For presentation at the Conference on Technical Applications of Superconductivity
to be held in Alushta, USSR, September 16-19, 1975.

BNL-20444
Conf-750950--1

The Brookhaven Program to Develop a Helium-Cooled Power Transmission System*

E. B. Forsyth
Brookhaven National Laboratory
Associated Universities, Inc.
Upton, New York 11973
USA

MASTER

ABSTRACT

The ever-increasing capacity demanded of power transmission circuits has forced overhead voltages into the UHV region. However there is significant resistance to the erection of supporting towers for aesthetic reasons and in many suburban regions of the U.S. the necessary rights-of-way simply no longer exist. After a year-long study of the application of cryogenic technology to electrical power transmission, workers at Brookhaven National Laboratory concluded that superconducting cables offered a possible means of providing long-distance power transmission without a reactive penalty and with very large circuit capacities in a small conduit. This alternative choice to UHV overhead transmission is the goal of an active development program.

The particular system under design consists of flexible cables installed in a cryogenic enclosure at room temperature and cooled to the range 6 to 9 K by supercritical helium,contraction of the cable is accommodated by proper choice of helix angles of the components of the cable. The superconductor is Nb_3Sn and at the present time the dielectric insulation is still the subject of intensive development. Two good choices appear to be forms of polyethylene and polycarbonate. Sample cables incorporating various dielectrics have been manufactured commercially in lengths of 1500 ft. and tested in laboratory cryostats in shorter sections of about 70 ft.

A test facility is under construction to evaluate cables and cryogenic components for this type of service, the first refrigerator uses a 350 H.P. screw compressor and three turbo-expander stages. It is hoped to achieve reliability of a very high order. The first three-phase tests will be conducted at 69 kV, although it appears that 230 to 345 kV is the most likely voltage range for future applications.

Extensive studies have been carried out in cooperation with utility companies to examine the technical and economic aspects of incorporating helium-cooled transmission systems into future networks. The results so far are very promising.

---

*Work supported by the National Science Foundation and the Energy Research and Development Administration.

For presentation at the Conference on Technical Applications of Superconductivity to be held in Alushta, USSR, September 16-19, 1975.

BNL-20444

The Brookhaven Program to Develop a Helium-Cooled Power Transmission System*

E. B. Forsyth+

Introduction

The transmission project at Brookhaven began in mid 1971 with a study of the problem and contemporary research on cryogenic transmission. The study was financed by the National Science Foundation under the program Research Applied to National Needs. An informal report was issued in December, 1971, which was followed by a formal version issued in early 1972[1]. The major conclusions of the study were:

"SPECIFIC RECOMMENDATIONS - The use of helium as a dielectric appears to have several disadvantages, including (1) the possibility of poor dielectric breakdown performance, and (2) the necessity for installing rigid cables in 40 to 60 ft sections.

Even in the early stages of conceptual development, cables must be designed to appeal to the utilities, particularly from an economic standpoint. Thus solid or laminar dielectrics are suggested, as they permit the cable to be made in lengths that can be reeled and pulled into place. Two of the designs presented for flexible superconducting cable appear to be technically attractive. These cables are very light compared with conventional cables of the same rating. It has been shown that concentrating on one parameter, for example, magnetic loss, does not lead to optimization of the total design. In particular, the higher critical temperature (T_c) and superior current-carrying capacity of niobium-tin compared with niobium allow a more practical line design. Because of the nonlinear properties of helium in the operating range the higher T_c permits a disproportionate improvement in the refrigerator system. In a practical line it will be a complicated problem to optimize the electrical, mechanical, and cryogenic designs of the cable. System requirements such as fault and overload performance will also enter the picture.

Although the study has concentrated on ac transmission, dc may be preferable for certain types of system operation. Some development or improvement of the associated breakers and converters is required, but the cables themselves appear to be relatively simple modifications of ac designs. Advantages of a flexible design still apply.

If superconducting cables become standard it is necessary to hoard all the helium possible. In addition to conserving the rich helium reserves, research should begin on economical ways of recovering helium from relatively lean supplies of natural gas before all the reserves are burnt. Helium will be essential for other projects (e.g., fusion generation) besides superconducting power lines. The abandonment of the helium conservation program is a disaster, to put it mildly."

---

*Work supported by the National Science Foundation and the Energy Research and Development Administration.

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

Based on these recommendations the superconducting transmission system under development at Brookhaven is analagous to conventional high pressure oil filled cables (HPOF), in this method a steel containment pipe is installed between manholes some 3000 feet apart. Flexible cables are pulled in and spliced in the manholes, which are then covered. Oil under pressure is introduced to fill the voids in the insulation and to provide a heat-conducting medium to the surrounding earth. In a superconducting version the steel pipe is replaced by the thermally-insulated cryogenic enclosure and flowing helium gas replaces the oil. Flexible superconducting cables will weigh considerably less than the conventional counterpart for the same voltage due to the elimination of most conducting material. This may ultimately permit longer lengths between splices than is now the case.

The work has concentrated on ac transmission as this would seem to be the earliest application. Thus a Nb_3Sn conductor had to be developed with low losses, high quench current and mechanical properties consistent with use in a flexible cable design. Although there is a natural tendency to concentrate on the problems of cable design when developing a new electrical transmission system, the fact is that the design of the cryogenic equipment is likely to pose equal, or greater problems. The cryogenic envelope containing the cables in a thermally-insulated environment is likely to cost more than any other single item in a superconducting transmission system. We have begun an active development program concerned with this class of equipment. The major areas of work may be subdivided as follows:

1) The design of cable conductor and conducting materials
2) The design of cable insulation and insulating materials
3) Mechanical and cryogenic equipment, including mechanical aspects of cable fabrication
4) Systems engineering
5) Construction of a field test facility

Conductor Development

A conductor was required with acceptable losses at 60 Hz. On the one hand the work at Linde[2] had shown niobium could probably be manufactured with low losses, but on the other hand our analysis of cooling system performance had indicated the relatively low critical temperature of this superconductor produced such a poor efficiency that this advantage was largely cancelled out. Our choice is Nb_3Sn, but measurements of hysteretic loss showed it could be a factor of 5 to 10 times larger than other heat loads on the refrigerator. A major goal of our early work was to reduce this loss. This has been successfully achieved[3] .

The theories of losses based on simple models have been in existence for several years, unfortunately no quantitative or qualitative correlation could be observed with measurements on Nb_3Sn. During the past year it has been found that the intrinsic loss characteristics of many Nb_3Sn samples are masked by losses arising in the solder and cladding used by manufacture of the tape. Once these parasitic effects are removed Nb_3Sn manufactured by several methods will possess low losses if certain metallurgical conditions on the grain size and surface roughness are met[4,5]. Typical Nb_3Sn surfaces are shown in Fig. 1 with qualitative correlation of losses.[3] The theory has been extended to include temperature dependence, and good agreement has been obtained between calculated and measured results[6]. This may be seen in Fig. 2.

Quench currents and critical currents have been measured for a number of commercial Nb_3Sn tapes at 4.2 K[7]. The measurements were made at 60 Hz. The observed quench currents in the as-received tapes are considerably lower than the critical currents, which can be determined by a new technique after stabilizing material is added. The temperature dependence over the entire range above 4.2 K was measured for two of the samples. The critical current falls off approximately as $1-(T/T_c)^2$.

Conceptually, one-phase of a three-phase power transmission system consists of a pair of coaxial tubes or pipes, with superconductor on the outside of the inner pipe and on the inside of the outer pipe. Although rigid versions of this concept have been under development for nearly a decade there are strong economic and technical reasons to develop a flexible form of cable. In this construction the conductor and insulation are wound as concentric helices, thus permitting many of the advantages of flexibility to be reaped at the expense of several new problems not encountered in plain concentric cylindrical designs. A model of cable made with simple helices is shown in Fig. 3. The electrical complications arising from helical current paths have been described in detail[8]. The practical manifestations are primarily heating of normal metal used in the cable and undesirable voltages appearing on the outer conductor.

For reasons of simplicity of fabrication, behavior with respect to fault currents and economy of material, it is desirable to use a single-layer helical structure. A simple helix generates an axial magnetic field of magnitude I/P. where I is the total current and P the helix pitch, and the field along the axis is the sum of the fields due to the inner and outer conductor;

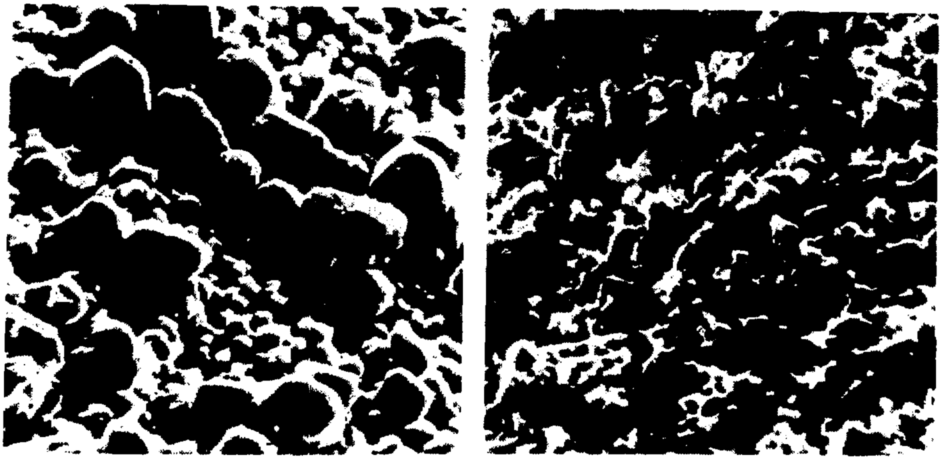
$$H_z = I_1/P_1 + I_2/P_2 \tag{1}$$

where subscript 1 and 2 denote inner and outer conductors, respectively. If $-I_1/P_1 = I_2/P_2, H_z = 0$. In addition there is an axial component of field in the annulus between the inner and outer conductors of magnitude I_2/P_2, thus the total field there is helical.

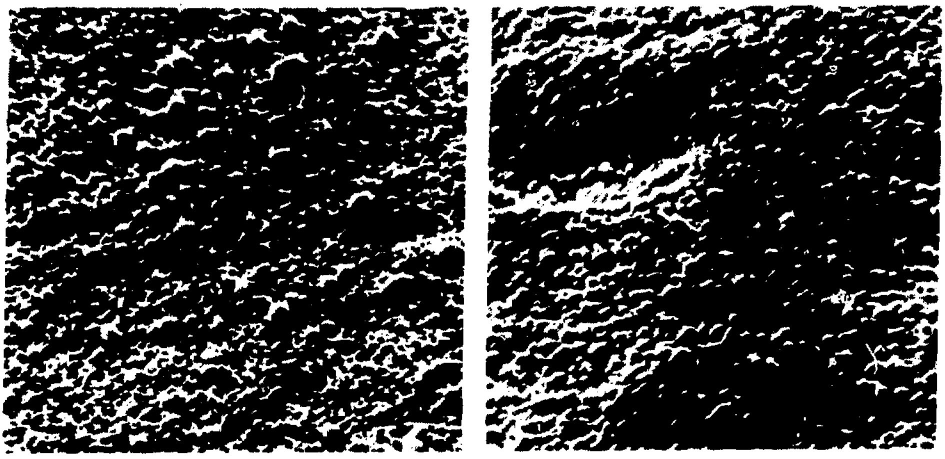
If there is normal metal inside the hollow core supporting the inner conductor, eddy currents are induced in it giving rise to heating. For the case of pure normal metal backing laminated to the superconductor the loss per unit area can be expressed as:

$$w = R_\delta \, (I_1/P_1 + I_2/P_2)^2 \tag{2}$$

where $R_\delta = \rho/\delta$ is the surface resistance in ohms, ρ is the resistivity of the backing and $\delta = \sqrt{2\rho/\mu_0\omega}$ is the skin depth. This expression is true only for a backing thickness $t \geq \delta$ and henical strip width $\gg \delta$. For $t < \delta$, the expression still holds if R_δ is replaced by $R_s = 4(t/\delta)^3 \, R_\delta/3$.



(a) IGC No. 1 (b) RCA-2119B



(c) KB-15 (d) BT-19

5 μm

Figure 1. Surfaces of four Nb_3Sn as shown by a scanning electron microscope. The upper two surfaces are commercially-prepared material intended for dc magnet applications and both exhibit relatively high hysteretic losses. The lower left-hand specimen is a commercially prepared tape with low losses and the lowest loss of the four is exhibited by the sample shown on the lower right, which was made at Brookhaven by the bronze diffusion method.

