polypropylene-T film (2 mil thick), has been determined at 100 Hz and 1 kHz in the temperature range 303 K to 323 K. The crystalline orientation in the BCLPP # 8, # 10, and # 17 was examined using wide angle x-ray diffraction. The dielectric loss characteristics of the Polypropylene-T film and of the polypropylene-polyurethane laminates 9-1955-3 (3-ply, green tint, Polypropylene-F layers) and 9-1955-6 (2 ply, red tint, Polypropylene-T layers) were determined between 4 K and 323 K.

3.2.3.1. Crystalline Orientation in Polypropylene Tapes Prepared by Battelle Columbus Laboratories

The crystalline orientation in the three tapes produced at Battelle Laboratories has been examined using wide angle x-ray diffraction. The BCLPP # 8 and # 17 were made from polypropylene homopolymer, the # 10 was made from a propylene-ethylene copolymer. The following salient features were observed. The crystalline regions in all three tapes are predominantly of the α -monoclinic crystalline modification of polypropylene. These regions are mostly uniaxially oriented with the chain molecules (c-axis) preferentially parallel to the machine direction. There is evidence, however, that a very small fraction of the α -monoclinic regions in all three tapes exhibits preferential orientation of the a-axis parallel to the machine direction. There is also distinct evidence of the presence in the BCLPP # 17 of a second, less stable, crystalline phase which exhibits uniaxial orientation (c-axis parallel to the machine direction).

3.2.3.2. Dielectric Loss Measurements at 100 Hz on Polypropylene Tapes and Films Between 303 K and 423 K

The dielectric loss ($\tan \delta$) of the BCLPP # 8, # 10 and # 17 tapes, as well as the Polypropylene-T film was measured at 10 K intervals between 303 K and 423 K. The effect of thermal cycling on $\tan \delta$ was also examined. The following salient features exhibited by the three BCLPP samples may be noted:

- i) $\tan \delta$ first decreased and subsequently increased with increase in temperature above 303 K in all three cases. The temperature corresponding to minimum $\tan \delta$ varied among the different tapes and was also affected by thermal cycling. The minimum in the $\tan \delta$ vs. temperature curves occurred in the temperature range 313 K - 353 K.
- ii) $\tan \delta$ at 303 K for the BCLPP # 8 (as-received) was 397×10^{-6} . The corresponding losses for the BCLPP # 10 and # 17 were 74×10^{-6} and 83×10^{-6} respectively.
- iii) The magnitude of the minimum in $\tan \delta$ exhibited by the three samples in the range 313 K - 353 K was as follows, $(65-76) \times 10^{-6}$ for the BCLPP # 8, $(20-37) \times 10^{-6}$ for the BCLPP # 10, and $(72-75) \times 10^{-6}$ for the BCLPP # 17.

- iv) $\tan \delta$ at all temperature below 393 K did not exceed 572×10^{-6} , 84×10^{-6} and 282×10^{-6} in the case of the BCLPP # 8, # 10, and # 17 respectively, irrespective of the thermal cycles they were subjected to. These figures represent upper bounds for the loss in the temperature range 303 K - 393 K.
- v) The BCLPP # 10 propylene-ethylene copolymer tape exhibited substantially lower dielectric loss than the BCLPP # 8 and # 17 polypropylene tapes over the entire 303 K - 423 K temperature range.
- vi) The data gathered so far indicate that all three tapes are subject to dimensional and dielectrical instabilities when heated at 353 K and at higher temperatures up to 423 K.

$\tan \delta$ for the Polypropylene-T film as-received was 46×10^{-6} at 303 K. The minimum in $\tan \delta$, which occurred at 333-353 K, was $(20-24) \times 10^{-6}$. $\tan \delta$ for that film did not exceed 129×10^{-6} at temperatures below 393 K.

3.2.3.3. Dielectric Properties of Polypropylene-Polyurethane Laminates at Cryogenic Temperatures

Dielectric loss measurements were carried out at 100 Hz and 1 kHz in the range 4.3 K - 323 K on the polypropylene-polyurethane laminate 9-1955-3 (3-ply, green tint, Polypropylene-F layers), the polypropylene-polyurethane laminate 9-1955-6 (2-ply, red tint, Polypropylene-T layers), and the Polypropylene-T film. The data of interest for superconducting cables are listed in Table 3.4. We shall confine ourselves in what ensues to the data obtained at 100 Hz.

$\tan \delta$ at 4.3 K - 10 K for the 9-1955-3 laminate corresponds closely to the loss levels found in the other three 3-ply laminates (9-1955-1, -2, -4) of the 9-1955 series all of which consisted of three layers of Polypropylene-F film. (See Semiannual Report, Oct. 1978-March 1979.) $\tan \delta$, which is in the range $(20-39) \times 10^{-6}$, exhibits the familiar upswing with decrease in temperature from 10 K to 4.3 K, which upswing is due to the antioxidant in the Polypropylene-F layers.

$\tan \delta$ for the 9-1955-6 laminate at 4.3 K - 10 K exhibited by the Polypropylene-T films ($\tan \delta = (5-10) \times 10^{-6}$, see Table 3.4) in the 9-1955-6, as compared to the Polypropylene-F films ($\tan \delta = 23 \times 10^{-6}$ to 32×10^{-6} , see Semiannual Report Oct. 1977 - March 1978), in the 9-1955-3. The slight increase in $\tan \delta$ with decrease in temperature from 10 K to 4.3 K which occurs in both the 9-1955-6 laminate and the Polypropylene-T is much less pronounced than in the case of the 9-1955-3 laminate and the Polypropylene-F. The Polypropylene-T film either contains very little antioxidant or it contains a different antioxidant than that in the Polypropylene-F. Finally, it is significant to note that the Polypropylene-T film exhibits the lowest levels of dielectric loss in the range 4.3 K to 10 K than any polypropylene film or tape we have studied so far.

Table 3.4

Dielectric Loss (Tan δ) of Polypropylene and Polypropylene-Polyurethane Laminates
at Cryogenic Temperatures

	(1)	(2)	(3)
	Polypropylene-Polyurethane Laminate 9-1955-3*	Polypropylene-Polyurethane Laminate 9-1955-6**	Polypropylene-T
	Tan $\delta \times 10^6$	Tan $\delta \times 10^6$	Tan $\delta \times 10^6$
T(K)	100 Hz(1kHz)	100 Hz(1kHz)	100 Hz(1kHz)
4.3	39 (105)	18 (143)	10 (34)
6	30 (83)	15 (33)	7 (27)
8	22 (61)	13 (22)	6 (18)
10	20 (51)	13 (20)	5 (15)

* 9-1955-3, 3-ply, green tint, Polypropylene-F layers.

** 9-1955-6, 2-ply, red tint, Polypropylene-T layers.

3.2.4. Polymer Impregnant Compatibility Studies

The long term chemical compatibilities of BCL-supplied tapes are tested at BNL in two typical cable oils maintained at 100°C. The two impregnants used at present are Amoco L-50E polybutene oil, and Sunoco XX naphthenic oil with 20% aromatic content. Dissolution, swelling, and shrinkage are monitored for total periods of 5000 h. In Table 3.5 compatibility for the three PP samples is shown after immersion time of 1500 h. These samples were rolled to a thickness reduction of approximately 4:1. The data, although preliminary, show trends in the compatibility of mildly oriented PP. The thickness and weight tend to increase and there is an accompanying reduction in tape length. It can be assumed from the data that approximately 50% of the increase in thickness appears to be due to swelling related to oil absorption and the remainder of the thickness change is probably due to partial relaxation and shrinkage of the orientation. The change was largest for Rexene samples and smallest for specimens made from the Hercules product. The effect reaches equilibrium within 1500 h.

3.3. Cable Radiography

Radiographs were taken of commercial cables supplied by Northeast Utilities (NU), Rennselaer Polytechnic Institute (RPI), and Power Technologies Inc. (PTI). Samples were examined with the newly installed "remote cable positioner" shown in Fig. 3.3.

Table 3.5

PERCENT CHANGE IN WEIGHT AND DIMENSION
OF ORIENTED POLYPROPYLENE SAMPLES AFTER 1500 h IN OIL AT 100°C

	PP-1		PP-2		PP-3	
	Phillips Marlex HGV-040-0		Rexene PP54H5		Hercules PA954	
	Amoco	Sunoco	Amoco	Sunoco	Amoco	Sunoco
Weight Change	+8	+8	+25	+26	+6	+7
Thickness Change	+13	+10	+26	+32	+11	+9
Length Change	-11	-9	-10	-11	-7	-7

Figure 3.3. Remotely Operated Positioning Device
for X-ray Analysis.

3.3.1. Northeast Utilities

Northeast Utilities requested that we radiograph a section of 345 kV pipe type cable that was removed from a circuit at the Northfield Mountain generating plant during a recent repair operation. The 12 inch sample was removed from the bottom of an enlarged pipe casing near the trifurcator for the lower terminal. Over a period of time the cable had slid down the inclined pipe and formed an "S" bend in the casing. Radiographs indicated no disturbances in the insulation of this section.

3.3.2. Power Technologies Inc.

BNL is engaged in a cooperative Thermo-mechanical bending study with PTI, in which PTI will perform a series of TMB tests on sections of a 200 ft length of 500 kV rated paper-oil cable purchased from the Pirelli General Cable Corp. Radiographs were taken of a "virgin", three-foot long section of this cable prior to bending. Additional radiographs will be taken following mechanical straining of similar samples.

3.3.3. Rensselaer Polytechnic Institute

Four sections of the new Pirelli 550 kV rated experimental cable were radiographed. This cable employs PPP synthetic tapes as the insulation. All sections examined contained manufacturing related defects such as slip planes, soft spots, and frequent sites of tape migration. Figure 3.4 shows the presence of severe tape migration in one sample, and the cable illustrated in Fig. 3.5 contains a severely damaged area. It may be possible that certain manufacturing related defects contribute to the severity of the subsequent TMB induced cable failure.

3.4. Dielectric Properties of Supercritical Helium Using a Plastic-Coated Gap

Partial discharge inception voltages were measured for a gap between aluminum disk electrodes with rounded edges coated with a polyparaxylylene film of 38 μm thickness. The flat area of the electrodes are 57, 570, and 2600 mm^2 . The gap lengths were varied from zero to 165 μm with a micrometer mounted on the top of the 4 inch cryostat. The gap length was double-checked by measuring the capacitance between electrodes with a capacitance bridge. The error in the measurement of gap length is less than 13 μm (0.5 mil). The partial discharge inception voltages in a mid-void gap of 2 x 2 mm^2 area in three layers of 102 μm polypropylene tapes were also measured. The temperature of helium was controlled near 8 K and the pressure was varied up to 210 psia (15 atmospheres).

Partial discharges were detected with a sensitivity of less than 1 pC with a J. D. Biddle detector. The applied voltage of 60 Hz was raised gradually and lowered rapidly as soon as the detection of partial discharge pulses occurred. The application of voltage was repeated with a minimum rest time of 20 - 30 seconds. In some cases where the repetition interval was only several seconds the inception voltage decreased considerably. As described below, the energy loss due to partial discharges is very small, but the repeated occurrence of the discharges may affect the inception voltage due to the accumulation of heat. The coating film was eventually broken down by repeated discharges.

Figure 3.4. Brookhaven National Laboratory Power Transmission Project Radiograph of 550 KV Cable No. XR-1 Taken 6" Right of Cable Center, Before Bending. July, 1979

Figure 3.5. Brookhaven National Laboratory Power Transmission Project Radiograph of 550 KV Cable No. XR-2 Taken of Damaged Area, Before Bending. July, 1979

The partial discharge inception voltage across the gap is calculated by Eq. (3.1):

$$v = \frac{V}{1 + \frac{t}{\epsilon d}} \quad (3.1)$$

where

v = voltage across gap

V = applied voltage

d = gap length

t = coating thickness

ϵ = relative dielectric constant of the coating insulation

The inception voltages are shown in Fig. 3.6 as Paschen's plot with the abscissa given as the product of helium density and gap length. The plots for the electrodes of 2550 and 570 mm² area correspond well with Paschen's law, and are distributed along a line slightly lower than the metal gap curve found by Meats (CERL) but are consistent with the plots of short cable samples shown in Fig. 3.7. However, the plots for the electrode of 57 mm² area are scattered upwards and the threshold levels coincide with the level of larger electrodes. The plots for the mid-void gap are similar to that of 57 mm² area electrode but lower than that of the threshold level of void gaps found by Meats, whose plots are scattered as shown in Fig. 3.6. The above results suggest an area effect for electrodes on the discharge voltage of a gap.

The area effect comes from the lowering of the discharge voltage by the roughness, the irregularity, or the adhering of small dust particles on the surface of an electrode. The probability of the presence of such weak points is proportional to the area of electrode. In an electrode of small area the discharge inception voltages are scattered owing to a low probability of occurrence of a weak point, but in an electrode of large area the discharge inception voltages are gathered near a threshold level.

On the surface of the plastic coating there are many micro-protrusions of the several μm , which disturb appreciably the stress distribution in a short gap. A more serious problem is the presence of dust particles adhering to the electrode. It is difficult to completely remove dust particles from the gap. Dust particles were usually observed by irradiating a light through the gap after set up of the electrodes.

The magnitude of the partial discharges is 10 - 100 pC at the inception voltage and rapidly increases above 1000 pC with a small increase in applied voltage. Assuming that the whole area S of the gap discharges instantaneously from the inception voltage v to zero voltage, the theoretical discharge magnitude:

$$q = \frac{1}{2} CSV \quad (3.2)$$

Figure 3.6. Paschens Plot of Partial Discharge Inception Voltages in a Gap Between Insulation Coated Electrodes.

Figure 3.7. Paschens Plot of Partial Discharge Inception Voltages in the Butt Gaps of Coaxial Lapped Plastic Insulation Samples.

where C is the capacitance of a plastic coating per unit area. This yields a value of q of more than 10,000 pC, even for the smallest 57 mm² electrode. From this fact, it is thought that partial discharges start from a small area less than 1 mm² and extend rapidly to a wider area with an increase in applied voltage.

In the short cable sample, the magnitude q of partial discharge at the inception voltage is less than 1 pC. This value corresponds to a discharging area S less than 0.005 mm² from the equation based on Eq. 3.3.

$$S = q/v \epsilon \epsilon_0 / d \quad (3.3)$$

where v is the discharge inception voltage across the gap (5 kV peak), $\epsilon \epsilon_0$ is the permittivity ($2.2 \times 8.85 \times 10^{-10}$ F/m) of insulation of thickness d (0.5 mm). That means again the partial discharge occurred over a small portion of the butt gap.

In an air gap located within homogeneous insulation, it is known that the partial discharge inception stress is the same as the breakdown stress between metal electrodes. At the inception of partial discharges the charges are deposited on the insulation surface. The electric stress in the gap is decreased rapidly by the counter stress due to the surface charges, and the discharge extinguishes within a hundred nano-seconds. Thus the partial discharge is suppressed to a very faint discharge located at a small area having the lowest inception voltage. However, with the increase of applied voltage, the radiation of light and electrons occur in a wide area at the same time.

The local temperature rise at the partial discharge point may be calculated by considering the energy loss, U, caused by the complete discharge of a volume with capacitance, C. Based on a helium heat capacity of 0.7 J/cm³-K the volume of the gap, 10⁻³m³, at a density of 110 kg/m³ will raise the temperature about 10⁻² K. At a supply frequencies of 60 Hz the rate of rise in an adiabatic situation is about 1 K/g. Although heat is transferred from the discharge site the temperature rise will decrease the helium density which may reduce the partial discharge inception level.

3.5. Short Sample Tests

A new polypropylene tape produced by Bordon Toyoba was tested to evaluate its loss characteristic and impulse strength. Table 3.6 gives the details of sample construction and summarizes test results. Sample 79-4 was constructed from sample 97-3 by replacing the outer screens and adding additional layers of polyethylene wound over the outer screen termination edge to relieve the electric stress at the screen edge.

Figure 3.8 shows the loss data for sample 79-4 as a function of density and electric stress. The discharge inception voltage levels shown in Fig. 3.8 are low and can be attributed to the split screen design necessary for loss measurement.

Table 3.6

Short Sample Results for Borden Toyobo Polypropylene
Sample Nos. 79-3 and 79-4

Construction Details:

- 5 Layers of 4 mil polypropylene (2 ply laminate)
- No center conductor screen
- One layer of cryovac over top butt spaces
- Al intercalated valeron screen over outer layer of dielectric
- Metal laminate (Kapton) over screen
- Split screen design to permit loss measurements

	SF ₆ (100 psia)		He (100 kg/m ³)	
Sample No.	79-3	79-4	79-3	79-4
Loss (tan δ) at 10 MV/mm	-	74x10 ⁻⁵	1.7x10 ⁻⁵	2.1x10 ⁻⁵
Impulse Strength	-		>166 kV/mm	Between 148.3 kV/mm and 159.4 kV/mm
Failure Mode	-		Surface flash-over from end of screen to center conductor	Near center of test sample, B.D. path included one (1) butt gap

Figure 3.8. Tan δ as a Function of Helium Density and Electric Stress for Polypropylene Coaxial Sample.

3.6. Development of New Partial Discharge Measuring Techniques

3.6.1. Detection of Partial Discharges with a Bridge Circuit

A bridge balance circuit has been developed to reduce the effect of external noises on partial discharge measurements for the General Cable test. The detection circuit is shown in Fig. 3.9. External noise and corona discharges in the high voltage bushing or HV connection cause pulse voltages of the same polarity at both detection impedances L_d and L'_d . The output of the differential transformer has a high frequency transient component as shown in Fig. 3.10. A low pass filter composed of a 10 mH inductor and a 0.01 μ F capacitor is used to further reduce the effects of external noise. The variations of output pulse amplitudes as a function of the setting of the resistance divider R_d are shown in Fig. 3.11. At the balance point external noise including corona discharges at the bushing can be distinguished by the difference in the variation of amplitude with the adjustment of R_d .

Test results for the General Cable H.V. test cable are shown in Fig. 3.12. In conventional detection circuits, the external noise sometimes exceeded 100 pC, but in the bridge detection circuit external noise was suppressed below 10 pC and the inception of internal discharges of several pC were clearly detected. Moreover, very large pulses starting at 64 kV were identified as external corona discharges, which probably occurred in the bushing. This was deduced by observing the variation of amplitude with the adjustment of R_d .

3.6.2. Location of Partial Discharge by Time Domain Reflectometry

The location of partial discharges, that is identifying the discharge points in a test cable, is essential for the voltage endurance test. The voltage change, v , on the conductor of cable caused by a partial discharge of q (pC) is expressed as follows:

$$v = qZ/\tau \quad (3.4)$$

where Z is the surge impedance of the cable and τ is the time duration of the partial discharge. The voltage change begins to travel in both directions (left and right) from the origin as two pulses of halved amplitude as shown in Fig. 3.13. The detected pulse V_d is twice the original traveling pulse amplitude due to reflection at cable end, therefore, V_d equals v .

If $q = 10$ pC,

$\tau = 10 - 100$ ns,

$z = 15 \Omega$,

then V_d is 1.5 to 15 mV, which is detectable with an oscilloscope.

The principle of location by traveling pulses is shown in Fig. 3.14. Serial reflected pulses follow after the direct traveling pulse. From the time difference between pulses, the distance x of discharge point from the cable end is calculated as follows:

Figure 3.9. Partial Discharge Detection Circuit Using a Balanced Bridge

Figure 3.10. Output Pulse Wave of Differential Transformer

Figure 3.11. Variation of Output Pulse Amplitude as a Function of Setting of Rd.

Figure 3.12. Partial Discharge Test Results for H.V. Test Cable Using Both Conventional and Bridge Circuits.

Figure 3.13. Traveling and Reflection of Partial Discharge Pulse in a Cable.

Figure 3.14. Principle of Location of Partial Discharge by Traveling Pulses.

$$x = \frac{\text{Time difference between 2nd and 3rd pulses}}{\text{Time difference between 1st and 3rd pulses}} \times \text{Cable Length} \quad (3.5)$$

The time difference between 1st and 3rd pulses corresponds to the return traveling time in the whole cable; approximately 1.2 μ s for a 100 meter cable.

Figure 3.15 shows test results for the 12 meter HV test cable simulating partial discharges at cable ends by means of injecting known charges from a pulse generator. Traveling pulse amplitudes corresponded well with the predictions of Eq. 3.4, but the distortion of pulse by a transient component made the reflected pulses a little unclear. However, in a 100 meter superconducting cable the reflected pulses may be readily distinguished because of the long traveling time compared with the pulse duration time and the low traveling loss in superconducting cable. The resolution of the time difference between pulses may be 0.02 μ s, which corresponds to the resolution of a cable distance equal to 1.6 meters.

3.6.3. Detection of Partial Discharge During Life Test at High Frequency Voltage

It is important to measure partial discharges during the high frequency life test. A conventional discharge detector amplifies the high frequency component from the ac power supply along with the partial discharge pulses, therefore, the high frequency component must be eliminating by filtering.