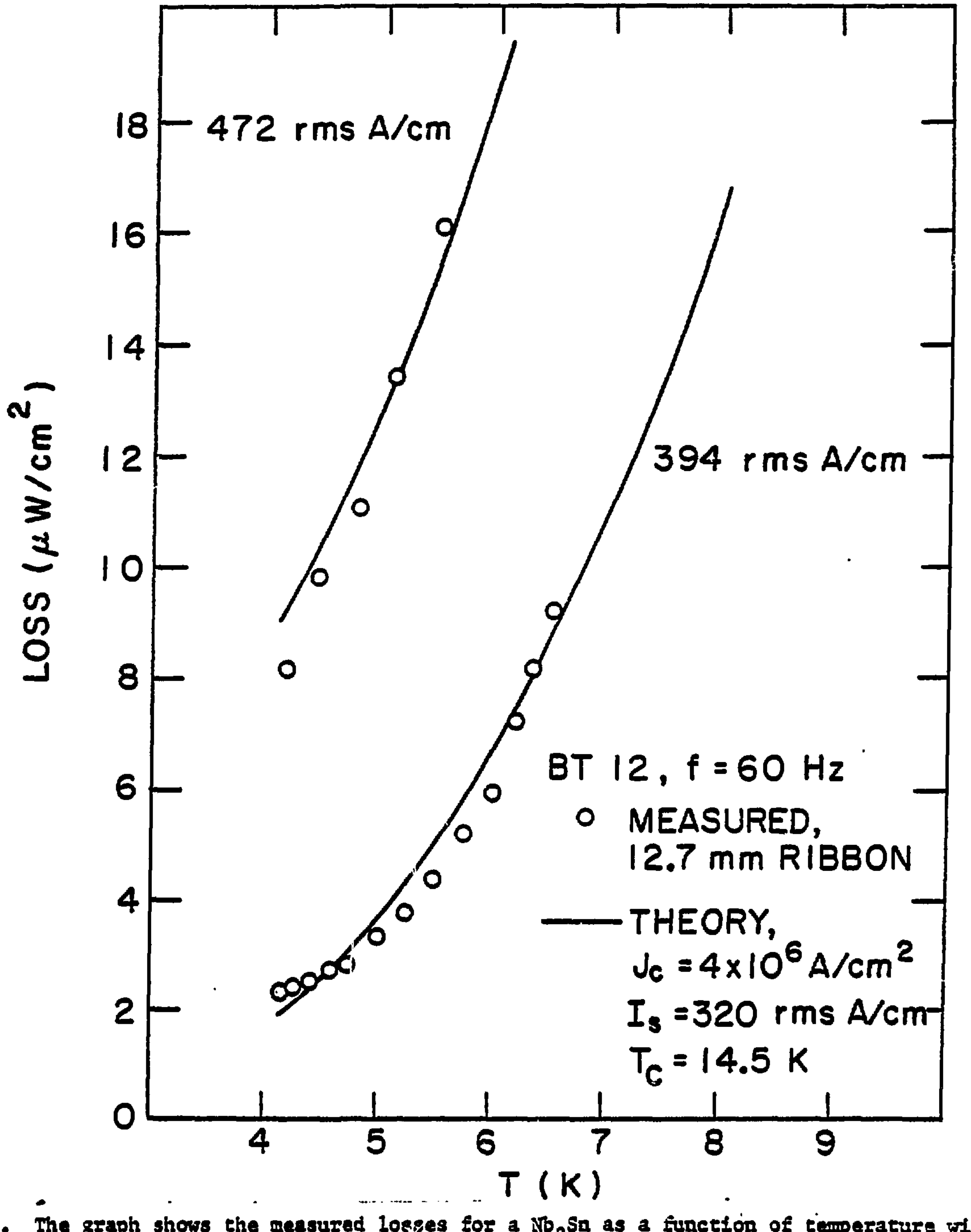


Figure 2. The graph shows the measured losses for a Nb_3Sn as a function of temperature with linear current density as a parameter. The solid lines show the losses predicted by a theoretical model developed at Brookhaven.

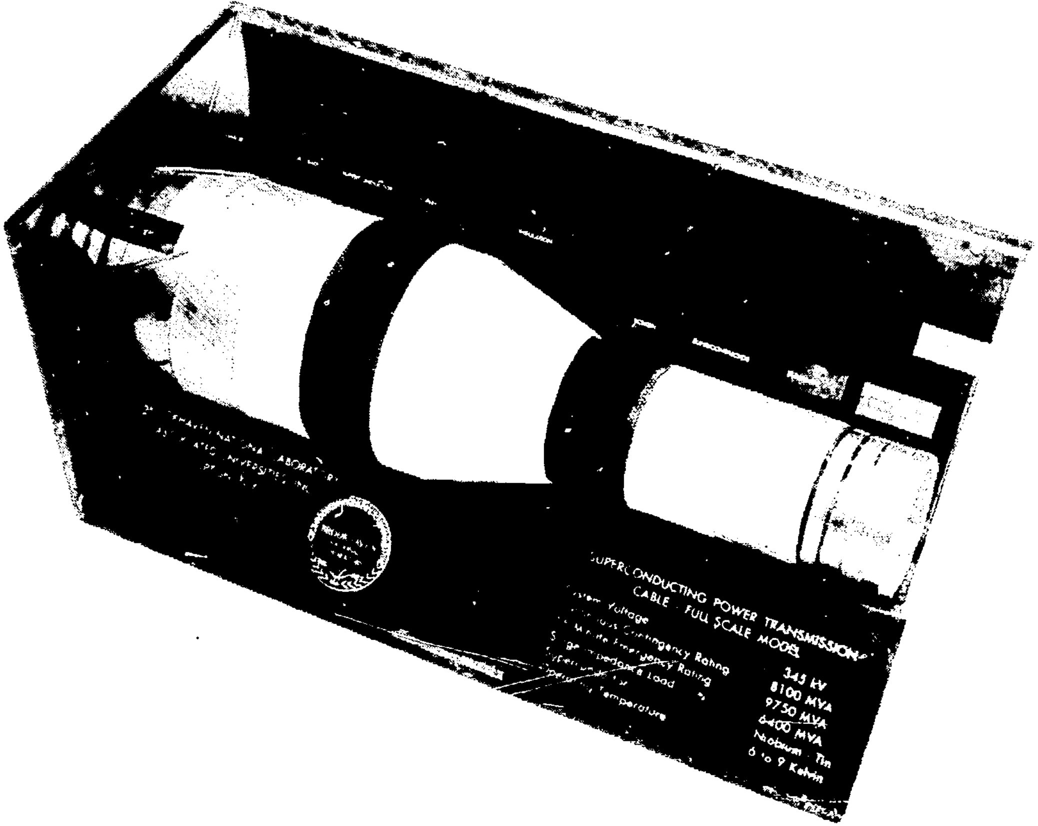


Figure 3. Full-scale model of a superconducting flexible cable designed for 345 kV system voltage. The conductors are constructed with a single layer helix.

The total axial flux enclosed by the outer conductor is the sum of that due to the currents in the inner and outer conductor:

$$\Phi_z = \mu_o(A_1\ I_1/P_1 + A_2\ I_2/P_2) = I_1F_1 + I_2F_2 \qquad (3)$$

where A is the area $\pi d^2/4$, d is the diameter and $F = \pi\mu_o d^2/4P$; the product FI is the axial flux due to I. This changing flux induces a circumferential emf in any path enclosing the outer conductor. If the closed path is a conductor, e.g., a tubular metal pressure vessel, the current due to the emf causes heating. This problem has been analyzed by Sutton[9]. The loss per unit length is

$$w' = \frac{t}{\pi\rho_3 d_3}(\dot{I}_1F_1 + \dot{I}_2F_2)^2 \qquad (4)$$

where ρ_3 is the resistivity of the tubular enclosure, d_3 is its diameter and dot denotes time derivative. If the conductor currents are equal and opposite, and $F_1 = F_2$, then ϕ_z and w' are zero.

On cool-down, it is desirable that the radial contraction be the same for all components of the cable. No axial contraction is permitted as the ends of the cable are rigidly fixed. It is easily shown that a cooled helical conductor, constrained at the ends, shrinks radially by an amount Δr, given by:

$$\Delta r/r = \alpha_c(1 + P^2/(\pi d)^2), \qquad (5)$$

where α_c is the unconstrained contraction per unit length. Note that P should not be long enough to cause an unacceptably high tensile stress in the axial direction. That component of the cable having the largest α_c determines $\Delta r/r$ for all other components; this is usually the insulating tape. With $\Delta r/r$ fixed, P/D is determined for every component. This analysis assumes no friction between components.

The helical structure thus imposes three simultaneous conditions on the cable designer:

1) Zero field in the cable interior, achieved when:

$$1/P_1 = 1/P_2 \qquad (6)$$

2) Zero flux enclosed by the cable, achieved when:

$$d_1{}^2/P_1 = d_2{}^2/P_2 \qquad (7)$$

3) Equal radial contraction of both conductors, achieved when:

$$P_1/d_1 = P_2/d_2 \qquad (8)$$

In general, cable made from single-layer helical conductors will only satisfy one of these conditions and the effects caused by the unsatisfied conditions must be minimized by other design modifications.

In addition to losses in the various components of the cable the voltage drop along the outer conductor is non-zero except when condition 7) is met. This introduces operational problems or requires the addition of extra electrical insulation.

The voltages differences may be calculated under the assumption the outer conductor is not grounded at both ends - this avoids the complication of a parallel resistive path. The outer conductor voltage is determined by capacitive as well as inductive effects, as shown in Fig. 4. The voltage drop along the complete cable must be calculated by integrating V_1 and V_2 along the entire length as given by the set of linear equations:

$$V_j = i\omega M_{jk} I_k \qquad (9)$$

where M is the mutual inductance per meter and

$$j,k = 1, 2.$$

Owing to the shunt capacitance, I_k is a function of position. For $P_1 = P_2$ and $I_2 = - I_1$ (no ground), $V_1 = i\omega I_1 L_1$, where L is the self inductance. This is identical to the drop in a tubular coaxial cable because there is no axial flux within the inner conductor coupling it to the outer conductor. The drop per unit length in the shield is:

$$V_2 = i\omega I_1 (F_1 - F_2)/P_1 \qquad (10)$$

which goes to zero as P_1 approaches infinity, the familiar condition associated with conventional coaxial cables made from seamless tubes. Under the fault condition consisting of a symmetrical line-to-line short circuit at the load end the charging current is further reduced. To good approximation, the voltage drop along the entire line under these conditions is then given by ℓV_j, where ℓ is the line length. The ratio of inner to outer voltage drops is:

$$V_2/V_1 = (F_1 - F_2)/P_1 U_1 \qquad (11)$$

For typical cable designs this ratio approaches unity, a very undesirable condition.

Since making $P_2 = P_1$ leads to so many complications, Sutton[9] suggested the use of a double helix to make each conductor. The two layers would be of equal pitch but opposite sense. Under certain conditions, the currents in the two helices are almost equal, and consequently there is no axial flux, making it possible to satisfy thermal contraction conditions when choosing the pitch. However, current flows on both surfaces of one layer in each conductor, making it necessary to have both faces superconducting (possibly with a very thin layer of good normal conductor or a high resistivity structural layer on top). If the superconductor is Nb_3Sn, the limited strain which can be tolerated necessitates a thin tape in order to meet bending requirements. These factors place a limit on the amount of normal metal stabilization which can be employed, consequently the relationship of quench current of double-layer conductors and desirable fault current capability must be carefully investigated.

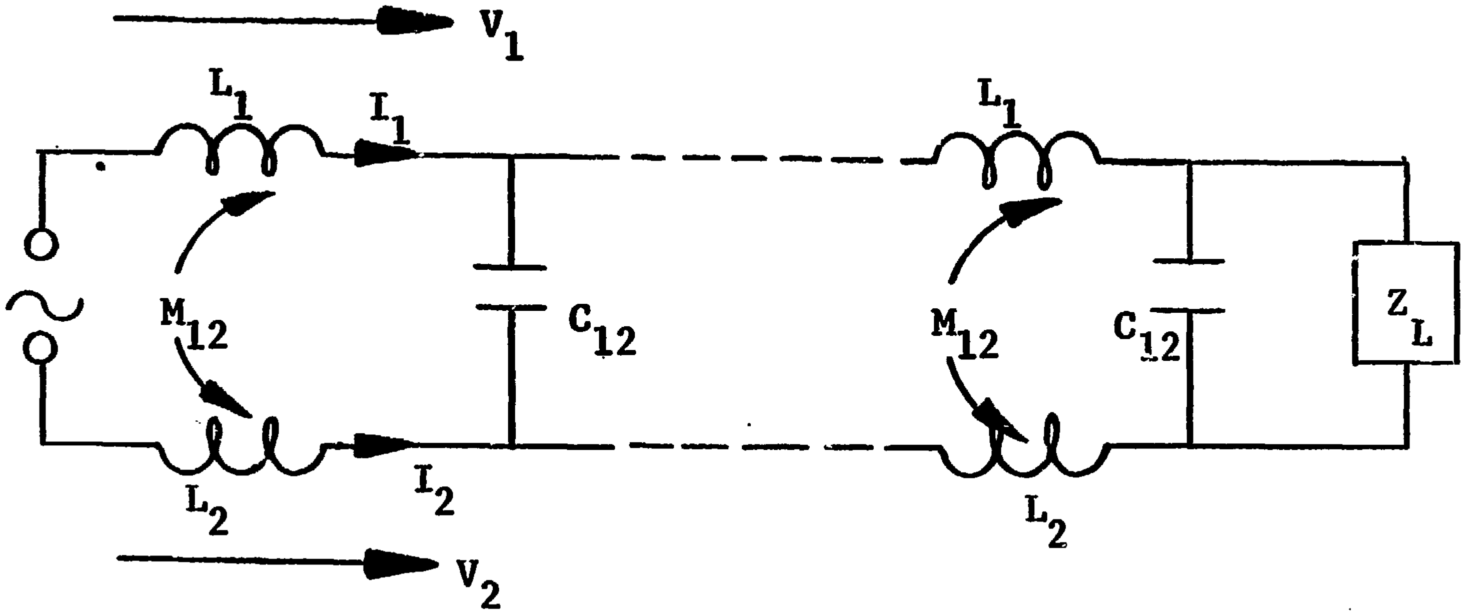


Figure 4. Equivalent circuit of an isolated-phase cable used to determine voltage drop on the outer conductor.

The inner helix of the inner conductor and the outer helix of the outer conductor could be backed with a thick layer of low resistance normal metal, but this could lead to an asymmetric quench situation, with excessive heating of the quench superconductor and voltage drop or current imbalance problems. Instead of backing only one helix of the inner conductor with normal metal, an additional helix of normal metal could be placed inside both superconducting layers of the inner conductor and perhaps the normal backing of the inner conductor helix could be detached for ease of fabrication. The complete array of conductors in the cable now consists of eight concentric helices arranged in pairs; from the inside out these would be a core consisting of two helices of normal metal having opposite pitch, and two helices of superconductor having opposite pitch, and an outer conductor consisting of the same double pairs in reverse order. This eight-layer configuration has not yet been analyzed, but it appears likely that an asymmetric quench (a quench in only one helix of a pair) would develop much less heating. Little current would be carried in the quenched layer because of the small difference in inductance between it and the underlying normal helix which has the same sense of pitch. The normal helix would have a much lower resistance than the superconductor in the quenched state.

The simplest and most economical method of winding the conductor of a coaxial cable to achieve flexibility is with both inner and outer conductors in the form of single helices. Of the three conditions which must be satisfied it is probably most important to ensure that the outside of each cable encloses no axial flux. This compromise leaves flux in the central cooling channel of each cable.

If both conductors consist of two helices having opposite but almost equal pitch of length, πd, the resulting coaxial structure excludes field from the center, has zero net axial flux and has zero shield voltage drop. Both pairs of windings have the same radial contraction, and would match a helically wound dielectric having twice the contraction coefficient. There is no difference in induced voltage between layers of the core or shield, thus eliminating any need for insulation and transposition of the two layers of the core. The absence of insulation possibly improves radial heat transfer, an important consideration during faults, and should improve superconductor stability by providing an alternate current path around local defects. The double helix has a magnetic field between the layers, which increases the superconductor loss slightly compared to a single helix and makes it impossible to put much normal metal even on the low field side of the high field superconductor. Hence the normal metal needed for huge fault currents must be present in the form of added pairs of helices inside the inner conductor and outside the outer conductor. It is thought that with such protection, recovery from quenches while carrying normal load current will be possible. The measurement of losses and quench currents for double helix cables is proceeding using machine-made models about 1 m long with plans to wind 15 m on the equipment shown in Fig. 5.

Cable Insulation

The dielectric insulation of a flexible transmission cable consists of lapped plastic tape impregnated in the butt-spaces by the helium coolant. For Nb_3Sn conductor this impregnant is typically supercritical helium in

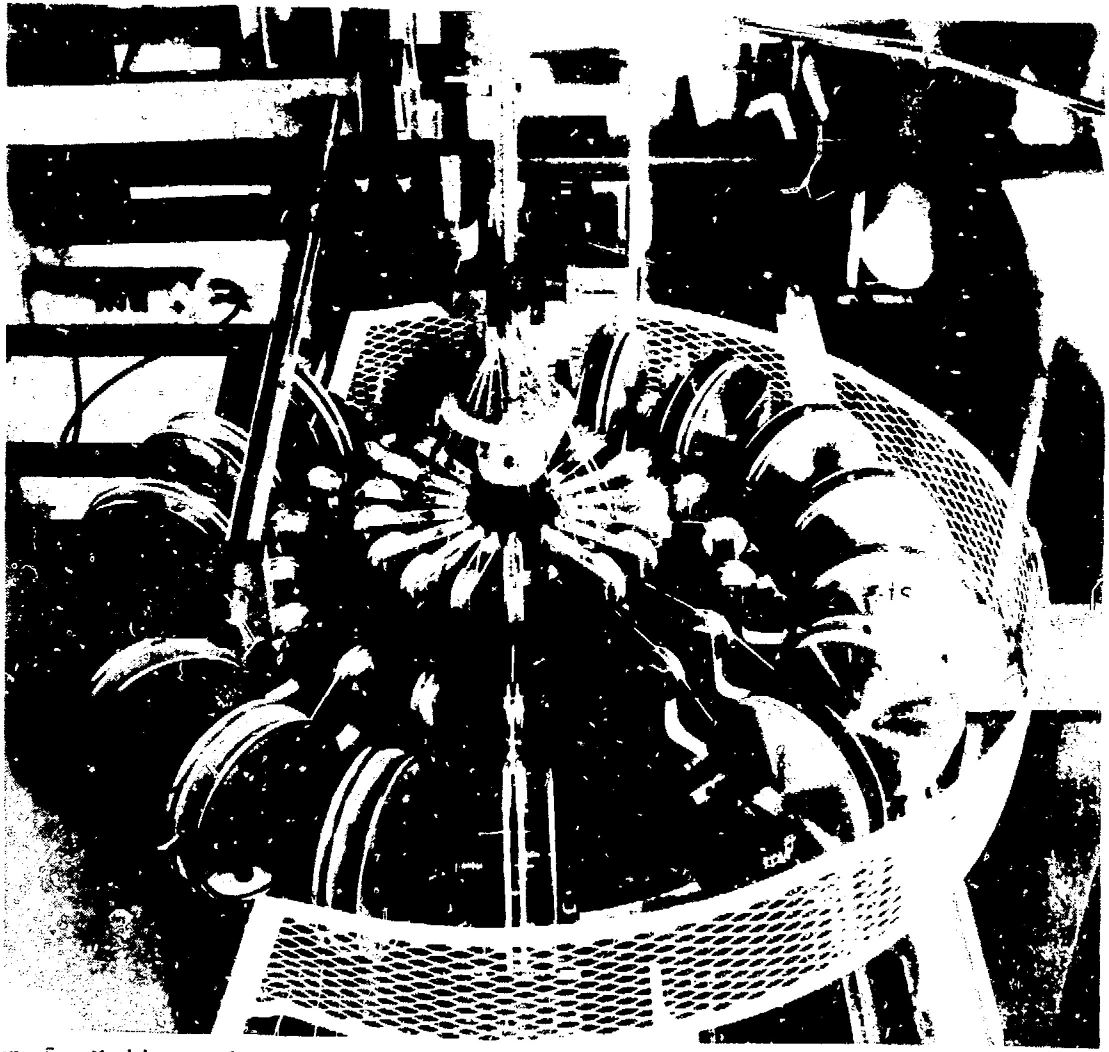


Figure 5. Machine used to construct short sample of cables for the evaluation of the superconducting tape. Samples in the range 1 to 15 m to be made with a diameter of about 3 cm.

the temperature range 7 to 9 K at 10 to 15 atmospheres[1]. Apparatus was constructed to evaluate the electrical performance of such an insulation using samples about 2 ft. long[10] . A photograph of the mandrel is shown in Fig. 6. Early tests indicated that films were much superior to synthetic paper-like tapes. The operating stress at the surface of the inner conductor has been set at 10 MV/m for current designs, this may be compared with typical results shown in Table I. This value produces both acceptable cable characteristics[11] and favorable economic comparisons with conventional systems[12] . Gas-impregnated dielectric systems behave quite differently than the more conventional oil-impregnated paper insulated cables which are commonly used in the U.S. for underground transmission. This is largely due to the mismatch of dielectric constants and subsequent stress intensification in the butt-spaces. It is important to determine acceptable corona inception and extinction stress, 60 Hz breakdown stress and impulse breakdown stress with both fast and slow rise-times.

One reason for choosing flexible cables as the preferred form of construction is that contraction on cool-down can be accommodated by changes in the radius whilst maintaining an invariant length. This is accomplished by choosing the pitch angles of the helices forming the various conductor and insulation components so that the radial contraction is the same. Due to the large contraction coefficients of plastic materials the insulation plays a dominant role in selecting the total contraction, a factor also influenced by the limited range of pitch that can be wound on conventional taping machines. These taping machines are designed to handle kraft paper, a strong, high-modulus material. Typical polymeric films are considerably more ductile and of lower yield strength than kraft papers, therefore modifications to the mechanical characteristics of plastic tapes and alterations to taping machine winding tensions will probably be required at some time in the future.

A preliminary screening of potential candidates eliminated the majority from further evaluation studies. Polyesters, polyimides, and polyurethanes were found to possess unacceptable dielectric properties. The Teflons and low density varieties of polyethylene were found to be mechanically inferior for this application. The materials remaining after the screening process and now under study are listed in Table II. The thickness, trade name, supplier and literature value of loss tangent and dielectric constant are included.

TABLE II

Dielectric Tape Candidates

Polymer Tape	Trade Name	Supplier	Thickness Mils	Thickness (μm)	Tan δ (4.2 K & 60 Hz)	Diel Const (4.2 K & 60 Hz)
Polyethylene, High Dens	--	IBM	0.75	19	$1.5\text{x}10^{-5}$	2.3
Polyamide, Nylon 11	Rilsan	Aquitaine	1.6	40	$2.5\text{x}10^{-5}$*	2.4
Polyethylene, oriented	Valeron	Van Leer	4.0	102	$0.7\text{x}10^{-5}$*	2.3
Polysulfone	Udel	Union Carbide	2.0	51	$3\text{x}10^{-5}$	2.5
Polycarbonate	Makrofol	Mobay	3.0	76	5x10-5*	2.9

*Value determined by Dr. C. N. King, Stanford University

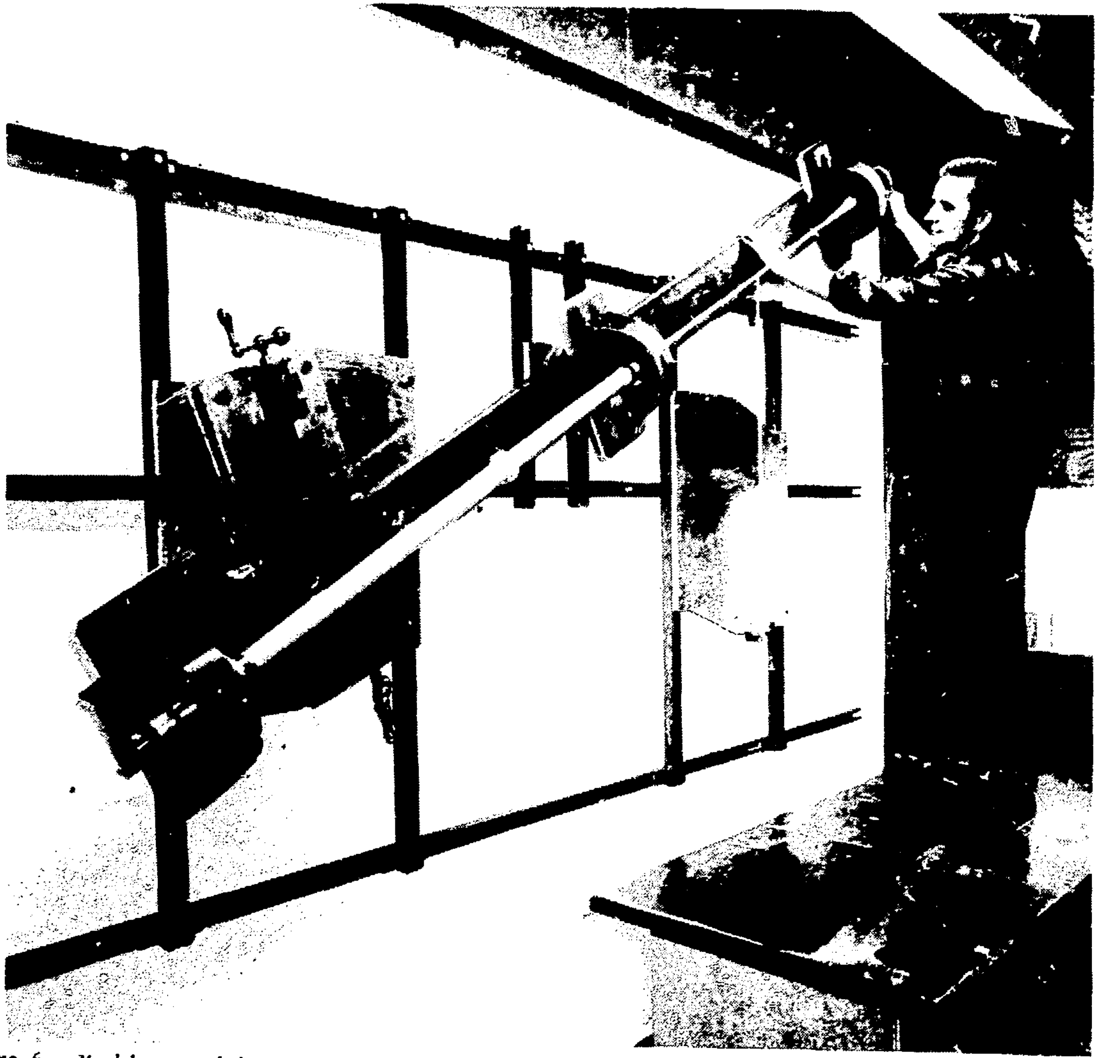


Figure 6. Machine used in the preparation of short samples of dielectric to determine corona inception, breakdown stress and other information concerning the cable insulation.

TABLE I

Electrical Tests on Short Samples

INSULATION	HELIUM DENSITY	CORONA INCEPTION LEVEL, MV/m, rms	IMPULSE BREAKDOWN, MV/m, rms
POLYETHYLENES (High Density) VALERON (oriented and Laminated)			
A) 8 layers of 100 µm thick tape with direction of lay reversed after 4 layers (0.826 mm total)	130 kg/m^3(7^{o}K)	12.6	Deterioration at 103 Breakdown at 114 (7th pulse)
B) 8 layers of 100 µm thick tape with no lay reversal (0.826 mm total)	100 kg/m^3(9^{o}K)	16.5	Deterioration at 123 Breakdown at 132 (3rd pulse)
CRYOVAC (Cross Linked and Oriented)			
20 layers of 38 µm tape no lay reversal (0.94 mm total)	100 kg/m^3(9^{o}K)	13.8	Deterioration above 148 as Mandrel Failed
	130 kg/m^3(7^{o}K)	16.0	
MYLAR			
10 layers of 76 µm tape with direction of lay reversed after 5 layers (0.76 mm total)	130 kg/m^3(7^{o}K)	13.4	Deterioration at 87 Breakdown at 115
POLYSULFONE (Udel)			
12 layers of 3 mil tape with direction of lay reversed after 6 layers (0.79 mm total)	130 kg/m^3(9^{o}K)	13.4	Breakdown at 131 (2nd pulse)

In addition to the tests on short samples electrical tests have been performed on sections of cable wound to BNL specifications by the Anaconda Wire and Cable Co. The sections are about 70 ft long so they can be cooled in the flexible Kabelmetal enclosure shown in Fig. 7. The cable has been operated at room temperature and under conditions appropriate for a superconducting cable. At present corona inception occurs at approximately one-half the value achieved for short samples, this appears to be due to deficiencies in the stress cones and is being corrected.