Figure 3.16 shows the circuit designed to permit separation of the partial discharges from the H.F. source. The first three LC filter sections attenuate the source frequency of 8 kHz by factor of 5×10^{-4} . The 3rd harmonic of the source is filtered by the next LC stage. With this arrangement a total attenuation factor of 5×10^{-5} is achieved. The rejection range of the filter is 7.9 ± 0.4 kHz for 6 db attenuation.

When the source is at 5 kV, the attenuated high frequency source component that is detected corresponds to a detected partial discharge equal to 60 pC. The minimum detected partial discharge magnitude is about 10 pC.

3.7. High Voltage Cable Tests

A polyethylene section of the General Cable test cable was cooled down in the 20 m enclosure and partial discharge inception stress, loss angles and impulse withstand were measured at helium temperature.

This cryogenic test attempted for the first time the follow:

- a) Cooling of a cryogenic cable using counterflow with "far end" expansion.
- b) Cryogenic test of 7.62 mm insulation wall thickness (previous maximum thickness was 2.54 mm).
- c) Evaluation of conductive conductor bedding layer between conductors and insulation screen.
- d) Fixed anchoring of cable ends during cooldown.

Refrigeration difficulties never permitted anticipated operating density of 100 kg/m³ to be reached. However, useful data was obtained at different densities during cooldown. Figure 3.17 is derived from these data and gives the loss angle ($\tan \delta$) as a function of helium density and stress. The cable was impulsed 10 times at a stress of 20.3 kV/mm. The loss curve that is plotted at a density of 68.4 kg/m³ (Fig. 3.17) was recorded after this impulse test.

Partial discharge measurements were difficult due to the presence of high background electrical interference. A bridge measuring technique was tried and indicated cable partial discharges occurred at 8.43 kV/mm with the helium density at 80.2 kg/m³. It is planned to repeat the experiment in the near future; every effort will be made to achieve a higher He density.

Figure 3.15. Traveling Pulses in the 12 m H.V. Test Cable.
Upper: 25 pC Injected Into Cable at Detection End.
End: 25 pC Injected Into Cable at Far End.

Figure 3.17. Loss Angle as a Function of Stress and Helium Density for 20 Meter Cable.

Figure 3.16. Partial Discharge Detection Circuit Used for High Frequency Life Test.

4. Mechanical Engineering and Facilities

4.1. BNL Taping Line

The existing Pirelli machine was converted to a superconductor tape winding machine, and it was relocated directly on the main Trafalgar taping line. The Gatto core tension puller was also installed on the main line and it was modified for back tension use. This equipment is now ready for initial operation.

Four Maillefer used taping heads were purchased and delivered to the BNL winding facility. These machines will be re-tooled for superconductor and stabilizer tape winding operations in the new wing. The dielectric tape re-winder was updated and modified for high production work and placed in operation. Both a metal tape re-winder and an instrumentation cable winding machine were designed and built. Also fabricated was a custom 1000 ft long cable consisting of 30 pairs of shielded cables for 5th Ave computer operations. Parts for the entire Trafalgar machine were ordered including: cable bushings, pad arms, tension rollers, and hysteresis tensioning devices.

The extension to the winding room and Building 820 (new wing) is currently going out for construction bids, after plant engineering completed its detailed design work. In-house work on the new expanded facility includes the cleaning and painting of the remaining 5 Trafalgar sections - preparing them for installation. New wing machine parts on order include drive chains, main roll-up guards, motor drive system, and a second Gatto core tension puller.

Cable # 103 has been in production during this period, at present the outer conductor is being laid.

4.2. Cable Tests

4.2.1. Cable # 102 Tests

Cable # 102 was cooled and operated at temperature with current twice during this period. The total time at temperature was 20 days during which electrical and cryogenic data were taken, see Section 2.4.4. As stated in the last report, efforts to verify the loss data obtained from the electronic wattmeter by calorimetric measurement were to be continued on this cable.

4.2.1.1. Cable # 102 Experimental Arrangement

Figure 4.1 is a flow and instrumentation schematic of the test installation. High-pressure helium enters the west box, passing through the cable core and through the superconductor transformer existing at point 8. The electrical heater is used to raise the helium temperature at point 9 enough to ensure that liquid is not formed following expansion through the J-T valve or expansion engine. The test cable is enclosed by a 5 cm stainless steel tube which forms the high-pressure shell for the cable. The low-pressure helium,

Figure 4.1. Flow and Instrumentation Schematic.

following expansion, passes from the east box to the west box through an annulus formed by the 5 cm tube containing the cable and the 10 cm tube which is the inner wall of the cryogenic enclosure. This low-pressure helium then returns to the refrigerator. In operation, the cable and its enclosures form the final heat exchanger of the refrigerator, with heat generated within the cable flowing to either the high- or low-pressure stream, depending upon which is lower in temperature. The heat influx through the enclosure insulation flows to the low-pressure stream. In this arrangement the cable, and its enclosure becomes a counterflow heat exchanger with internal heat generation.

Temperature sensors 2 through 7 are located in the cable core in the high-pressure flow. Sensors 11 through 16 are in the annulus of the low-pressure return flow, and sensors 15 through 18 measure the temperature of the static high-pressure helium on the outside of the cable. The rest of the temperature sensors are located inside the high- and low-pressure piping. Pressure sensors and orifice-type flow meters are placed so that the mass flow and thermodynamic properties of the helium streams can be determined. The temperature sensors are connected to a mini-computer that measures the resistance and converts it to temperature in Kelvin which is then printed out as shown in Fig. 4.2. The mini-computer also continuously samples temperature sensor 13 and raises or lowers the heater current to maintain this temperature constant at $7.25^{\circ} \pm 0.03^{\circ} \text{ K}$. This value and the sensor to be used were determined experimentally in order to maintain the temperature through the length of the cable as constant as possible without current on the cable.

4.2.1.2. Experimental Procedure

In order to establish a base line or static heat leak condition, the refrigeration rate was set by adjusting all of the refrigerator operating parameters with the trim heater controlled by the computer. The system was allowed to run for up to 24 hours without current on the cable, until temperature stability was reached. This was repeated a number of times during the two-week test. The same procedure was followed when current was applied to the cable, except that no changes were made on the refrigerator settings. Only the trim heater varied, and this was done by the computer to hold temperature 13 at the predetermined value. During tests with current on the cable, the system was allowed to operate until stability was reached. In one test the current was held at 500 rms A/cm for a period of 75 hours. Tests were made at 300, 400, 500 and 570 rms A/cm, with resulting data recorded for analysis.

Figure 4.2 shows the temperature data with no current on the cable (note heater power of 44.80 watts). Figure 4.3 is the same data plotted by the computer as a temperature profile for the test section. Figure 4.4 is the temperature data taken with 500 rms A/cm on the cable, and Fig. 4.5 is the corresponding temperature profile plot. The heater power at this condition has been reduced to 35.97 watts in order to maintain the temperature at point 13 within the pre-set limits.

08:00:00

#	Ch	ID	Location	I (uA)	R (ohms)	T (kelvin)
15	LSC	#16 570	hi pres, He in from refriger	50.011	533.35	7.120
46	CryoCal	#6984	int core, 12.19 m (at W end)	50.088	457.04	7.191
45	CryoCal	#6412	int core, 10.97 m	50.096	464.97	7.194
44	CryoCal	#6283	int core, 7.75 m	50.086	479.81	7.187
43	CryoCal	#6942	int core, 4.52 m	50.086	462.77	7.201
42	CryoCal	#7272	int core, 1.30 m	50.082	401.64	7.202
41	CryoCal	#6973	int core, 0.15 m (east end)	50.079	464.58	7.204
33	LSC	#16 035	xmfr out, east end box	20.019	545.14	7.521
31	LSC	#16 588	xmfr, aft heater, b4 exp eng	20.019	262.60	9.798
32	LSC	#16 478	after expansion engine	20.019	420.99	7.565
21	LSC	#16 436	outside ss can, 0.15 m (east)	19.999	467.67	7.208
22	LSC	#16 216	outside ss can, 1.30 m	19.999	541.25	7.205
23	LSC	#16 280	outside ss can, 4.52 m	20.001	457.74	7.212
24	LSC	#16 193	outside ss can, 7.75 m	19.998	518.20	7.233
25	LSC	#16 287	outside ss can, 10.97 m	19.999	433.68	7.264
26	LSC	#16 285	outside ss can, 12.19 m	19.999	394.95	7.261
16	LSC	#16 571	low pres rtn to refriger	50.015	445.76	7.647
11	CryoCal	#6879	ext cable, 1.30 m from east	50.019	477.16	7.206
12	CryoCal	#6936	ext cable, 4.52 m from east	50.018	422.44	7.227
13	CryoCal	#6889	ext cable, 7.75 m from east	50.017	424.40	7.198
14	CryoCal	#6876	ext cable, 10.97 m from east	50.019	505.19	7.205

Figure 4.2. Steady State Temperatures, no Current in Cable.

Figure 4.3. Computer Plot of Temperature Distribution in Cable #102; no Current in Cable.

13 Jun 79
Heater Power = 35.97 watts. 09:00:00

#	Ch	ID	Location	I (uA)	R (ohms)	T (kel)
1	15	LSC #16 570	hi pres, He in from refriger	50.016	524.27	7.178
2	46	CryoCal #6984	int core, 12.19 m (at W end)	50.090	446.90	7.261
3	45	CryoCal #6412	int core, 10.97 m	50.098	450.40	7.294
4	44	CryoCal #6283	int core, 7.75 m	50.091	454.44	7.366
5	43	CryoCal #6942	int core, 4.52 m	50.089	429.75	7.431
6	42	CryoCal #7272	int core, 1.30 m	50.089	364.51	7.468
7	41	CryoCal #6973	int core, 0.15 m (east end)	50.090	425.60	7.487
8	33	LSC #16 035	xmfr out, east end box	20.022	459.49	8.181
9	31	LSC #16 588	xmfr, aft heater, b4 exp eng	20.023	255.84	9.908
10	32	LSC #16 478	after expansion engine	20.022	425.50	7.529
11	21	LSC #16 436	outside ss can, 0.15 m (east)	20.002	464.32	7.234
12	22	LSC #16 216	outside ss can, 1.30 m	20.001	533.00	7.260
13	23	LSC #16 280	outside ss can, 4.52 m	20.001	446.87	7.285
14	24	LSC #16 193	outside ss can, 7.75 m	20.002	507.54	7.310
15	25	LSC #16 287	outside ss can, 10.97 m	20.001	422.76	7.343
16	26	LSC #16 285	outside ss can, 12.19 m	20.001	385.73	7.333
17	16	LSC #16 571	low pres rtn to refriger	50.022	441.89	7.677
18	11	CryoCal #6879	ext cable, 1.30 m from east	50.022	462.38	7.303
19	12	CryoCal #6936	ext cable, 4.52 m from east	50.019	407.94	7.324
20	13	CryoCal #6889	ext cable, 7.75 m from east	50.019	407.99	7.307
21	14	CryoCal #6876	ext cable, 10.97 m from east	50.021	492.58	7.284

Figure 4.4. Temperatures With 500 rms A/cm on Cable.

Figure 4.5. Computer Plot of Temperature Distribution in Cable #102; Cable Current - 4000 A.

4.2.1.3. Analysis of Data and Results

From the recorded temperature and pressure data, the enthalpies at all points and the densities, where required, were determined, using the computer functions developed by Arp.* The mass flow was calculated from the data for flow meters FM-1 and FM-2 and also from the relationship:

$$\dot{m} = \frac{Q_H}{h_9 - h_8} \quad (4.1)$$

where:

Q_H = trim heater power in watts

h_8 and h_9 are the enthalpies before and after the heater.

While making these calculations it was determined that the temperature at point 10, as recorded, was incorrect. Since all of the tests were run using the Joule-Thomson (J-T) valve, the enthalpy at 10 is required to be equal to the enthalpy at 9 because of isenthalpic expansion. Using the constant enthalpy relationship, a new temperature and density were calculated for each set of data and then these values were used in calculating the mass flow at FM-1 and subsequent heat balances. The three mass flows calculated were within good experimental agreement and it was decided to use the value calculated by the heater balance because it fell between those of the two flow meters.

It is obvious that a great number of heat balances could be made from the data available, and quite a few were tried. The one presented here was selected because it gave the most consistent static loss results.

To find the electrically produced losses it is necessary to establish the static losses, which are then subtracted from the total losses found with current on the cable. The following relationships were used:

$$Q_{HL} = \dot{m} (h_7 + h_{17} - h_1 - h_{10}) \text{ heat leak, watts} \quad (4.2)$$

$$Q_T = \dot{m} (h_7 + h_{17} - h_1 - h_{10}) \text{ heat leak, watts} \quad (4.3)$$

$$Q_E = Q_T - Q_{HL} \text{ current-induced heat, watts} \quad (4.4)$$

The heat leak, Q_{HL} , was calculated for a number of sets of data taken over a period of two weeks and the arithmetic average, 10.516 watts, used to calculate the electrical losses Q_E . Figure 4.6 shows the results of these calculations plotted against the current density. The upper curve was drawn using the calorimetric measurements, which the lower curve is from the electronic wattmeter. The slopes of the two curves are very nearly identical, with the calorimetric measurements a factor of 1.52 - 1.56 higher than the wattmeter measurements.

It would be very difficult to say that the wattmeter readings are in error from these data. The shorted end is included in both measurements. The losses in the transformer connection are not included in the wattmeter measurements, but it is possible that these losses are included in the calorimetric measurement, as well as some conduction losses through the connection because of heat generated in the transformer.

* Arp, V., "New Forms of State Equations for Helium," Cryogenic 14, 593, Nov. 1974).

Figure 4.6.

4.2.2. H.V. Dielectric Cable Test

4.2.2.1. Test Installation

The first test cable, wound by General Cable Corporation has now been installed in the cable test enclosure and cooled to below 10.5 K. A preliminary voltage test has been performed, see Section 3.7.

To prepare the cable for this test, it was removed from its storage reel and cut to length 18.9 m (61' - 9"). End fittings were attached to the inner core and phenolic spacers were clamped to the outside of the cable to center it in the enclosure. The cable assembly was then hand carried across the street and pulled into the test enclosure. The mechanical and electrical components of the cable itself had all been previously assembled in bench tests using short sample cables. These components included the lead jacket seal, the outer conductor termination and the end attachment to the core and inner conductor. Due to these previous "practice" runs, these parts of the cable were assembled with few difficulties. In particular, the lead jacket seal, which separates the high pressure helium from the lower pressure return flow had been extensively assembled and tested at NBS, Boulder as well as at BNL. Outboard of the lead terminations the simulated outer conductor was terminated over an epoxy glass cone. This cone brings the conducting tapes far enough away from the dielectric insulation to permit soldering. These conductors terminate in a metal flange, and for this voltage test, only a shielded instrument wire was brought out. Figure 4.7 is an end view showing the lead jacket seal, the outer conductor flange and the hand applied stress cone. Figure 4.8 shows the cable end attached to the Westinghouse Bushing. A cylindrical voltage shield was installed over this bolted connection. At the outer end, the cable inner conductor and core were attached to a bore metal tube, with an elliptical end cap. This tube was centrally supported from the grounded copper pressure vessel by an epoxy-glass disc. Thus the cable was anchored at both ends against axial motion. The voltage test apparatus and cable assembly are shown in a section view in Fig. 4.9. A schematic helium flow diagram with temperature, pressure and flow instrumentation is shown in Fig. 4.10.

4.2.2.2. First Cooldown

Cooldown of the system proceeded smoothly down to about 20 K. At this point one of the far-end piston expansion engines failed due to a faulty valve. The second smaller expansion engine repeatedly stopped running and had to be restarted. This made continuous operations very difficult, as we were not prepared for shift operations. Nevertheless, the system was maintained between about 20 K and 10 K for approximately one week. The cable was cooled to 8.5 K except at the bushing end where the temperature stayed above 10 K. Changing the flow rate of the bushing cooling gas did not seem to change this condition, Fig. 4.11 shows an example of conditions achieved. The run was terminated when the helium bleed line for bushing cooling developed a gross leak inside the SF₆ insulated air entrance bushing enclosure.

Figure 4.7. Cable Termination - Lead Seal, Outer Conductor
& Stress Cone.

Figure 4.8. Cable Attached to Westinghouse Bushing.

Figure 4.9. Section of H.V. Test Apparatus Showing Both Ends.

Figure 4.10. Helium Schematic With Instrumentation.

Figure 4.11 Computer Schematic of Temperatures in the HV Test Apparatus

Although the desired temperature of 6 - 8 K was not achieved the test can be considered reasonably successful for the first cooldown attempt. This test is significant because all of the components in this test apparatus are scale models of the 5th Avenue termination. When repairs to the expansion engines and leaks are completed, a second cooldown test of this cable will be made.

4.3. Analysis of Cable Bending on Superconducting Tapes

Careful dissection of some model cables after bending indicates incipient wrinkling or buckling of the superconducting tapes.

The strains, both extension and shear, imposed on the tape by bending the cable have been calculated. They exceed permissible limits if the tape does not shift within the cable during bending. The resulting stresses on the tape will depend on the amount of shifting permitted by the friction forces between cable layers. Because the integrity of the superconductors can be threatened, experimental measurements of tape shift and possible modifications of cable construction may be required.

4.3.1. Analysis of Bending Geometry

It is assumed each strand of superconductor in the cable consists of a flat tape wound as a uniform helix at about 45° to the length of the cable, y . Let helix H in Fig. 4.12 be the center line of the superconducting tape lying on the surface of a circular cylinder of radius r which represents the substrate on which the tape is wound during construction of the cable. Denote the steepness of the helical curve H by the angle ϕ which it makes with the circumferential distance $x = r\theta$ around the cylinder.

When the axis of the cable is bent to a radius R , the cylinder becomes part of a torus and the curve H is the curve in Fig. 4.12 becomes the curve H on the torus as shown in Fig. 4.13.

If we assume that lengths along the axis y of the cable remain unchanged during bending and that circular sections of the cable remain circles of radius r centered on the axis and with planes normal to the axis, then the elements z of the original cylinder become circles z of radius $R + r \cos \theta$ where θ is the azimuthal angle of the helix around the axis at each section as shown in Fig. 4.12. Thus the increments along y and z bear the relation:

$$g(\theta) = \frac{dz}{dy} = \frac{R + r \cos \theta}{R} = 1 + \rho \cos \theta \quad (4.5)$$

to each other, where the parameter ρ is given by:

$$\rho = \frac{r}{R} \quad (4.6)$$

and thus ρ specifies the degree of bending of the cable. Typically, if superconducting tape is wound at 2 ins diameter in the cable and the cable is then wound on a

Figure 4.12. Coordinate System of Helical Tape Wound on a Straight Cylinder.

Figure 4.13. Situation When Cylinder Become a Torus Due to Bending.

100 in diameter drum, $\rho \approx 0.02$; or, if the cable is bent on a 50 in diameter mandrel, $\rho \approx 0.04$.

In going from cylinder to torus the strain in the surface of the torus is a pure extension e in the z directions. The strain components are, therefore,

$$e_x = 0 \quad (4.7)$$

$$e = e_z = \frac{dz}{dy} - 1 = g - 1 = \rho \cos \theta \leq 0.04 \quad (4.8)$$

$$\gamma_{xz} = 0 = \text{shear strain} \quad (4.9)$$

Referred to new axes s and t taken along and transverse to the curve H this strain system at each point of the torus surface has the components

$$e_s = \frac{1}{2} e (1 - \cos 2\theta) = e \sin^2 \theta \quad (4.10)$$

$$e_t = \frac{1}{2} e (1 + \cos 2\theta) = e \cos^2 \theta \quad (4.11)$$

$$\gamma_{st} = e \sin 2\theta = 2e \sin \theta \cos \theta \quad (4.12)$$

where θ is the angle the curve makes with the x direction. Note that for $\theta = 0$ s and t go over into the x and z axes.

For a 45° helix the strains are

$$e_s = e_t = \frac{1}{2} e \leq 0.02 \quad (4.13)$$

$$\gamma_{st} = e \leq 0.04 \quad (4.14)$$

These strains would be transferred to the superconducting tape only if the tape is completely bound to the torus surface. In that case, e_s , for example, would easily exceed some permissible strain, say ± 0.002 , by an order of magnitude.

To avoid this threat the tape must be able to shift sufficiently within the cable during bending.

It is plausible to assume that, if the tape slips when the cable is bent, the points at the inside and outside of the bend will not slip because symmetrical forces act. Thus the points R in Fig. 4.13 where $\theta = \pm n\pi$, $n = 0, 1, 2 \dots$, will be nodes of the motion, and the tape will tend to shift between nodes to reduce and equalize the strain.