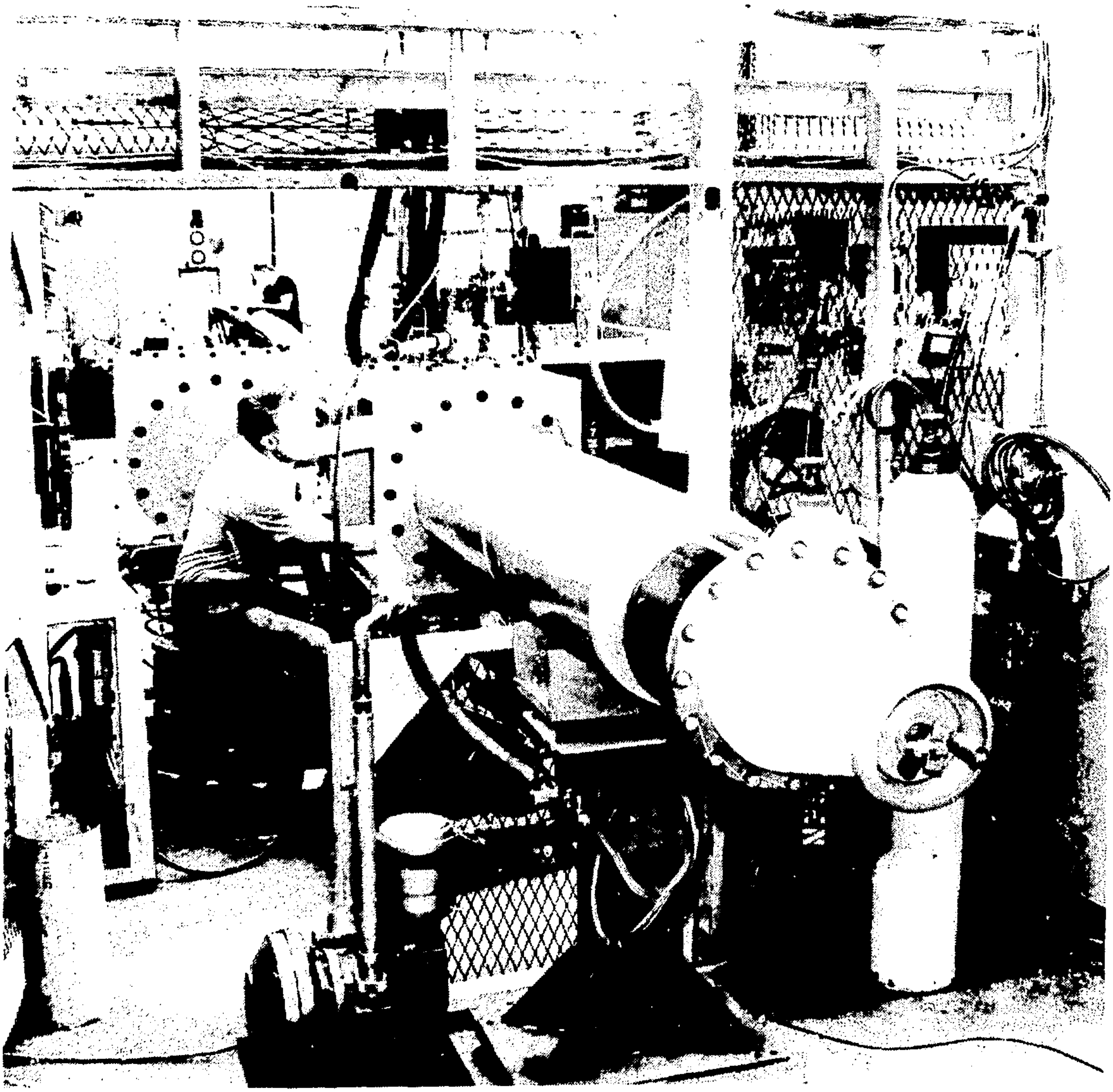
Examination of the dielectric and mechanical properties of the five tapes evaluated indicates that none simultaneously fulfills all the requirements of superconducting cable design, however, several have excellent properties and are close to meeting these requirements. Polyethylene easily meets the dielectric requirements but was found to possess substandard yield strengths and tensile moduli. Polyamide and polysulfone exhibited acceptable yield strengths but their moduli are probably still too low for satisfactory taping. Also, the dielectric properties of these materials may be slightly outside design specifications. The polycarbonate was found to possess completely acceptable mechanical properties but its loss tangent appears to be much too high.

As part of an effort to optimize the characteristics of these films, corrective action was initiated in several ways. Experimental samples of Makrofol will be prepared with reduced concentrations of solvent, dyes, and other additives in order to reduce the loss tangent and dielectric constant of this material. Modifications will be made to the polymerization and extrusion processes of polyethylene, polyamide, and polysulfone in order to improve the moduli, yield and tensile strengths of these films. Finally, blends of polyethylene with other polymers are being fabricated in order to increase the cryogenic ductitility of this film. Once an acceptable short-term design of insulation is achieved many problems will remain. In particular mechanisms of long-term degradation must be investigated, a topic which has received little attention for materials at cryogenic temperatures[13] .

The preliminary results obtained with the 70 ft. sample cable indicate that many practical problems have still to be overcome in the design of terminations, stress cones and the cable itself. There is some evidence that the armoring process caused pinching of the polyethylene insulation. For these reasons the somewhat lower corona inception levels measured in the large sample are explainable and better techniques should lead to substantially better performance.

Cryogenic Engineering

The activities in this area include refrigerator design, helium flow studies, the design of cryogenic enclosures, the design of pothead terminations and the construction of a variety of laboratory cryogenic apparatus. As a result of the analysis of a 43 mile transmission system performed with the cooperation of the Long Island Lighting Company [12] (LILCO) it became apparent that the cryogenic enclosure constituted a major share of the cost and this equipment must be carefully optimized to provide adequate performance.



re 7. The Kabelmetal cryostat used for dielectric testing of 20 m cable specimens. The feedthrough pothead bushing is seen in the foreground.

The first cryostat to be tested is similar to the design of a cryogenic liquid transfer line. The design uses all stainless steel construction, expansion bellows, bayonet joints, and does not have refrigerated radiation shields or refrigerant return lines, this approach has a larger heat leak but a potentially lower cost than the other candidates.

Two pieces of 2.5 m in length each with a bayonet joint forming a 5 m test section have been constructed, see Fig. 8. As constructed, the only non-metallic parts of the system are the alunimized mylar and polyester fiber paper of the multilayered insulation. Aluminum foil and glass fiber paper could be substituted for the high temperature bake-out requirement. The internal pipe supports are all metal and consist of wire cable assemblies used as tensile members. The cables are attached to rings fitted to the inner and outer pipe. A male and female bayonet joint make it possible to seal, pump and bake the complete vacuum system at the factory. The only field welds required seal the helium gas and this can be accomplished with s single circumferential weld. The bayonets are fabricated by spinning and hydroforming to reduce the number of welded joints. The inner helium tube is 102 mm x 2.1 mm wall stainless steel. The outer tube is 203 mm O.D. x 6.3 mm wall stainless steel. The assembled test section 5 m long contains one bayonet joint and two inner pipe supports. After assembly ten inches of urathane foam insulation were added to the outside of the vacuum-multilayer insulation, allowing a liquid nitrogen trace line to be used. This addition allows the exterior vacuum wall to operate at 78 K as a radiation shield but, more importantly, the temperature gradient across the bayonet is reduced. The performance of the enclosure was evaluated using a supercritical helium refrigerator. At a pressure of 1.2 atms the heat leak at the bayonet joint is about 5 W. At a pressure of 8 atms this increases to 8 W due to gas conduction in the annular space of the bayonet joint. The heat leak into the enclosure other than at the joint is too small to measure.

Kabel und Metallwerke (Kabelmetal) was probably the first commercial company to produce a cryogenic enclosure for Laboratory testing of superconducting power transmission cables. Their product was first used by AEG-Telefunken of Germany and Prof. Klaudy of the Institute for Low Temperature Research at Graz, Austria[14].

Kabelmetal is a large German company that produces metal products and electrical cables. Their unique Wellmetel machine was originally developed to apply a corrugated metal sheath over large power cables. By forming one corrugated tube over another, an insulated flexible pipe can be made. Such a pipe, with foam insulation in the outer annular space, is widely used to transport hot water for domestic heating service. A double walled pipe, with vacuum insulation in the outer space, is being used to transport liquid nitrogen. The nitrogen line, and the corrugated cable sheath are being manufactured in the U.S. under licensing arrangements with Kabelmetal.

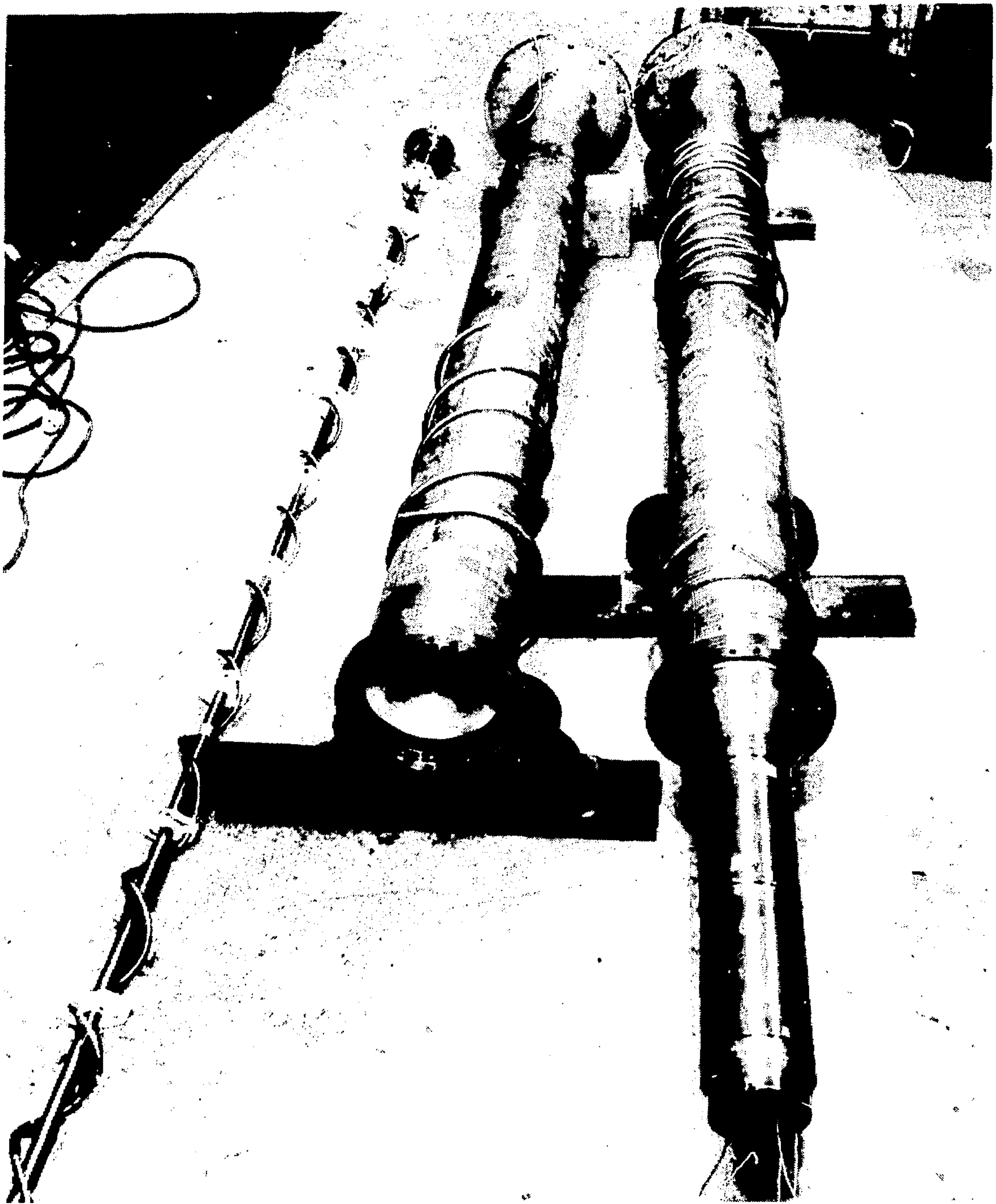


Figure 8. The cryostat and bayonet joint used in the first test of a cryogenic envelope for cable applications.

The four walled cryogenic enclosure for superconducting cables or liquid helium transport was developed jointly by Kabelmetal, AEG and Linde AG. (See Fig. 9 for construction details.) The four tubes are fabricated by automatic machinery and only the spacers between tubes and the multilayer insulation are applied by hand labor. Kabelmetal feels confident that the entire operation could be done automatically, if production quantities justified the necessary capital investment. This candidate cryogenic enclosure departs from the desired design criterion in several respects. The inside diameter is smaller than desired (7.4 cm) and no internal return paths are provided for the cable and shield refrigerants. The construction uses long axial welds, and the thermal insulating vacuum spaces are not sealed off in manufacture. Although these are major departures from the desired design, the commercial availability of this cryogenic enclosure made it desirable for evaluation.

An analysis of the performance shows the heat leak to the cable space of the Kabelmetal envelope is 0.1 ± 0.03 watts/meter. The design figure was quoted at 0.1 watts/meter. The heat leak to the liquid N_2 shield is 3.7 ± 0.3 watts/meter. This value is a factor of 2 higher than the design figure of 1.8 watts/meter. During these tests the insulating vacuum was always 5×10^{-6} Torr or lower and nothing has been found that explains the high shield losses.