The length of the helix in Fig. 4.12 from $\theta = 0$ to $\theta = \pi$ is, where $\theta_0 = \text{constant steepness angle}$:

$$s_0 = \frac{\pi r}{\cos \theta_0} \quad (4.15)$$

The corresponding length of the trace H in Fig. 4.13 can be shown to be:

$$s_1 = \frac{\pi r}{\cos \theta_0} \left[1 + \frac{\rho^2}{16} \sin^2 2\theta_0 + \dots \right] \quad (4.16)$$

Hence, if the tape slips lengthwise only, without friction the mean strain is

$$\bar{\epsilon}_s = \frac{s_1}{s_0} - 1 = \frac{\rho^2}{16} \sin^2 2\theta_0 \quad (4.17)$$

or for $\theta_0 = 45^\circ$, $\bar{\epsilon}_s = \frac{\rho^2}{16} < 0.001$ for $\rho < 0.04$, which would be acceptably below the 0.002 limit postulated above. With friction, however, the strain cannot equalize completely along half period of H.

If the tape slips within the cable it would shift both laterally and longitudinally toward the shortest curve or geodesic G in Fig. 4.13 on the torus between the nodes at $\theta = 0$ and π

4.3.2. Length of the Geodesic

The length s_2 of the geodesic G in Fig. 4.13 compared to s_0 for $\theta_0 = 45^\circ$ can be shown to be

$$\frac{s_2}{s_0} = 1 - \frac{1}{2} \rho^2 + \dots \quad (4.18)$$

so that the geodesic is actually shorter than the original uniform helix on the cylinder before the cable is bent. With even the slightest friction the tape would not shift completely to the geodesic and in the actual case probably not even far enough to relieve all lengthwise strain.

The ideal geodesic is the curve having no curvature in the surface of the torus. Therefore, in the actual cable with friction the centerline of the shifted tape would retain some curvature in the torus surface. For a tape of finite width this implies more tension at one edge and less at the other with a resulting tendency to wrinkling at the inside or compression edge.

Another way of picturing this effect is as follows:

The first order shear strain calculation gave $\gamma_{st} = \rho \cos \theta$ for the unshifted trace helix H; this varies from $+\rho$ to $-\rho$ as θ increases from 0° to 180° . Some of this shear variation would be retained in the shifted tape with friction.

The metal taps will resist having the shear $\gamma_{st} = \rho \cos \theta$ imposed on it when the cable is bent, thus promoting the slippage against friction. A quantitative picture of the angles involved can be obtained by calculating the amount by which the steepness angles θ_1 for H and θ_2 for G in Fig. 4.13 deviate from the original $\theta_0 = 45^\circ$ in Fig. 4.12 when the cable is bent.

For this case

$$\tan \phi_1 = 1 + \rho \cos \theta = 1 + \gamma_{st} \quad (4.19)$$

$$\tan \phi_2 = \frac{1 - 2\rho^2 + \dots}{\sqrt{2} (1 + \rho \cos \theta)} \quad (4.20)$$

The results are summarized in Table 4.1.

Table 4.1
Changes in Taping Angle During Bending

<u>Position</u>	<u>$\rho = 0.02$</u>	<u>$\rho = 0.04$</u>
Outside Bend, $\theta = 0^\circ$	$\phi_1 = 45.467^\circ$	$\phi_1 = 46.123^\circ$
	$\phi_2 = 43.843^\circ$	$\phi_2 = 42.667^\circ$
	$\phi_2 - \phi_1 = -1.724^\circ$	$\phi_2 - \phi_1 = -3.456^\circ$
Inside Bend, $\theta = 180^\circ$	$\phi_1 = 44.421^\circ$	$\phi_1 = 43.831^\circ$
	$\phi_2 = 46.134^\circ$	$\phi_2 = 47.241^\circ$
	$\phi_2 - \phi_1 = 1.713^\circ$	$\phi_2 - \phi_1 = 3.410^\circ$

4.4. Cable Terminations and Enclosures

4.4.1. Low Temperature H.V. Feedthrough Bushings

Two more bushings, No. A4 and No. A5 were delivered by Alto Development Corporation. Both of these appeared to be in excellent condition but both bushings cracked during assembly. Part No. A4 cracked at one end cone while being removed from the ambient temperature voltage test fixture. The end cone was shortened by remachining, but the bushing cracked a second time while end fittings were being welded to the inner conductor tube. Rapid expansion due to heating of this tube caused the surrounding epoxy to crack.

Bushing A5 cracked while it was being prepared for a warm voltage test. A red penetrating dye was applied to one crack and soon appeared in a crack on the opposite side. See Fig. 4.14. The cause of this failure is now known but Mr. Alex Wojciechowicz of Alto Development Corporation did state that these large castings can have very high residual stresses even after prolonged

curing at elevated temperature. Alto will alter the epoxy ingredients and the curing cycle to make the castings less brittle. The end fittings for the inner conductor have been modified so that these can be bolted on without welding. Alto has now delivered two more castings, A6 and A7. Both of these have now been finished and the external heat exchanger tubing has been epoxied in place.

Westinghouse Electric Corp, has delivered their second casting W-2. None of the above new bushings have yet been tested but they all appear to be in excellent condition.

4.4.2. Horizontal Current Leads

The first set of horizontal current leads has now been assembled and is being instrumented for a current test in liquid helium. The assembly is shown in the photograph Fig. 4.15. This test will be performed in the dewar previously used for fault current testing of one meter cables.

The problem of soldering the superconductor strips to the cold ends of the conductors has now been solved. Many of the difficulties encountered in the soldering of the early current leads was due to poor quality plating. After being soldered in an oven, portions of the superconductor strips always seemed to peel off because the plating did not adhere to the aluminum conductor.

Several combinations of plating materials were tried. These included copper on aluminum, copper on nickel, tin on nickel, solder on nickel and gold on nickel. This last combination appears to give the most consistent and reliable results. Although the gold layer is very thin (2.5×10^{-4} mm) it is unaffected by oven temperature or solder flux. Two sets of current leads have now been plated successfully and superconductor strips have been soldered in place. The first set was cast with epoxy resin and the second set is ready for casting.

The outer conductor has been re-designed. In the original design, the outer conductor tube was formed of spirally wound and continuously brazed heat exchanger tubing. For the larger diameter this tube is marginal for the hoop stresses induced by the internal pressure. The new design uses a 8.9 cm ($3\frac{1}{2}$ ") outside diameter tube with a spirally wound rectangular heat exchanger tube brazed to the outer surface. The outer conductor tube is a 6061 aluminum alloy, with a cross sectional area of 12.6 cm^2 (1.95 in^2).

4.4.3. High Current and Voltage Bushing

A pair of 4 kA current leads have been designed to fit the existing Alto bushing mold. These current leads are not expected to effect the high voltage performance of the bushing since the basic geometry and the voltage screen surfaces remain unchanged. The Alto mold consists of two conical end sections and a center portion that is split axially into two halves for removal after casting. The high current bushing will be cast with

Figure 4.14. Cracks in the Epoxy Casting Part No. A5.

Figure 4.15. Lead Assembly to be Used for Initial Current Tests.

the same conical ends but the center portion of the mold will be replaced by the outer current lead, with two flanges attached.

The current leads for this bushing are a modification of the horizontal leads now being prepared for a current test (Section 4.4.2.). The inner conductor is 6.35 cm (2.5") outside diameter and is assembled from 3 separate tubes joined axially by two circumferential welds. The center tube in the temperature transition region is formed of spirally wound heat exchanger tubing brazed into a finned, hollow walled tube. Both end sections are heavy walled tubes 1.27 cm (0.5") thick. The warm end of this conductor has a spirally wound coil formed of 0.64 cm (0.25") diameter tubing brazed into it for liquid coolant. The cold end of the conductor and a portion of the heat exchanger section will be plated to receive superconductor strips. In addition, a 0.64 cm (0.25") diameter straight-through tube is provided for instrument wires. The heat exchanger tube in the temperature transition region was formed of 1100 aluminum alloy has a nominal cross sectional area of 3.1 cm^2 (0.40 in^2). The effective area, based on resistance measurements is expected to be about 50% higher than the nominal, or about 4.6 cm^2 (0.61 in^2). This area can be reduced slightly by machining.

The heavy walled tubes of the inner conductor are 6061 aluminum alloy because electrical grade tubing in this size was not readily available. This should not cause any serious problem since the warm tube is liquid-cooled and the cold tube is covered with superconductor. The outer conductor tube was fabricated of 6061 aluminum alloy with an estimated RRR of 2.8. A standard extruded tube was chemically etched to obtain the optimum cross sectional area of 13.2 cm^2 (2.05 in^2). The finished outside diameter is 20.17 cm (7.940"). The chemical etching was done by LIMCO, the vendor who does the aluminum brazing. It is a very economical way to reduce wall thickness of a tube. Two end flanges and a spirally wound heat exchanger were brazed to the outside of the tube. The first set of conductors for the high current bushing has now been brazed and is being assembled. A total of four sets of conductors and outer screens are being fabricated.

4.4.4. Flexible Cable Enclosure

The flexible cable enclosure fabricated by Kabel und Metallwerke, Hannover, Germany, arrived at BNL on 21 August 1979. This enclosure was designed to be interchangeable in size and function with the rigid enclosure at our outdoor test site. Flexibility was achieved by fabricating both the inner helium tube and the outer vacuum pipe with corrugated stainless steel tube. The vacuum space was baked out and pumped at the plant. The pumpout ports are sealed with O-ring plugs that can be opened with detachable valve operators. Kabelmetal chose this method of sealing the vacuum space because they did not have the tooling to make cold weld pinch-off seals. The pressure in the vacuum space was $17 \text{ } \mu\text{m Hg}$ when the enclosure arrived at BNL. The rate of rise in this enclosure will be monitored regularly for comparison with the rate of rise in the rigid enclosure.

Some of the pertinent sizes and features of the flexible enclosure are shown below:

Helium tube - inside diameter 203 mm (8.00 in.)

Vacuum pipe - outside diameter 390 mm (15.35 in.)

Overall length - (including one joint) 18.9 m (62.0 in.)

Type of multilayer insulation used:

Perforated Mylar, aluminized both sides

Polypropylene fleece - spacer material

Number of layers - multilayer insulation 100

Design valve - heat in-leak 8.7 w total (0.46 w/m)

Minimum bending radius - 9.1 m (30.0 in.)

Normal bending radius - 22.9 m (75.0 in.)

This enclosure was purchased for evaluation of suitability for use where curved sections are required. Rigid enclosures can be fabricated in curved configurations, but are expensive and require custom designs for every bend or offset. This design of flexible enclosure could be bent in the field as required. Future tests required for the proper evaluation of this enclosure include:

- a) Heat in-leak in a curved configuration
- b) Friction measurements between a cable and the corrugated tube when a cable is pulled around a curve.
- c) Wearability of the corrugations during cable pulling.

4.5. Cable Cores

4.5.1. Metallic Cable Core Mark II

The Pirelli Cable Company appears to be on schedule in the fabrication of the new cable core. All of the copper alloy strip has been rolled and performed and a hand-made sample has been made. The winding of the copper alloy strip unto an aluminum tube mandrel is scheduled during the month of October. Fabrication is expected to be completed during calender year 1979.