The data also indicates that the four flexible tubes of the Kabelmetal envelope do not always act as four independent bellows. Bending the line, or perhaps cooling it, can cause adjacent tubes to partially lock and to apply unpredictable loads. Although these effects were not very large, they should be investigated further. The third enclosure to be evaluated is based on the rigid design used in the LILCO study. It was made to Brookhaven specification by the Cryenco Division of Cryogenic Technology Incorporated. Three vacuum welds must be made in the field for each joint. The individual enclosure sections each have their own sealed-off vacuum insulation, but the joint between sections must be insulated, welded, and evacuated. This enclosure is basically a rigid design. Special flexible sections have been designed to allow enough bending to clear obstructions. The inner stainless steel pipes containing the cables are not welded together. A bellows is slipped over the inner pipe and is welded to the pipe end. A stainless steel tube is slipped over the bellows and is welded to the inner end of the bellows. The outer end of these tubes are welded together during the field installation. This arrangement allows the contraction forces in the inner pipe to be counteracted in part by the pressure forces. The outer vacuum jacket is fabricated from mild steel. Thermal conduction between the cold inner pipe and the warm outer jacket is held to a minimum by the use of two G-11 fiberglass cylinders as separators at each end. Refrigerant tubes pass through the vacuum space and penetrate a steel ring separating the two fiberglass tubes. Multilayer insulation is wrapped in the vacuum space between the inner pipe and outer mild steel vacuum jacket. Aluminum foil is attached to the refrigeration tubes passing through this insulation space forming two refrigerated radiation shields with the multilayer between the foil and metal walls. An additional tube and foil wrap is placed close to the

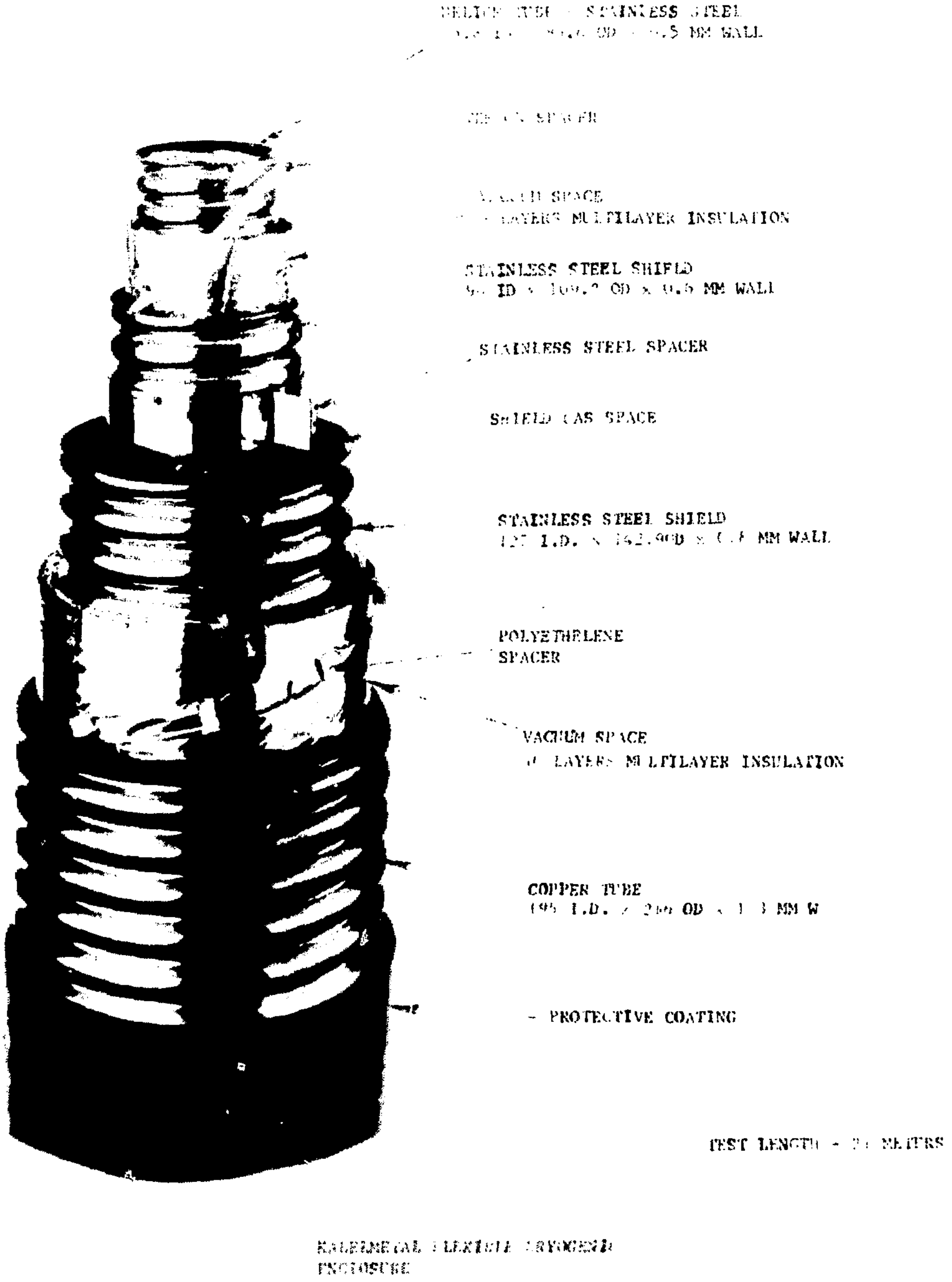


Figure . Construction details of the flexible cryostat developed by Kabelmetal. The cryostat consists of four concentric corrugated pipes. The middle annulus is used as an intermediate temperature shield. The inner and outer annuli are continuously evacuated.

inner pipe to act as a return path for the refrigerant used to cool the cables. The temperature of this return line is near 8 K. Thus, heat leak through the cryogenic enclosure does not reach the cables, but is diminished by the multilayer insulation and is intercepted by the three refrigerated shields.

Making the field joint calls for welding the tubes together that surround the bellows, connecting the refrigeration tubes, wrapping multilayer insulation, and welding on a short section of vacuum jacket. A getter material is placed next to the cold surface before wrapping the insulation. The volume between the enclosures is evacuated and sealed off. Seals are backed with a dry nitrogen gas to prevent deterioration.

Although the design apparently provides good thermal properties the cryostat is relatively complicated and expensive. In particular, the high-temperature shield and thermally-insulated helium return pipes contribute to the complexity. In an attempt to simplify the cryostat an intensive investigation has been made using both computer-assisted analysis and experimental measurements on the Kabelmetal cryostat to incorporate the cable and cryostat as a heat exchanger element in the refrigeration system. This requires an expansion engine at the far end of the cooling loop. The performance to be expected from this mode of operation has been described in detail[15,16]). In this method of cooling the helium-flow stream is expanded at the far end of the transmission line cooling section and returns as either a low pressure gas or two-phase liquid. Expansion of the cooling helium flow is accomplished by means of an engine to extract work or a Joule-Thompson valve. If such a system is used, significant improvement may be made in such components as the cryogenic enclosure, primary refrigerator and in the cable design.

In general, the high pressure helium gas flow will be contained by the electrical cable within the enclosure. If this is a flexible cable the outer jacket should be gas-tight. This can be accomplished by means of a corrugated sheath and is a well-known technique. If the conductors are arranged in the form of rigid pipes, it is only necessary to insure the outside pipe, forming the current return path, is gas tight. Alternatively a concentric envelope can be used which is not thermally insulated from the annulus carrying the return gas flow.

It should be pointed out that very small leaks in either the rigid or flexible cables will be tolerable. The only requirement is that the leak does not produce a significant reduction in the pressure of the coolant in the cable. At the end of a cooling section, at a distance determined by thermodynamic and hydrodynamic considerations, the cooling gas is expanded as described above.

Many advantages for power transmission cooling systems can be realized:

1. Thickness of enclosure inner wall - due to the fact that the gas in the inner space of the enclosure is at a significantly lower pressure than systems with equal pressures in the cable and the inner space of the enclosure, it is possible to reduce the thickness of metal forming the inner pipe of the enclosure.

2. Simplification in construction of enclosure - systems designed with equal pressure in the cable and the enclosure inner space require a thermally insulated return line for the helium. This line is eliminated in the system under discussion.

3. Equalization of temperature in the cable - the gas returned to the lower pressure volume of the enclosure is at a lower temperature due to expansion at the far end. Due to heat flow between this gas and the gas in the cable, the cable is thus cooled from either end. This permits a reduction in the maximum temperature excursion of the cable or a larger cooling section for a given temperature rise. If necessary, heat transfer between the two gas flows can be adjusted by modification of the outside surface area of the cable jacket. In fact, the cable and enclosure form a counterflow heat exchanger. Great care must be taken to differentiate this system from enclosure designs proposed in the past in which heat flows between the cable and the returning gas, but in which no expansion occurred at the far end. Only counterflow systems in which the coolant's temperature is lowered at the far end below the temperature of the coolant as it enters the cable will operate correctly.

4. Reduction of heat leak at enclosure joints - joints between adjacent sections of the enclosures constitute extra sources of heat leakage, this is particularly true in sealed vacuum systems which require a vacuum seal at the joint between the high temperature and low temperature walls of the enclosure. Due to the reduction in the operating pressure in the inner space of the enclosure, the mechanical strength of the sealing components may be reduced and thus reduce heat leak due to termal conductivity. In addition, significant heat leakage occurs due to conduction in the gas trapped in the annulus around the seal. This source is also reduced by reducing the pressure in the enclosure inner volume.

5. Reduction in helium inventory - the total amount of helium stored in a transmission system is significantly reduced by reducing the pressure in the inner volume of the cryostat. This also reduces the time necessary for cool-down and warm-up.

6. Improvement in dielectric strength of cable - in a superconducting system the coolant helium plays a role in the maximum voltage stress which can be permitted. In general, it is desirable to have as high a density of helium as possible. Because in this system only the cable is pressured, this permits operation at a higher pressure than may be desirable if the complete enclosure is pressurized to a high level.

7. Improvement in heat transfer within the cable - because a high pressure may be employed within the cable, the heat capacity of the coolant removing heat from the dissipative elements in the cable is increased. This is especially important when the cable is subject to great variations in heat loading, such as during fault conditions.

8. Improvement in refrigerator efficiency - in the form of this system in which two-phase liquid is returned the efficiency of the refrigerator system is improved in the low temperature region (4.5 to 5 Kelvin) due to the elimination of a circulating pump and/or liquid bath heat exchanger.

9. Reduction in end forces - the end forces on the enclosure are significantly reduced due to the use of low pressure gas in the inner volume of the enclosure.

10. Elimination of unstable operation - it is well-known that helium cooling systems may exhibit unstable operation when operated near the transposed critical line. The choice of two distinct operating regions for the coolant, namely high pressure go and low pressure return, permits the operating points to be located well away from the transposed critical line and thus reduces the possibility of instabilities.

Systems Engineering

Every effort has been made at Brookhaven to make design choices during the course of the development of superconducting cables which will ultimately lead to a system which is technically and economically attractive to the utility companies. However, Brookhaven's primary experience is not in the field of power system engineering and thus it is essential that these decisions are reviewed by competent engineers at an early stage. This has been accomplished by joint investigations by Brookhaven and engineers from participating utility companies of potential situations in which superconducting transmission may be used. These situations take the form of planned extensions of transmission facilities in which the power level, restrictions on overhead lines or other factors indicate that superconducting cables may be employed. Naturally it is understood that the present early development stage of superconducting systems prevents any serious comtemplation of an actual installation. The purpose of the studies is to:

i) Produce cost estimates which will be more credible than those obtained in previous studies.

ii) Identify technical problems which may have been overlooked up to now, so that they can be attacked while the design concepts are still flexible.

The first study of an actual utility system transmission requirement was a very cursory look at the Consolidated Edison facilities to the north of New York City. A preliminary technical design of the cables was developed without any economic analysis. The purpose was to determine if it was possible to achieve correct impedance matching, and thus proper load sharing, between superconducting and conventional transmission systems. The results were encouraging enough to warrant a much more comprehensive study in cooperation with the Long Island Lighting Company. At present a study of a potential 10,000 MW 350 mile application is being performed in cooperation with utility companies in Pennsylvania. Before describing these studies in more detail a brief review will be given of the simple relationships used to relate network parameters to the conductor magnetic field and insulation electric stress, the subject has been explored in depth in other papers[1,11]. The relationships may be defined in terms of an admittance, Y, as follows:

$$Y = \frac{J_s}{E}\text{, mho, where .....} \tag{12}$$

J_s is the rms transport current per unit length of circumference of inner conductor, A/m. (J_s is often referred to as the 'linear current density'.) E is the rms electric field strength at the insulator just adjacent to the inner conductor, V/m. It can be shown that for superconducting cables, where the current is carried in a negligible depth of conductor:

$$\bar{Z}_L = 0.475Y\text{, km}^{-1}\text{ .....} \tag{13}$$

$$\bar{Z}_c = \frac{3.0 \times 10^5}{\epsilon_r} Y\text{, km .....} \tag{14}$$

$$\bar{Z}_o = \frac{378}{\sqrt{\epsilon_r}} Y \text{ .....} \tag{15}$$

where, $\bar{Z}_L$ = per unit series reactance of each km, 60 Hz.

$\bar{Z}_c$ = per unit shunt reactance of each km, 60 Hz.

$\bar{Z}_o$ = per unit surge impedance load (SIL).

ϵ_r = relative dielectric constant.

Y is a useful parameter because many important superconductor characteristics can be expressed as a function of J_s and insulation properties as a function of E. Typical values for cable systems based on Equation 12 through 15 are given in Table III.

The long-range plans of the Long Island Lighting Company (LILCO) include the addition of four nuclear units, each of a nominal 1150 MWe by the early 1990's. For the purposes of the study it has been assumed all four units will be located at a site near Shoreham, permitting a point-to-point transmission system to be studied. The Shoreham site would require a transmission system with a capability of about 4800 MVA to major substation, Ruland Road, located near the Nassau County-Suffolk County border some 43 miles away. Systems analysis and right-of-way engineering evaluation have already been performed by LILCO in planning a 345 kV overhead and high pressure oil-filled (HPOF) system. After a preliminary survey the company did not press further consideration of dc transmission as the high cost of converter terminals cannot be justified over the distances involved. For the case study three different superconducting schemes evolved which appeared appropriate for more detailed technical design and cost analysis, the routes are shown in Fig. 10. The basic designs of the superconducting cables were made at Brookhaven using

TABLE III

Typical Surge Impedance Load Capacities for Flexible Superconducting Cable Transmission Systems

Common Properties of All Designs:

Linear current density, A/m : 42,700
Electric field at r_1*, MV/m : 10
Relative dielectric constant, : 2.6
r_2/r_1 : 1.5
$\bar{Z}_L$, km : 2.02×10^{-3}
$\bar{Z}_c$, km^{-1} : 493

System Voltage, kV	SIL, MVA	Cable Outer Dia, cm	Containment Pipe Outer Diameter, cm
69	320	3.5	30
138	1,280	6.5	35
230	3,530	11.0	47
345	7,860	16.0	57

*r_1 and r_2 are the inner and outer radii of the insulation.

measured properties of the superconductor[3]. The electric stress under normal conditions is under the level for corona inception[17], refer to the section on insulation design of this paper for a fuller discussion of cable design. The heat loads and refrigeration designs were also carried out at Brookhaven. The design and cost estimate of the cryogenic envelopes were prepared by the Cryenco Division of Cryogenic Technologies using a design described in the section on cryogenic engineering. The technical characteristics of the design were compatible with the overall operation of the cooling system. The investigations of system stability, route planning and installation were jointly carried by LILCO engineers and a consulting firm in this field: Power Technologies Inc. The cost of cable fabrication was also prepared by Power Technologies Inc., based on material prices estimated by staff at Brookhaven.

The technical aspects of the study have been described in the literature[12], a summary of the three plans developed is given in Table IV. A summary of costs for each superconducting together with corresponding conventional transmission equipment with the same ratings is given in Table V.

From a technical standpoint no obstacles have been detected which appear to block the ultimate appearance of superconducting cables in transmission networks, under the assumption of the study. It must be emphasized that at the present time development of superconducting cables in the U.S. is concerned entirely with laboratory-scale equipment. A proper assessment of superconducting transmission will only be possible after the construction of prototypes of a size more comparable to actual transmission systems.