A change order to Pirelli was placed during the first week of October, increasing the quantity from 1000 feet to 2400 feet. Since a substantial portion of the cost on the original order was for engineering, design and tooling, the incremental cost increase for this additional length is relatively small.

4.6. Fifth Avenue Facility

A major effort was made during the past six months to complete the superconducting cable enclosure installation and to conduct a thermal test of the complete system.

4.6.1. 100 m Cryogenic Enclosure

Trifurcator boxes were installed at each end of the cable enclosure. These boxes provide an insulating vacuum volume for making various system terminations and transition connections to the refrigerator and main control build. A 100 meter copper coaxial line was installed inside the 8" box for the thermal test. All of the above systems and components were helium mass spectrometer tested prior to operations. Closure pieces for the 8" MVE line and internal flexible pipe were designed, fabricated, installed and tested. A cable support system was designed to restrain MVE line movement. Eight cables are employed at each end to contain the 18 ton forces developed by system gas pressure. Four cables are installed at each end to maintain pre-extension in the bellows for thermal construction requirements.

All of the helium gas storage tanks required re-work. Leaks were found around the welds on the threaded bosses which provided piping connections to the tanks. Helium gas was transferred from the tanks and pipes and then caps were welded over the bosses.

4.6.1.1. Performance of Enclosure Vacuum System

Two years have now elapsed since the five sections of cable enclosure at the outdoor test site and one spare section arrived at BNL. The pressures in the factory sealed vacuum spaces are summarized in Table 4.2 and appear to be quite stable. The rate of rise for all sections has declined slightly since the last report and continues at a very acceptable level.

4.6.2. Refrigerator/Compressor/Gas Management

Several new components were installed. The helium gas management systems were modified to control and direct refrigeration to the load. Helium gas storage and the load were connected to provide safe system shutdown. The screw compressor oil management system was modified. Automatic control valves were installed to prevent oil sump overflow after system shutdown. A liquid level was installed for the oil sump. An oil separator tank was installed between the compressor suction and the compressor low pressure ballast tank to remove entrained oil that is transferred from the compressor to the ballast tank on compressor shutdown.

Compressor room control panels were modified to include additional Moore controllers, flow meters, and pressure indicators which provide information and system control to and from the trifurcator boxes. A new control panel was installed in the main control room which duplicates the

Table 4.2

Pressure Changes in Vacuum Space of Six Cable Enclosures

	100-Meter Line (5 Sections)			
	Average of 5	Best Section	Worst Section	Spare (Section 6)
Oct. '77 pressure reading $\mu\text{m Hg}$	7.4	4.0	10.8	8.3
Oct. '79 pressure reading $\mu\text{m Hg}$	41.2	26	53	80
Rate of rise $\mu\text{m Hg/year}$	16.9	11.0	21.1	35.9
Apparent leak rate 10^{-7} atm-cc/sec	10.8	7.0	13.2	23.0
Projected pressure after total of 5 years $\mu\text{m Hg}^*$	92	59	116	188
Projected pressure after total of 10 years $\mu\text{m Hg}^*$	176	114	222	367
Volume of vacuum space - 1537 liters/section				

* At room temperature.

information and control of the downstairs control panel. The old Graid air drier was replaced by a larger drier with a capacity that matches our load requirements and reduces the chances of contamination and freezing.

4.6.3. Superconducting Cable Thermal Test

The plant construction and preliminary start up tests were completed on August 31, 1979. On September 10, 1979, the system test began and operated successfully, around the clock, for 5 days. All systems and controls work well. The insulating vacuums reached expected levels and maintained them throughout. No helium leaks were found during the run. The system did not reach operating temperature. However, if it had not been for power interruptions and personnel fatigue, a more successful first test would have been achieved. Considering the complexities and size of the system the project personnel were indeed pleased with the system and the initial overall performance.

4.6.4. Building and Construction

Two sheet metal tunnel arch sections were constructed over each T-box. All associated electrical and mechanical services were connected from the main service building. Services included compress H_2O /glycol coolant, electrical power for vacuum pumps, electrical power for lights and general service.

A light work shop was constructed adjacent to Building 933. The shop was constructed from a 12 x 10' surplus trailer. I-beam and gussets were installed to strengthen the trailer superstructure. Grading, concrete floor and bulkheading was required for support and to match existing elevations. Electrical and mechanical services were provided for all light machine tools. Machine tools were relocated from the old trailer. The trailer was painted to match the existing building. A Halon extinguisher system was installed along with a gas furnace and heat distribution system.

4.7. Low Temperature Thermometry

4.7.1. Facility Computer Instrumentation

In September, computer monitoring of the temperature at various locations in the refrigeration system was attempted for the first time. It was found that the electrical noise voltages for those sensors in the refrigerator room were considerably higher than the signal voltages. However, the cables going to the computer monitoring equipment had been simply grafted onto the old cables at a remote terminal board. Consequently, good shielding of the signals was not maintained. New shielded cables are being installed. A further difficulty resulted from the use of a different design for the current supplies that were built by the Instrumentation Department. In order to cancel the effects of thermal emf's on the measurements the Instrumentation Department had been asked to provide supplies capable of reversing the direction of the constant current. It has been standard procedure in our laboratory to accomplish this by using the electrical equivalent of a reversing switch. Then, letting R be the unknown resistance to be determined and ϵ the thermal emf,

$$V_1 = I_1 R + \epsilon \quad (4.21)$$

$$V_2 = I_2 R + \epsilon \quad (4.22)$$

where V_2 and I_2 are the voltage and current after reversal. Since our laboratory constant current supplies are very stable (the magnitude of I_1 and I_2 are equal to within 0.03%), we have

$$I = I_1 = -I_2 \text{ and} \quad (4.23)$$

$$R = \frac{V_1 - V_2}{2I}, = \frac{1}{2}(V_1 + V_2) \quad (4.24)$$

The Instrumentation Department does not use a reversing switch to obtain a reverse current however. Instead, the polarity of the voltage to the operational amplifier is reversed. Unfortunately, as a result of zero offsets in the amplifier, the forward and reverse currents are not of the same magnitude and often differ by as much as 0.6%. A solution to this difficulty has been proposed by the Instrumentation Department. It assumes that the measurements of I_1 and I_2 are not significantly affected by thermal emfs or by zero drift in the measuring analog-to-digital converters. Then, if I_1 and I_2 are taken to be exact,

$$R = \frac{V_1 - V_2}{I_1 - I_2} \quad (4.25)$$

and

$$\epsilon = \frac{1}{2} V_1 + V_2 - \frac{(I_1 + I_2)(V_1 - V_2)}{I_1 - I_2} \quad (4.26)$$

Preliminary measurements of well-shielded signals indicate that the resistance values obtained will be within 0.5% of their actual values when $R > 10 \, \Omega$. If R is less than this, the resistance values obtained may fluctuate by + 4% due to measurement errors. Fortunately R is greater than $10 \, \Omega$ for temperatures less than about 70 K. The 0.5% accuracy at lower temperatures will result in temperature errors at 20 K and above due to the logarithmic dependence of the R-T curve for germanium sensors.

4.7.2. Calibration of Temperature Sensors

Considerable effort was expended in testing and calibrating germanium temperature sensors. Apparatus was constructed and programs written to allow screening tests and dipping tests to be performed at BNL using a desktop computer to control the measurement process. Screening tests had not been performed initially, but were found to be necessary since the sensors as-received from the manufacturer vary widely in quality. Some, in fact, are inoperable. As the need for these initial checks became apparent, the sensors were first checked manually. The extent and reliability of these checks, however, varied as a result of their being performed by different individuals. Although open leads internal to the sensor itself, either at room temperature or upon cooling to liquid nitrogen temperature, were always detected if present by these tests, resistive shorts between the sensor element and its case frequently were not. Consequently, a test apparatus was constructed and a program written so that the desktop computer could perform full screening tests quickly and automatically. The calibration of the temperature sensors is done at the Ames Laboratory in Ames, Iowa and it is important to utilize the time there as efficiently as possible. Therefore, it is decided to perform the dipping tests at BNL. In the dipping test, a sensor is cycled between room temperature and liquid helium temperature about ten times. The resistance values obtained are then plotted as a function of temperature to check the stability and reproducibility of the resistance at about 4.2 K. (The temperature varies because of changes in atmospheric pressure.) If the sensor shows

instabilities in resistance which correspond to greater than 2 mK variations, it is not calibrated. The dipping tests are also performed using the desktop computer, which also plots the results obtained.

To date, 120 germanium sensors have been purchased. Of these, 66 have received computerized screening tests, and 32 were tested manually. Seventy have been calibrated, including the four carefully calibrated standards. A few failed after calibration. As a result of screening and dipping tests, it was determined that five had open leads, six had shorts to the case, twenty had resistive contacts, four were noisy or unstable at liquid helium temperatures, and three had values of resistance at liquid nitrogen or helium temperatures that disagreed significantly with the values provided by the manufacturer. Not all of these 38 resistors have been rejected, in fact, some have been calibrated. Unfortunately, there is no simple way of deciding whether a high lead resistance at liquid nitrogen temperature will be so high as to result in measurement difficulties at 6 K. Twenty-two have received no screening tests, so their reliability and quality is unknown. However, five of these were dipped, calibrated, and installed before a regular testing procedure had been formulated.

4.8. Pressure Measurement

During the reporting period, a Heise digital pressure indicator was obtained for absolute pressure measurements between 0-300 psia. It is accurate to + 0.07%. The meter provides a continuous ASCII encoded serial output signal. Our desktop computer system includes a RS-232C serial interface for communication to its Diablo printer at 300 bps. The interface was used successfully to read the pressure information sent from the Heise pressure meter. Initially, we hoped to switch the signal lines to the interface between the printer and the pressure meter under computer control so that both operations could be performed with the computing controller. Unfortunately, the pressure meter provides its information at 120 bps, a rate which exceeds the mechanical capability of the printer. The rate switch is internal to the interface itself. Rather than modify the interface to allow switching of the rate using external relays, another is being purchased that will be dedicated to transferring data from devices operating at the higher rate. An advantage to this solution is that the additional serial interface will also allow data to be transferred between the computing controller and BNL's large mainframe computers, thereby eliminating the tedious and error-prone procedure of transferring such information manually.

4.9. Helium Research in Support of Superconducting Power Transmission, Prepared by NBS - Boulder

Three tasks were undertaken during FY 79:

- i) Investigation of SPTL cooldown.
- ii) Measurement of cable radial permeability to gas flow.
- iii) Evaluation of thermal flux meters as a means of detecting deterioration of the cryogenic enclosure thermal insulation.