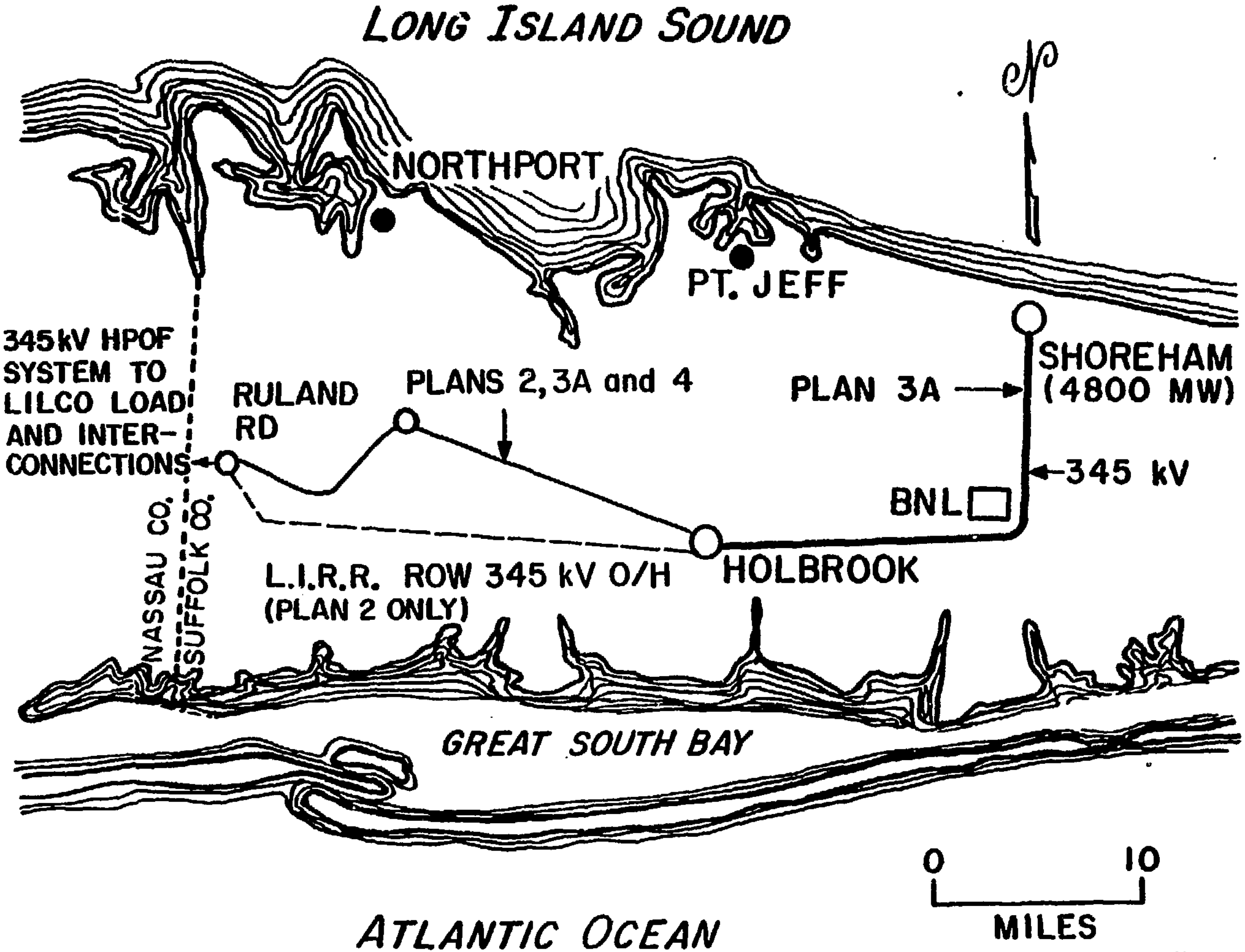


Figure 10. Map of the transmission system studied in cooperation with the Long Island Lighting Company. Plan 2 consists of two circuits at 138 kV from Ruland to Holbrook. Plan 3A consists of two circuits at 345 kV from Ruland to Shoreham. Plan 4 consists of three circuits at 345 kV from Ruland to Holbrook.

TABLE IV

Flexible Superconducting Cables Basic Design Parameters

	Plan 2	Plan 3A	Plan 4
Voltage, kV	138	345	345
No. of Circuits/Single Circuit Normal MVA	2/1300	2/2400	3/1600
(Continuous Contingency MVA)	(2100)	(4800)	(2400)
Length of Circuit, km.	35.6	68.4	35.6
(Mile)	(22)	(42.5)	(22)
Inner Conductor Radius, cm.	2.68	3.01	1.83
(Inches)	(1.06)	(1.19)	(0.72)
Radius of SC Shield, cm.	3.61	5.83	5.44
(Inches)	(1.42)	(2.30)	(2.14)
Outer Dia. of Cable, cm.	8.1	12.4	12.04
(Inches)	3.19	(4.88)	(4.74)
Max Electrical Stress, kV/cm.	100	100	100
(V/Mil)	(254)	(254)	(254)
Mean rms Stress, kV/cm.	86	71	55.2
(V/Mil)	(218)	(180)	(140)
Normal Current, kA.	5.5	4.0	2.67
Dielectric Constant of Insulation.	2.2	2.2	2.2

The use of transformers in plan 2 clearly introduces technical problems and a substantial cost penalty. The transformers are large and their reactance makes it difficult to match the impedance of the superconducting circuit to the parallel overhead circuit impedance. This match is necessary to obtain proper load sharing between both systems. Considered alone the 138 kV circuit seems attractive except that substation design to handle 2600 MVA at 138 kV is not practical using present-day equipment.

The circuit breakers required do not seem to call for significant advances in present technology except for plan 3A, where the continuous contingency current for the superconducting design is 8,000 A. This continuous rating is beyond present technology for 345 kV breakers.

Clearly, at the present time, it is not possible to assess the operating reliability of superconducting transmission systems. There seems to beevery possibility that the cables will be extremely reliable as there is virtually

TABLE V

Cost for Flexible Superconducting Cables Compared with Conventional Circuits

	Plan 2		Plan 3A		Plan 4	
	SC	Conventional	SC	Conventional	SC	Conventional
1. Number of Circuits	2	Double Ckt OH + 2-345 kV HPOF	2	9-345 kV HPOF	3	9-345 kV HPOF
2. Installed Cost of System (see Table VI, Item 7)	$64,000,000	$65,600,000	$189,800,000	$344,200,000	$139,500,000	$178,200,000
3. Reactive Compensation	-	$ 1,400,000	-	$ 24,200,000	-	$ 12,200,000
4. Demand, Capitalized Energy and Maintenance	$ 2,500,000	$ 7,900,000	$ 13,000,000	$ 42,000,000	$ 5,200,000	$ 22,000,000
5. Transformation Required	$21,000,000	-	-	-	-	-
6. Circuit Breakers Required	$ 7,700,000	$ 4,200,000	$ 6,000,000	$ 11,200,000	$ 11,900,000	$ 16,100,000
7. TOTAL INSTALLED COST FOR EQUIVALENT SYSTEMS INCLUDING ALL ASSOCIATED STATION COSTS	$95,800,000	$79,100,000	$208,800,000	$421,600,000	$156,600,000	$228,500,000
8. Total MVA, Normal Load	2,600	NA	4,800	4,800	4,800	4,800
9. Dollars/MVA-Mile	$1,760	NA	$1,020	$2,070	$1,470	$2,160
8a. Total MVA, Continuous Contingency Rating	4,200	NA	9,600	5,400	7,200	5,400
9a. Dollars/MVA-Mile	$1,036	NA	$510	$1,840	$980	$1,920

no temperature change associated with load variations. Representatives from the industry firmly believe that refrigerators properly designed for this class of service can provide acceptable reliability. Of the three plans examined it must be conceded that plan 3A may not provide complete contingency protection as the failure of both circuits would result in the shutdown of generation at Shoreham. Thus the cost estimates for plan 3A are potentially the lowest for a very high capacity transmission system. Plan 4 has the same capacity as plan 3A but three circuits are used, thus surpassing most conceivable contingency criteria. The financial penalty imposed by the third circuit can be seen by comparing specific costs in Table V.

Table V shows that the costs of superconducting systems appear to be quite attractive, in each plan the single most expensive item in the materials section is the cryogenic envelope. This factor has been influential in deciding on the cryostat development program described in the section on cryogenic engineering. Although a completely overhead 345 kV system is unlikely because of lack of right-of-way and environmental considerations it has been estimated that such a system comprising five circuits 43 miles long would cost about $110 million, including cost of breakers and capitalized losses. This figure can be compared to the cost of $209 million on line 7, Table V for the superconducting version of plan 3A. This is a significant improvement in the cost differential for an underground system and represents a important step towards the goal set by the Electric Research Council of bringing overhead and underground transmission costs into line[18]. If the cost analysis had been based on present worth the financial advantage of superconducting schemes compared with HPOF cables would have been less noticable in this case study. Conventional underground cable circuits could be installed to match the steady growth of generation capacity, but the fewer number of superconducting circuits would have to be operational from the beginning. This is not an unusual problem in the installation of high-capacity systems, which are often underutilized in the early years of operation.

Caution must be used when extrapolating the figures obtained in this study to other cable concepts, other sites and other times. A few generalizations can be made: the installation cost of flexible superconducting systems is not a large percentage of the whole, hence, these systems may be attractive in more built-up areas, where installation is more difficult. The energy costs of superconducting cables are much less than conventional methods, if fuel continue to rise in the future this factor will favor superconducting systems. In the cases studied it was not necessary to include the cost of acquiring right-of-way. If this had not been the situation it seems likely the addition of this cost would also favor superconducting systems, which require only one or two trenches. In addition, the high capacity with fewer circuits significantly reduces space requirements at substations, due to fewer terminals and breakers and the absence of reactive compensation. It is interesting to compare the specific costs generated in this study with earlier figures. Some previous studies were presented in the Brookhaven report on underground transmission[1]. The figures for superconducting transmission cover a spread, with cost estimates made by the Linde Division of Union Carbide Corporation[2] forming the lower bound and Brookhaven estimates forming the upper limit.

The comparison with this study is summarized in Table VI. Specific cost estimates are shown for a continuous maximum rating without circuit breaker and transformation costs. The figures for plans 2 and 3A show reasonably good agreement with previous BNL estimates. The Linde figures are uniformly optimistic, but it must be recalled these are based on 1969 dollars and are for single circuit designs. The heavy financial penalty of a third circuit in plan 4 is clearly emphasized when comparing specific costs.

TABLE VI

Comparison of Cost Estimates

Plan	Circuits	Continuous Contingency Power, MVA	Specific Cost Linde Study $/MVA-Mile+	Specific Cost BNL 50325 $/MVA-Mile	Specific Cost of Cable only, LILCO Study $/MVA-Mile
2	2	4,200	350	650	730
3A	2	9,600	250	510	490
4	3	7,200	275	520	910

+Based on a single circuit design.

In order to study possible applications of superconducting cables in long-distance applications advantage has been taken of a report on the transmission facilities required a hyperthetical 10,000 MW generating park located in western Pennsylvania. The power will be transmitted approximately 350 miles to loads in eastern Pennsylvania. Several H.V. ac O/H and one dc scheme were considered and analyzed to determine cost and efficiency. For comparison purposes the superconducting system has been designed to replace a 3-circuit 1,300 kV ac O/H design. The preliminary electrical design has been arranged to provide the same steady-state load flow and stability margin as the reference O/H system. Three plans have been considered which are described below. A simplified one-line diagram for a base case of 10,000 MW generation is shown in Fig. 11. A double circuit runs to the Alburtis Substation near Allentown and a single circuit to the Midsite Substation near Philadelphia. The p.u. voltages, MW and MVAR were computed at Power Technologies Inc.

The helium-cooled designs are all for 500 kV, a convenient voltage as this avoids the use of transformers at the load end. A brief summary of each plan follows:

Plan 1

Two circuits from the generation site connect to Alburtis. A third circuit connects the generators to Midsite. A link between Alburtis and Midsite is made, but has not been examined in detail. All three circuits require series capacitive compensation and shunt reactors, the compensation is similar to the scheme required using three 1,300 kV/O/H circuits. Because of the heavy compensation this scheme makes the most economic use of the cables.

PJM ENERGY PARK STUDY

Base Case from GPU
(40 % Series Compensation)

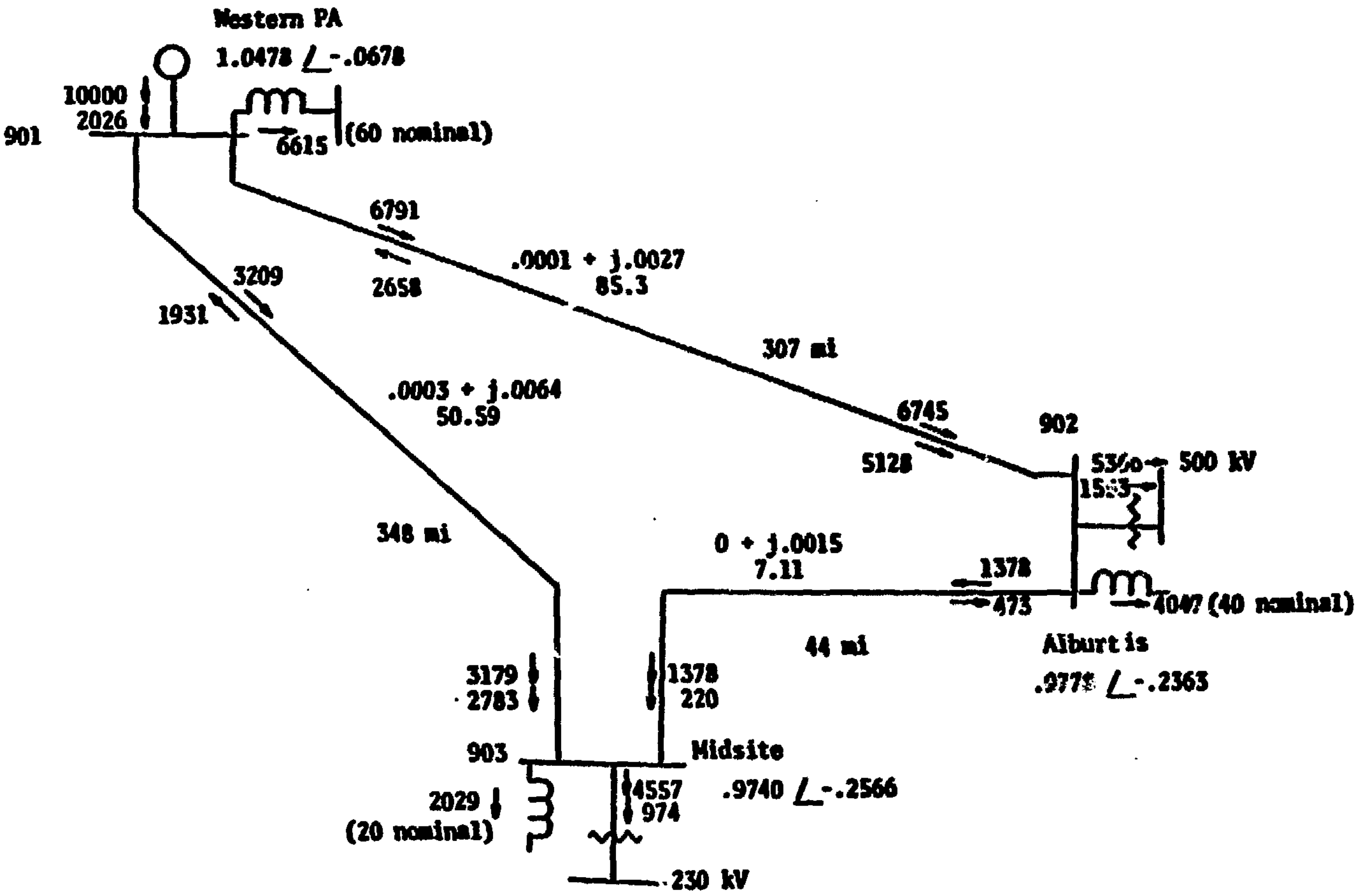


Figure 11. One-line diagram of the transmission system studied in Pennsylvania. Generation of 10,000 MW in western Pennsylvania is connected to substations at Alburtis and Midsite. The case shown is for the 1300 kV three-circuit overhead design used as a comparitive reference.

Plan 2

Three circuits as in plan 1 connect the generating site to the Alburtis and Midsite Substations. By operating the cables at lower current density the series capacitive compensation can be eliminated. In the past series compensation has resulted in undesirable subharmonic system resonances and has been blamed for turbine blade failure. Thus elimination of this type of compensation is technically desirable.

Plan 3

In this plan the single circuit used in plans 1 and 2 from the generating site to Midsite is increased to two circuits. This is a "super-reliable" design because it may be argued that three circuits provide adequate contingency protection for O/H systems but not for underground, due to the much longer time needed to repair the latter. By having two double circuits to each substation the reliability can also be improved by providing a bus-bar connection in the mid-span region. Thus only half a circuit is lost for the first level of contingency operation. No series compensation is required for this design.

A summary of the important circuit characteristics of the three plans under study is given in Table VII. In all cases a base case generation of 10,000 MW is assumed.

The design parameters of cables for each plan are shown in Table VIII. For the purposes of this study, transformer tap changes were not made. Reactor sizes were chosen instead to give a reasonable voltage level. Of course, if a system such as this were to be actually designed, it would be necessary to go further into consideration of transformer tap ratios, reactor sizes, and operating voltage levels to achieve an optimum design. Again, this is merely a technical feasibility study and not a planning study so factors such as these are of relatively less importance.

Based on a sequence of load flow tests, system performance with superconducting cables is comparable to that using UHV overhead. The 500 kV cables eliminate a step of transformation in going to 1300 kV overhead, giving a reduction in the system reactance which helps to compensate for the higher reactance of the cables. The cables have somewhat higher charging than the overhead line, but not nearly on so great a scale as would occur with conventional cables. The heavy loading of the superconducting cables negates much of the charging, allowing compensation with reactors as with the UHV scheme.

In order to investigate transient stability, probably the most important characteristic of long-distance transmission which determines the cable operating conditions, the energy park system under consideration may be regarded as of a large generator feeding its load through long circuits with no local tie-in to the rest of the power system. All other generation is remote from the energy park. For purposes of an initial investigation into

TABLE VII

Design of Circuits (10,000 MW Generation

Parameter	Mode of Operation	Gen-Alburtis	Gen-Midsite
Distance, km	-	498	563
1,300 kV O/H			
Number of Circuits		2	1
MW	Normal	6,791	3,209
MVAR		2,658	1,931
Plan 1			
Number of Circuits		2	1
MW	Normal	6,729	3,271
MVAR		5,043	2,698
Series Impedance, 100 MVA Base		0+j0.0074	0+j0.0168
Shunt Susceptance, 100 MVA Base		113	64
Number of Circuits		2	0
MW	Conting.	10,000	-
MVAR		2,412	
Number of Circuits		1	1
MW	Conting.	5,285	4,715
MVAR		1,014	1,547
Series Impedance, 100 MVA Base		0+j0.0148	0+j0.0168
Shunt Susceptance, 100 MVA Base		57	64
Number of Circuits		2	1
MW	Conting.	6,128	3,872
MVAR		5,394	1,910
Plan 2			
Number of Circuits		2	1
MW	Normal	6,787	3,213
MVAR		7,994	4,442
Series Impedance, 100 MVA Base		0+j0.0052	0+j0.0118
Shunt Susceptance, 100 MVA Base		161	91
Number of Circuits		2	0
MW	Conting.	10,000	-
MVAR		5,608	-
Plan 3			
Number of Circuits		2	2
MW	Normal	5,200	4,800
MVAR		6,359	7,324
Series Impedance, 100 MVA Base			
Shunt Susceptance, 100 MVA Base			
Number of Circuits		2	1
MW	Conting.	6,768	3,232
MVAR		5,529	3,211
Number of Circuits		1½	1
MW	Conting.	5,912	4,088
MVAR		2,313	2,329

TABLE VIII

Cable Design

Parameter	Plan 1	Plan 2	Plan 3
Nominal operating voltage, kV:	550	550	550
Maximum stress at nom. voltage, MV/m:	10	10	10
System design voltage, kV:	500	500	500
Maximum stress at design voltage, MV/m:	9.09	9.09	9.09
Rated Power (500 kV), MVA:	4,260	5,440	4,123
Operating current density, rated power, A/cm:	244	217	218
Rated current, kA:	4.92	6.29	4.76
Max. continuous contingency power (500 kV), MVA:	5,200	5,730	4,701
Max. continuous contingency current density, A/cm:	300	232	250
Max. continuous contingency current, kA:	6.0	6.62	5.43
Relative dielectric constant of insulation:	2.2	2.2	2.2
Hysteretic loss, rated power:	negligible	negligible	negligible
Hystaretic loss, continuous contingency power:	negligible	negligible	negligible
Dielectric loss, nominal operating voltage, W/km:	140	200	152
Dissipation factor:	1×10^{-5}	1×10^{-5}	1×10^{-5}
Inner conductor radius (to superconductor), cm:	3.18	4.61	3.49
Outer conductor radius (to superconductor), cm:	8.64	9.17	8.67
Cable O.D., nominal, cm:	19	20	19

transient stability, it is sufficient to represent the energy park generation, the UHV or cryogenic circuits, and the stations to which they connect, combining the rest of the world into a simplified equivalent. This reduces the problem at hand to a two-machine problem. Due to the large inertia of the interconnected system and its remoteness to the energy park, it is also sufficient to assume infinite inertia back in the equivalent so the problem further reduces to one machine swinging against an infinite bus.

The equivalent circuit for the rest of the world was chosen to give the same flows and voltage angles in the UHV system as in the load flow cases used in the steady-state analysis. Substituting the cryogenic cables into the system for the 1300 kV and eliminating the 500-1300 kV transformers also resulted in comparable flows and angles. Transient stability cases were performed using the line data for plans 1, 2 and 3. Each plan involved a three-phase fault at the generator resulting in the tripping of the Generator-Midsite line in 3.0 cycles. (In plan 3 where there were initially two circuits to Midsite, only one was taken out.)

The reactors used at Midsite and Alburtis for the transient stability tests were the same as used in the steady-state load flow tests. At the generator, the value of the shunt reactor was of little consequence in the load flow study since the generator held the station voltage and as long as the generator reactive power output was within limits, the system was satisfactory. It would then be recognized that any reactor which would allow the generator to operate within var limits would give identical results in the rest of the system. If this system were actually to be built, the specific reactor value would depend on such things as light load behavior and economics. Considering transient stability, another factor enters. On some of the load flow cases the generator was required to absorb vars. This was perfectly satisfactory for a load flow feasibility study, but resulted in too low an internal generator voltage for the stability study. Accordingly, reactors were added to the generator bus to bring up the generator internal voltage. This had no effect at all on the rest of the system but did reduce the angle between the internal generator voltage and the rest of the system, giving improved stability performance.

When lines are removed from service it would be necessary to remove reactors as well in order to prevent an undervoltage condition from occurring. This was seen as merely a relaying consideration and therefore not a problem. This same is true for the transient stability condition. It is necessary to arrange the relaying to provide for reactor tripping in the event of a line outage. This relaying of reactors may be accomplished in several ways. One possibility would be to directly connect the reactors to the cables so when the cables were switched out the reactors would automatically follow. This connection is desirable from a switching standpoint as will subsequently be shown. If more flexibility were to be desired, additional circuit breakers and relaying would be required. In actual planning for a superconducting cable transmission system, availability of the associated switchgear would have to be ascertained.

For the purposes of this feasibility study, the same criteria as the base 1300 kV O/H case is used, namely a three-phase fault cleared in 3.0 cycles.

In any extended work, consideration must be made of the applicability of different criteria to the several alternatives. U. S. practice has been to consider three-phase faults, often with unsuccessful reclosing, for the determination of transient stability. On other countries, where transmission lines are longer and the system is not as tightly connected, a circumstance comparable to the essential radial connection to the energy park, less severe criteria, such as line-to-ground or two-wire-to-ground faults are often used. Such less severe criteria may be applied to overhead construction where it is true that these types of faults often dominate the line performance. Additional stability under these conditions can be provided by such expedients as adding resistance to the transformer neutrals to limit ground fault current. For underground cable systems, however, three-phase faults would likely be most common due to the nature of dig-ins or the fact that a fault on one-phase would quickly spread to the other phases, becoming a three-phase fault. For actual planning work, then, a closer consideration should be given to the stability criteria employed.

For switching surge performance calculations, it is possible to consider a model incorporating only the area in the immediate vicinity of the switching in question. This is due to the relatively little effect of lines only a short distance from the affected one. The study was performed to determine the range of expected switching surge overvoltages which could occur during energizing operations. Plan 3 was chosen, using the four cables from the energy park generation. This plan was chosen because the cable parameters were between those of the compensated plan 1 and the uncompensated plan 2 which only used three cables from the generator. Other switching operations such as fault clearing and line dropping were not investigated. In a complete study for actual planning of a cryogenic cable system these should be checked as well. The results of the study indicate that the cable could be energized with presently available 500 kV switching equipment if the reactors were permanently connected to the cable. An energizing distribution of 50 random circuit breaker closings were calculated, using breakers with 400 ohm pre-insertion resistors. The range of closings for the distribution was a maximum span of 180 degrees from the first to the last pole over a range of 360 degrees for the first pole closed.

The reactors on the cable ends were chosen for these tests to compensate 100 percent of the cable charging. This is done to limit the voltage at the open end under steady state conditions to 100 percent. A shunt reactor compensation of 50 percent of the charging would give an open circuit voltage at the far end of the order of 140 percent. This could mask the results of the switching surges. It should be noted this is one more factor to consider when choosing reactor values for a system such as the one under study. The maximum surge obtained was 2.36 per unit at the open end of the cable and 1.52 per unit at the sending end.

An additional consideration is the selection of circuit breakers. The expected fault duty at the generation site would be in excess of 90 kA, symmetrical. This is substantially above the presently available ratings (63 kA) or even the projected levels of 83 to 85 kA. However, some form of additional bus reactance, perhaps in the form of a bus tie reactor, could probably be used to limit the fault current. This is a problem inherent in the large energy park and would be common to any transmission system chosen. This application also involves back-to-back switching of cables. This is especially difficult duty for breakers both from an inrush current standpoint and from a line-dropping standpoint.

At the present state of circuit breaker technology, 600 amperes is about the maximum line charging that a breaker can interrupt. This means that for application of this length of superconducting cables either improved breakers must be available or the reactors must be permanently connected to the cables so that the breaker never sees the line charging. This is a problem common to cable systems and does not impair the feasibility of superconducting transmission but is a matter to be considered before the actual construction of such a system. This is also an additional consideration in sizing the reactors on an actual system.

For application to an actual system careful attention must be paid to inrush current. Steady state charging current into the cable with the line open at one end and reactors permanently connected would be about 4000 amperes if the reactors compensated 100 percent of the charging. This result does indicate that a cable this long can be energized, a problem with conventional oil filled cables when the charging current under open circuit can exceed the cable ampacity.

The application of surge arresters on cables usually results in particularly severe duty for such arresters. For the maximum case obtained in the random closings, a standard 420 kV surge arrester was applied at the open end (Midsite). The maximum arrester current was computed to be 4.5 kA, which is at least twice the allowable. However, it is probable that a special arrester having different characteristics from standard ones would be capable of being applied to protect the line and equipment. Such applications are well known for cable installations. In the LILCO study, described previously, the switching surge tests showed a strong high frequency component due to the resonance of the cable. The longer cables involved in this energy park study (over 300 miles) have a much larger travel time for pulses to move down the length of the cable and return, and the system does not exhibit similar high frequency oscillations.

The chief virtue of the designs calculated is that they do replace the reference 1,300 kV O/H system in a technically acceptable manner. However, even without a detailed economic analysis, it is clear that the reactances values dictated by network considerations result in poor utilization of the superconductor. The obvious improvement is to increase the electric stress above 10 MV/m. For example, a stress of 15 MV/m would result in far better use of the superconductor and significant reductions in the sizes of the cable and envelope. A comparison of some important parameters of the plan 1 cable based on stresses of 10 and 15 MV/m are shown below in Table IX. The reactances and power capacities of both designs are the same, hence the steady-state and contingency loads flows, etc., are unchanged.