All tasks have been completed except long term field testing of the thermal flux meters.

4.9.1. Cable Cooldown Experiments and Analysis

We have previously numerically modeled the cooldown of a full scale BNL cable so the purpose of the present work was both to confirm these earlier calculations, as well as to develop and experimentally test a general model of counterflow cooling of transmission lines.

If we consider a simple constant property and a constant mass flow counterflow cool down and set $(hP)v = (hP)u$ and $Av = Au$, then the process is described by:

$$\frac{1}{b} \frac{\partial u}{\partial \tau} = - \frac{\partial u}{\partial y} + w - u \quad (4.25)$$

$$\frac{1}{b} \frac{\partial v}{\partial \tau} = \frac{\partial v}{\partial y} + w - v \quad (4.26)$$

$$\frac{\partial w}{\partial \tau} = u + v - 2w \quad (4.27)$$

with initial conditions :

$$u = v = w = 1 \text{ for all } y \text{ at } \tau = 0 \quad (4.28)$$

and boundary conditions :

$$\begin{aligned} u &= \eta \text{ at } y = 0 \\ u &= v \text{ at } y = 1 \end{aligned} \quad \text{for } \tau > 0 \quad (4.29)$$

The second boundary condition is for single ended cooldown. For double-ended cool down, the effective length is 1/2 that of the single ended case.

The nomenclature for the discussion in this section is:

A cross sectional area

b heat capacity ratio = $\frac{(\rho AC)_w}{\rho AC_p}$

C specific heat of solid

C_p Specific heat at constant pressure for gas

h film coefficient + 1/2 solid resistance

ℓ length of transmission line

L dimensionless length = $\frac{hP\ell}{\dot{m}C_p}$

m mass flow rate of gas

N_{tu} number of transfer units = $\frac{UP\ell}{\dot{m}C_p}$

P heated perimeter

Q total rate of heat leak to the transmission line

t time

T temperature

u normalized temperature of go stream = $(T - T_f)_u / (T_i - T_f)$

U overall heat transfer coefficient between the go and return streams.

v normalized temperature of return stream = $(T - T_f)_v / (T_i - T_f)$

w normalized wall temperature = $(T - T_f)_w / (T_i - T_f)$

x position

y dimensionless position = $\frac{hPx}{\dot{m}C_p}$

ρ density (gas if unsubscripted)

τ dimensionless time = $\frac{hP}{(\rho AC)_w} t$

τ' dimensionless time = $\frac{UP}{(\rho AC)_w} t$

Subscripts

cd cool down

i initial condition

f final condition

ℓ $x = \ell$ position

o $x = 0$ position

u go stream

v return stream

w wall

Equations 4.25 through 4.29 were solved both by numerical techniques and by an approximate analytical method which assumes a sinusoidal temperature profile for u . The experimental temperature profiles in figure 4.16 show this to be a good approximation. As indicated by figure 4.17 the agreement between the numerical and approximate analytical methods is excellent. The approximate solution which also accounts for a constant heat leak Q is:

$$\frac{u}{u_0} = \left(1 - \frac{L}{\pi} \frac{Q}{u_0 m C_p} \right) \exp \left(- \frac{\pi^2}{2L^2} \frac{1}{1 + \frac{\pi}{2L}} \tau \right) + \frac{L}{\pi} \frac{Q}{u_0 m C_p} \quad (4.30)$$

For large L and $Q = 0$, 4.30 gives $\tau' = 0.262 N_{tu}^2$ (4.31)

for 90 percent cool down of a line cooled at both ends.

In addition to relating the dimensionless length to the number of heat exchanger transfer units N_{tu} , the analysis also suggests τ'/N_{tu}^2 as a correlating parameter. Figures 4.18 and 4.19 coalesce the experimental data to a single curve, although the dimensional cool down times for the LN₂ experiments differ by more than a factor of 10.

The agreement between equation 4.30 and the experimental results (figure 4.18) is sufficient so that equation 4.30 may be used for cases where the cable heat capacity varies by only a factor or two or so. For cool down to helium temperatures, equation 4.31 gives a good approximation of the overall cool-down time, particularly if a value of 0.3 is taken for the constant.

4.9.2. Cable Permeability

In case of a rupture in the lead sheath of the cable, it is important to know how much leakage from the pressurized (15 atm) cable might occur.[†] Our measurements of the cable permeability were intended to define the magnitude of the problem rather than to give a precise value for the leak rate at the anticipated operating conditions.

The apparatus and the cable are the same ones that were used previously for thermal cycling of a BNL model cable^{*}. Five gas taps in the lead sheath are connected to individual wet test gas flow meters. These gas taps are formed by soldering (Wood's metal solder) 4.8 mm ID copper tubes into holes cut in the lead sheath. They are symmetrically spaced from the axial centerline at cm intervals, so that the end taps are 10 cm from the end clamp assemblies of the 229 cm long cable.

^{*} Daney, E.D., Editor, "Helium Research in Support of Superconducting Power Transmission," NBSIR 79-1618, National Bureau of Standards (U.S.) 1979.

[†] Editor's note: The major interest at BNL in this measurement is whether or not a pressure jacket is needed - it is!

Figure 4.16. Experimental Cooldown for Counterflow Cooling.

Figure 4.17. Cooldown Curves for the Center ($x/l = 0.5$) of a Line With Both Ends Cooled (Counterflow Cooling) - Comparison of Eq. 4.30 With the Numerical Calculations. W is the Normalized Temperature at the Midpoint of the Line and τ' is the Dimensionless Time.

Figure 4.18. Experimental Cooldown Results ($x/l = 0.5$, Both Ends Cooled: $x/l = 1$, One End Cooled) - Cooldown to 76K. (The Parameters for the Sinusoidal Approximation (Eq. 4.30) are: $L(N_{tu}$, for Double Ended Case) = 15, $QL/m/C_p = 0.05$.

Figure 4.19. Experimental Cooldown Results ($x/l = 0.5$, Both Ends Cooled: $x/l = 1$, One End Cooled) - Cooldown to 6 K.

Thus, the experiment measures the leak rate between the pressurized bronze core of the cable and 4.8 mm diameter holes in the lead sheath spaced at 70 cm intervals. The effect of end leakage (between the core and the lead sheath) is given by the difference between the flow rates of the center tap and the end taps.

The measured cable leak rate is given in figure 4.20 for an operating temperature of 76 K. Making a correction to the expected operating conditions using the expression:

$$G \sim \sqrt{\frac{\rho \Delta P}{\mu}}$$

we obtain a leak rate of about 15 g/s - extremely high. Here G is mass flux, ρ density, ΔP pressure difference, and μ viscosity.

From these measurements we conclude that any significant rupture of the lead sheath will lead to an unacceptably high leak rate from the pressurized core. The high permeability of the composite within the lead sheath also suggests that some fluid convection in this layer may accompany forced flow inside the bronze core. If this occurs, then the thermal conductance across the wrapped dielectric may be very much higher than anticipated. Because this conductance is critical to the performance of the SPTL, we strongly recommend that the radial thermal conductance of a cable be measured under the expected operated conditions, i.e., with supercritical helium flowing through the core.

4.9.3. Evaluation of Thermal Flux Meters

Integrity of the thermal insulating vacuum in the transmission line cryostat sections is essential to the successful operation of the line. Because vacuum gauges which measure the insulating vacuum directly introduce an additional unacceptable risk of vacuum leak, a non-intrusive means of vacuum or heat leak indication is highly desirable. Thermal flux meters have been proposed for this purpose, and although meters are available from industry, their successful application for this purpose requires detailed study.

The experimental study proceeded in two stages. First, the sensitivity of 4 pairs of commercial heat flux sensors were evaluated in the laboratory. Then, the sensors were evaluated under field conditions, i.e., buried and subjected to diurnal and longer term variation of the soil temperature. These field tests are still in progress.

In the laboratory test apparatus (figure 4.21, four pairs of heat sensors from different manufacturers are mounted on a 51 cm (20-inch) O.D. 861 cm (24 inch) 101 steel pipe. The average sensitivity of the sensors is 12 V/W/cm². One pair of sensors is curved to match the pipe contour, whereas the three other pairs require copper adapter plates between the curved pipe and the flat sensors. Two pairs of sensors are mounted at 0 and 180 degrees and two pairs at 90 and 270 degrees.

Uniform heat flux is generated by a heater mounted on the inside surface of the pipe. It is fabricated from 60 series-connected segments of stainless steel shim stock .05 mm (.005 inch) x 25.4 mm (1 inch) x 61 cm (24 inch). The range of heat fluxes is 10⁻⁵ to 10⁻³ W/cm². Convective heat transfer within the pipe is prevented by polyurethane foam which fills the pipe. Penetration of moisture into the heater during the field tests is prevented by epoxy-fiberglass end seals.

For the laboratory tests, a constant temperature environment was provided by the copper thermal shield and outer shell of perlite insulation. A temperature controlled bath-circulator maintains the shield at constant temperature.

Experiments were run with the annular gap between the steel pipe and copper shield filled with air and with sand. Figure 4.22 which gives the laboratory measurement results for one pair of sensors, shows both a zero shift and a small change in sensitivity between the air and sand results. In both cases, the response is quite linear. Figure 4.23 gives the heat sensor signal for the initial field test. The heater power is zero, the depth of burial (pipe axis) is 1.5 m, and the sensor is mounted at the top of the pipe. The pipe was buried on August 20, 1979, nearly a month before the beginning of the record. At the nominal enclosure heat flux of 28 μ W/cm² the laboratory measurements with sand gave a response of 400 μ V.

For the heat sensors mounted on the top and bottom of the pipe, we observed a variable heat flux which is several times the nominal enclosure heat flux. For the side mounted sensor (figure 4.23 the variation of the heat flux has about the same magnitude as the nominal enclosure heat flux.

Diurnal variations of the heat flux are quite small because of the depth of burial of the pipe. However, it appears that seasonal and shorter term variations (perhaps associated with weather patterns) are quite significant. Continued monitoring of the field installation will be required to determine the field sensitivity of the heat sensors. So far it would appear that side mounting is the preferred position, and that changes in enclosure heat flux of the same order as the nominal heat flux might be detected.

Figure 4.20. Permeation Rate Through BNL Cable (70 cm Spacing of Gas Taps).

Figure 4-21. Heat Sensor Laboratory Test Apparatus.

Figure 4.22. Laboratory Results for One Pair of Heat Flux Sensors.