The flow of reactive power in the systems considered produces the interesting result that rated and continuous contingency MVA are not widely disparate. In general the VAR component is largest during normal or

TABLE IX

Comparison of Plan 1 Designs

Parameter	Stress of 10 MV/m	Stress of 15 MV/m
Operating current density, rated power, A/cm:	244	366
Max. cont. contingency current density, A/cm:	300	450
Hysteretic loss, max. contingency current, W/km:	neg.	neg.
Dielectric loss, W/km:	140	140
Inner conductor radius, cm:	3.18	2.1
Outer conductor radius, cm:	8.64	5.8
Cable O.D., cm:	19	13

rated operation. Although plan 1 has the same compensation scheme as the reference 1,300 kV O/H system it must be conceded that shunt compensation in plans 2 and 3 is large. Whether this much is acceptable depends on an economic assessment. The total compensation for the various systems under study is shown in Table X.

TABLE X

Comparison of Compensation

Plan	Total Series Comp., per unit	Total Shunt Comp., per unit
Reference 1300 kV O/H	0.4	1.2
# 1	0.4	1.2
# 2	0	1.9
# 3	0	1.8

The Test Facility

All work up to the present time has been confined to laboratory-scale equipment. This is a very necessary first stage to investigate the more fundamental properties of conductors, insulation and cryogenic apparatus. However, it must be stressed that this work will provide little information of interest to utility companies; they are more interested in questions of reliability and economics. Designs must evolve of steadily increasing size and capacity so that these questions can be resolved for equipment of representative size. If no unsurmountable problems arise in the course of this development the ultimate test will be the installation of a prototype superconducting transmission system as part of a utility network. The analyses of utility systems suggest system voltages for actual applications will lie in the range 230 to 345 kV. Clearly there are many paths that lead from the present experimental equipment to installations of these capacities. The goal at Brookhaven is to construct a relatively low-power or model system which forms a first step. The areas which can be investigated with this facility are:

1) Commercial fabrication of long cryostats.
2) Installation of long cryostats.
3) Design of reliable refrigerators for this class of service.
4) Supercritical helium flow and stability.
5) Purging and cooldown procedures.
6) Effect of transient heat pulses.
7) Commercial fabrication of flexible superconducting cable.
8) Pulling and splicing of flexible superconducting cable.
9) Design of terminals and potheads.
10) Actual demonstration of 3 phase power transmission at a limited power level.
11) Testing of single-phase cables at a voltage more appropriate for prototype designs.

The site for this facility has been chosen so that it is beneath an existing 69 kV overhead feeder. A lay-out is shown in Fig. 12, the test site under construction is shown in Fig. 13. The choice of initial voltage levels for the model is determined mainly by the technical choice of cable at Brookhaven, namely, a flexible cable with lapped plastic insulation. The constraints necessary to simultaneously satisfy all the requirements imposed by mechanical, cryogenic and dielectric considerations are severe. The severity increases with radial thickness, thus early cables should be relatively small; at 69 kV the cable will be about one inch in diameter, this seems an appropriate size to start with. The 69 kV feeder to the laboratory provides a method of studying 3 phase effects in superconducting cables. However, higher voltages can be tested on a single-phase basis using special transformers. If necessary cables rated up to 200 kV to ground could be tested in the same cryostat as the 69 kV 3 phase cables, these cables correspond to a 345 kV system voltage.

The electrical test equipment will be provided to test the cable under the following conditions:

1) Determine corona activity up to a factor x 3 of rated voltage.

2) Determine that the cable is capable of withstanding lightning and switching surge voltages appropriate for the operating voltage.

3) Continuous operation up to 120% of rated current and voltage.

4) Fault current waveform consisting of 3-6 cycles at x 10 rated current.

In deciding what level is appropriate for the facility at this stage in the development of superconducting cables the problem is to minimize the investment while at the same time possessing the maximum range and flexibility of test conditions. Table XI shows some characteristics of typical cables and the test gear for the voltage levels under consideration. It can be seen the complexity and size of the test equipment increase rapidly with system voltage.

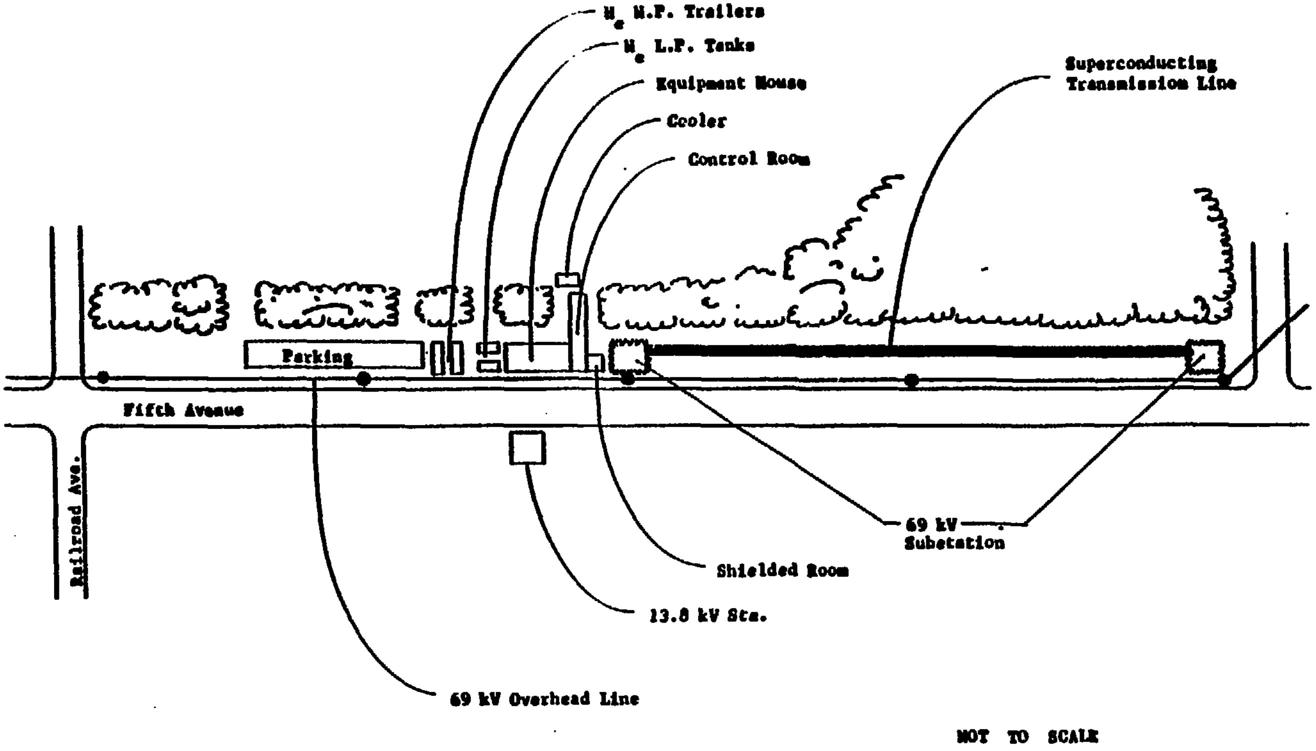


Figure 12. General plan of the test facility site. Construction of the equipment building has commenced so that the refrigerator can be tested prior to tests on cables.

Figure 13. Construction of the equipment building and control room at the test facility site on 5th Ave. at Brookhaven. Two 69 kV overhead feeders to a laboratory substation can be seen on the right.

TABLE XI

Electrical Characteristics for Different System Voltages

System Voltage, kV	Cable O.D., Ins	Rated Current, amps	Capacitance of 1000 ft	Resonant Corona-Free Transformer	Impulse* Supply
69	1.25	3,000	0.16 mF	120 kV at 7A for test length of 1000 ft	500 kV, stored energy of supply 100 kJ for 1000 ft test Clearances 4 ft plus 10 ft height
138	1.8	4,000	0.12 mF	240 kV at 10A for test length of 1000 ft	1000 kV, stored energy of supply ~ 200 kJ for 1000 ft test Clearances 5 ft plus 12 ft height

*The ratings shown are based on recommended BIL plus 125% qualification test in excess of BIL. This is in accordance with AEIC Specification 5-74 for 69 kV cables.

Although a major function of the refrigerator is to cool test sections of horizontal cryostats and cables the design of the refrigerator should reflect certain constraints imposed by the intended application. Thus as well as meeting the requirements of power capacity and mass flow the refrigerator must demonstrate good reliability and high efficiency; characteristics which will be very important in a utility company application. At the present time there is no single refrigerator in commercial production which meets all the necessary requirements. However, the major components comprising compressor, heat exchanger and expansion engine have been developed with acceptable characteristics and a composite refrigerator combining the appropriate elements appears to be a feasible goal. The performance required for the test facility is shown in Table XII.

TABLE XII

Required Refrigerator Performance for the Test Facility

1.	Low temperature load	500 W
	a. minimum inlet temperature to the load	6 K
	b. maximum temperature rise across load	2 K
	c. inlet pressure to the load	15 atm
	d. maximum normal pressure drop across the load	1 atm
2.	Cooling flow for terminations	1.5 g/sec

The compressor is of the oil-lubricated screw type. The selection is based entirely on the inherent reliability of this type of compressor and the experience gained when used with other gases. This choice requires the development of a 100% effective oil removal system, which seems technically feasible. The long term goal is still a non-lubricated compressor but with the reliability associated with the lubricated machine. This appears possible but it is a development project of some magnitude and should be carried out by a compressor manufacturer. There is also the possibility that, when compressors of larger capacity and power are required, centrifugal compressors with many stages will be possible, these are inherently large capacity machines. A full description of the refrigerator has been presented[16].

The purification system is a full-flow type in which the total output of the compressor must pass through the purifiers prior to use in any part of the refrigeration system. The technology of purifying gases is quite well in hand, so it becomes a matter of selecting a combination of methods and arranging them in stages such that the effluent helium gas contains only a few parts per billion of hydrocarbon impurities. Perhaps the largest problem is the detection and control instrumentation, which is required to monitor the gas for residual impurities. The purification system itself is built in a duplicate manner so that a fresh purifier can be put in service when the other has reached its extraction capacity. After some operating experience the normal time for operation with a given purifier will be known and controls will be provided to automatically switch to a clean purifier and initiate the clean-up and reactivation of the dirty one. It is also necessary to provide for the unforeseen situation where the purifier reaches its capacity in less than the normal interval. Detection equipment must recognize this condition, signal an alarm and switch to the outer system if it is ready. If it is not, the refrigerator must be shut down until maintenance personnel have corrected the problem. The detection and control system must have an even higher degree of reliability that the other components of the system and development and evaluation of existing equipment will be necessary.

Acknowledgements

The work described in this paper was performed by the members of the Power Transmission Project at Brookhaven. Several members have made written contributions in the sections concerned with their specialities. I also gratefully acknowledge the work performed for us by various consulting and engineering organizations in the U.S. In particular portions of the section on Systems Engineering were written by the staff of Power Technologies Incorporated of Schenectady, New York.

I should also like to thank officials of the National Science Foundation and the Energy Research and Development Administration for their understanding and support.

References

1. Forsyth, E. B. (Editor), Underground Power Transmission by Superconducting Cable, BNL 50325, March 1972.

2. Long, H. M. et al., Superconducting Cable System, EEI Project RP-78-7, Final Report, Edison Electric Institute, New York, Oct. 1969.

3. Suenaga, M. and Garber, M., Low-Loss Niobium-Tin for Superconducting AC Power Transmission Application, Science, 183, 952, (1974).

4. Bussiere, J. F., Garber, M., and Suenaga, M., The Effect of Cladding Material on AC Losses of Commercial Nb_3Sn Tapes, J. of App. Physics., Vol. 25, 756, 1974.

5. Bussiere, J. F., and Suenaga, M. , Reduction of AC Losses of Nb_3Sn by Surface Treatment, J of App. Physics.,(in press).

6. Bussiere, J. F., Garber, M., and Shen, S. W., The Temperature Dependence of AC Losses and Self-Field Critical Currents in Nb_3Sn., Applied Physics Letters, December 1974.

7. Garber, M., Shen, S., Bussiere, J., and Morgan, G., AC Critical Currents of Commercial Nb_3Sn Tapes, IEEE Trans. on Mag.,Vol. MAG-11, No. 2, March 1975.

8. Morgan, G., and Forsyth, E.B., Considerations of Voltage Drop and Losses in the Design of Helically-Wound Superconducting AC Power Transmission Cables. Presented at the Cryogenic Engineering Conference, Kingston, Ontario, July 1975.

9. Sutton, J., Induced Circumferential Currents and Losses in Flexible Superconducting Cables, to be published in Cryogenics.

10. Forsyth, E. B., Britton, R. B., Dean, J., Jensen, J. E., and Minati, K. F., A Supercritical Helium Facility for Measuring High-Voltage Breakdown., Advances in Cryogenic Engineering, 19, Plenum Press, 1974.

11. Forsyth, E. B., Predicted Characteristics of Superconducting Transmission Cables, Proc. Conf. on High Voltage DC and/or AC Power Transmission, London, 1973, IEE Pub. # 107.

12. Forsyth, E. B., Mulligan, G. A., Beck, J. W. and Williams, J. A., The Technical and Economic Feasibility of Superconducting Power Transmission: A Case Study, Trans. IEEE in Power App. and Syst., PAS 94, 161, 1975.

13. Anishchenko, N. G., and Minein, V. F., Investigation of the Short-Term Dielectric Strength and Service Lives of Lavsan Insulation, Pribory i Tekhnika Ekoperimenta, No. 6, 176, 1973. Plenum Press Translation UDC 621-59.

14. Klaudy, P. A., Ubertiefstgekuhlte, Besonders Supraleitende Kabel, Vol. 89, Elektrotechnik und Maschinenbaie, p. 93-110 (1972).

15. Dean, J. W., Jensen, J. E., A Supercritical Helium refrigeration for Superconducting Power Transmission Cable Studies, Presented at the Cryogenic Engineering Conference, Kingston, Ontario, July 1975.

16. Jensen, J. E., An Advanced Refrigeration System for the Brookhaven Superconducting Cable Project, Presented at a Symposium at the Krzhizhanovsky Institute, Moscow, Sept. 1975.

17. Forsyth, E. B., McNerney, A. J., and Muller, A. C., Dielectric Design Considerations for a Flexible Superconducting Power Transmission Cable, Presented at the Ctyogenic Engineering Conference, Kingston, Ontario, July 1975.

18. Electric Utilities Industry Research and Development Goals Through the Year 2000. Report of the R&D Goasl Task Force to the Electric Research Council, June 1971., ERC Publ. # 1-71.