Figure 4.23. Preliminary Field Results for Heat Sensor Mounted on Side of Pipe

5. Visits, Meetings and Publications

5.1. Visits to BNL

<u>Date</u>	<u>Visitor(s)</u>	<u>Affiliation</u>	<u>Purpose</u>
18 April '79	Sr. Engineering Students Maritime College	NYC	A. McNerney gave tour of Power Transmission Project.
31 May '79	N.D. Pewitt & G. Paseyna		E. Forsyth gave tour of Power Transmission Project.
3-17 June '79	E. L. Blinkov S. I. Lutidze	USSR	Participate in the US-USSR Exchange in S/C Power Transmission. (See Section 5.3.1.)
19 June '79	E. D. Eich	PTI	Consultation with Power Transmission Project.
20 June '79	EPRI Task Force		Visited BNL and toured Power Transmission Project.
13 July '79	Donald Allgrove	6th District Suffolk County	Toured Power Transmission Project.
8 August '79	A. Heath	PSEG	Discussed cryogenic transmission.
6 September '79	T. Garrity	DOE Hq.	Annual reivev of Power Transmission Project.
12 September '79	Richard Traut	Simplex Co.	Discussion of PTP and the relationship with the Ocean Thermal Energy Conversion Riser Cable Dev. Program.
10-11 September '79	W. Lehmann	Frankfort, Germany	Toured and discussed Power Transmission Project.
12 September '79	Linac Conference at BNL		W. Harrison and G. Morgan gave tours of Power Transmission Project.

<u>Date</u>	<u>Visitor(s)</u>	<u>Affiliation</u>	<u>Purpose</u>
21 September '79	Director and Financial Officers of Power Companies		R. Thomas gave tour of Power Transmission Project.
23 September '79	Dr. V. A. Goncharov Mr. S. G. Gosteev Dr. A. A. Panov	USSR	Participated in the US- USSR Exchange in S/C Power Transmission. (See Section 5.3.3.)

5.2. Visits by BNL Personnel

<u>Date</u>	<u>Name</u>	<u>Place</u>	<u>Purpose</u>
1 April '79	E. B. Forsyth	Atlanta, Georgia	Presented paper at the 1979 IEEE/PES Trans. and Distri. Conf. & Expo.
4-12 April '79	J. E. Jensen	Boulder, Colorado	Visited NBS
23-27 April '79	W. E. Harrison	Boulder, Colorado	Presented paper at the Electrochem. Society Meeting.
6 May '79	E. B. Forsyth	Boston, Mass.	Attended Symposium on S/C Materials and Devices.
11-23 May '79	K. F. Minati	Germany & Graz, Austria	Inspected Cryogenic Envelope at Kabelmetal.
13-17 May '79	E. B. Forsyth	Aspen, Colorado	Presented paper at Conference on Public Policy Aspects of High Capacity Trans.
21-24 May '79	G. H. Morgan J. E. Jensen	PA	Attended course on heat exchanger design.
30 May '79	A. C. Muller R. Porter	Columbus, Ohio	Reviewed progress of high modulus tape development program at Battelle.
24 June - 10 July '79	J. Bussiere M. Garber	Moscow & Kiev, USSR	Participate in US-USSR Exchange in S/C Power Transmission (see Section 5.3.2.).

<u>Date</u>	<u>Name</u>	<u>Place</u>	<u>Purpose</u>
1-10 July '79	R. Thomas D. Farrenkopf	Ames, Iowa	Assisted in calibrating sensors for measuring low temperature measurements.
23 July '79	A. C. Muller	Memphis, TN	Reviewed progress on laminated tape development at Bryce.
24-25 July '79	A. Minardi	Providence, RI	Supervised embossing of dielectric tapes at Northeast Paper Converting Co.
1-2 Aug. '79	A. J. McNerney	Pittsburgh, PA	Engineering Inspection at Westinghouse Research Laboratory.
2 Aug. '79	R. J. Gibbs	Westboro, Mass.	Inspected charcoal absorbers for screw compressor oil removal system at the Helix Corp.
27-31 Aug. '79	K. Horii	Milan, Italy	Attended Internal Sym. on High Voltage Engineering.
1-12 Sept. '79	A. J. McNerney	London, England	Presented paper; visited CERL and Bolney to exchange information on materials and techniques used in HV cable construction & design.
5-7 Sept. '79	A. Minardi	Wilmington, DE	Attended course on GPC equipment at DuPont.
16-30 Sept. '79	J. E. Jensen S. Amoretty	Moscow & Leningrad USSR	Participate in 7th Meeting of the US-USSR Coordinating Committee on Scientific and Technical Cooperation in the Field of S/C Power Transmission (see Section 5.3.4.)

5.3. US-USSR Exchange

Four meetings were held in the US and USSR under the agreement for technical exchange. Summaries of these visits are given in the following sections.

5.3.1. June Visit of Soviet Scientists to BNL

The purpose of this visit was to take part in experiments to characterize the ac losses and other current related parameters of superconducting cable # 102. This working visit was in fulfillment of item No. 3 of Appendix 3 to the Record of the Sixth Meeting of the US-USSR Coordinating Committee on Scientific and Technical Cooperation in the Field of Superconducting Power Transmission signed 6 October 1978. All planned tests of the cable were completed during the visit of the Soviet experts. Data were discussed along with the analysis methods. Copies of data and analyzed results were presented to the Soviet experts. Discussions on topics of mutual interest were held with other available experts from BNL attending.

The program was arranged to alternate experimental demonstrations with visits to relevant laboratory facilities and discussion sessions so as to minimize the fatigue and loss of efficiency attendant on holding too many discussions in series without a break.

5.3.2. June-July Visit of BNL Scientists to USSR

The main purpose of this trip was to participate in the fabrication and characterization of rigid composite Cu/Nb/Nb₃Sn tubular conductors at the Institute for Metal Physics (IMP) in Kiev. These tubular conductors are being developed in collaboration with the Krzhizhanovsky Institute for use in their rigid ac transmission line. The joint experiments conducted by the US-USSR groups consisted in studying the formation of Nb₃Sn layers inside Nb tubes and measuring the critical temperature and critical current of the formed layers.

5.3.3. September Visit of Soviet Scientists to BNL

The purpose of the visit was to allow the visiting Soviet experts who arrived in BNL on September 8, 1979, to take part in collaborative experiments with BNL staff on high voltage dielectrics, as called for in item 4 of Appendix 3 to the Record of the Sixth Meeting of the US-USSR Coordinating Committee on Scientific and Technical Cooperation in the Field of Superconducting Power Transmission.

All planned tests of the cable were completed during the visit of the Soviet experts. Data were discussed along with the analysis method. Copies of data and analyzed results were presented to the Soviet experts. Discussions on topics of mutual interest were held with other available experts from BNL attending.

The program was arranged to alternate experimental demonstrations with visits to relevant laboratory facilities and discussion sessions so as to minimize the fatigue and loss of efficiency attendant on holding too many discussions in series without a break.

5.3.4. September Visit of US Side of Coordinating Committee to USSR

A review of the work in both countries indicated progress toward the goal of large scale demonstration of superconducting power transmission. In the Soviet Union there are two developmental cables, both for ac service. A rigid coaxial spacer cable with pressurized helium dielectric and niobium tin conductor being developed jointly by the Krzhizhanovsky Institute and Mosenergo (the Moscow regional electric utility) and a flexible coaxial wrapped tape insulated cable also using niobium tin conductor being developed by the All-Union Research Institute of the Cable Industry. (In the US only one cable is under development, a flexible tape insulated cable using niobium tin conductor for ac service.) We saw the rigid cable installation at the Mosenergo Test Facility but did not see the flexible cable. Neither cable has had extensive cryogenic testing but the coaxial cable has just passed the vacuum integrity test and is awaiting cooldown. These cryogenic tests are scheduled for late 1980. Electrical tests for both cables cannot be undertaken until very late 1980 or early 1981. In the meantime, laboratory investigations of cryogenic and superconducting parameters of components will be underway and joint experiments in both countries have been planned for 1980. The schedule for these experiments is given in the report to the US-USSR Joint Committee on Energy. A proposal by the Soviet committee to extend the cooperation to include other superconducting developments such as generators and magnetic energy storage was discussed. A counter proposal by the US to defer this extension until the completion and testing of the large scale experimental and pilot commercial cable installations was adopted. The US position that materials development and the metallurgy and fabrication of superconductors for transmission lines are integral parts of the cooperative program was discussed at some length. Both sides agreed to work toward including these areas in future visits and cooperative experiments.

In Leningrad we saw the new high voltage testing facilities of the Direct Current Institute which, when completed, will be equivalent to those available in the West. The equipment is fabricated in East Germany by TUR, Dresden, to designs and specifications by the Institute. This facility will be employed in the US-USSR superconducting generator development of Glebov's Institute, the All-Union Research Institute for Electrical Machinery. They have working demonstrations of dc generators and motors with brush commutation, and dc homopolar machines both with static superconducting field, ac generators with rotating superconducting fields and a flux pump for space application. We saw the stator and rotor for a 20 MVA, 3000 rpm, 6.3 kV superconducting turbo alternator in a test laboratory and witnessed a half speed run-up of the rotor cryostat. Glebov's Institute works closely with the Scientific Institute of Electrosila and at Electrosila we saw a superconducting 2 MW turbo alternator on a test stand along side conventional alternators on test.

The development of superconducting machinery seems to be moving at a more deliberate pace than the cable development and there seems to be closer coordination between the experimental institutes and the manufacturing organizations. There is a superconductivity subcommittee of the National Science and Technology Committee which is charged with coordinating overall activity. The heads of the institutes engaged in various tasks are members. Glebov and Levitov sit on this subcommittee along with others representing cryogenics and materials.

5.4. Publications

Proceedings of the Fifth US-USSR Symposium on Superconducting Power Transmission, held at Brookhaven National Laboratory, Sept. 5-6, 1978, BNL 51078.

E. B. Forsyth, A. J. McNerney and M. Meth, Load Excitation at the Superconducting Cable Test Facility, presented at the 7th Symposium held under the auspices of the US-USSR Technical Exchange Committee on Superconducting Power Transmission, Moscow, USSR, Sept. 1979.

J. E. Jensen, Calorimetric Measurement of AC Losses in Superconducting Cables of Short Length, presented at the 7th Symposium held under the auspices of the auspices of the US-USSR Technical Exchange Committee on Superconducting Power Transmission, Moscow, Sept. 1979.

A. C. Muller, X-Ray Examination of Insulation in Lapped High Voltage Underground Power Transmission Cables, to be presented at the ASNT Fall Conference, St. Louis, MO., Oct. 15-19, 1979.

G. H. Morgan and A. C. Muller, Bending Behavior of Lapped Plastics EHV Cables, to be presented at the Int. Symposium of Electrical Insulation, Boston, Mass. June 9-11, 1980.