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AC SUPERCONDUCTING CABLES*

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INTRODUCTION

AC superconducting power transmission systems have been under active development for a little over a decade. During that period many technical options available in the design of cable construction, cable conductor, cable insulation and system components were investigated in Europe and the U.S. Only one project in Austria is now active in Europe and in the U.S. the effort has come to be concentrated on the flexible Nb_3Sn cable under development at Brookhaven. This emphasizes the paramount need to produce cost-effective designs for which the economics are evaluated in systems studies carried out in cooperation with electric utility companies. These studies have had a continuous impact on the course of development at Brookhaven.

BASIC CHARACTERISTICS OF AC SUPERCONDUCTING CABLES

It is useful to be able to express system characteristics such as per unit series reactance, per unit shunt reactance and per unit surge impedance load (SIL) in terms of properties of the conductor and insulating materials. This is most easily done by defining an admittance, Y, as follows:

$$Y = \frac{J_s}{E}\text{, mho, where} \qquad (1)$$

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DISCLAIMER

J 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 (1) that for superconducting cables, where the current is carried in a negligible depth of conductor, then:

$$\overline{Z}_L = 0.475Y, \text{ km}^{-1} \tag{2}$$

$$\overline{Z}_C = \frac{3.0 \times 10^5}{\varepsilon_r} Y, \text{ km} \tag{3}$$

$$\overline{Z}_0 = \frac{378}{\sqrt{\varepsilon_r}} Y \tag{4}$$

where,

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

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

$\overline{Z}_0$ = per unit 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. The hysteretic loss of the superconductor is a major factor when considering the design of the cooling system. Niobium has about the same loss as Nb_3Sn but the associated refrigeration is less efficient than a niobium-tin design (2). In addition niobium has a relatively low critical field (current or magnetic field which causes a transition out of the superconducting state) which restricts the maximum value of J_s to the range 30-50 kA/m. Niobium-tin has a very high critical field but consideration of hysteretic loss will probably limit the maximum operating value of J_s to the range 40-80 kA/m.

Various methods of insulating superconducting cable have been proposed, in rigid systems the helium coolant may be used for insulation (3) and in flexible or rigid designs an impregnated tape may be used (4). For example, the rigid, superconducting, helium insulated cable developed by the Linde Division of Union Carbide in the U.S. was designed for a BIL of 15 MV/m. This is about half the measured breakdown stress under the same conditions of temperature and pressure. The ratio of operating stress to BIL has still to be determined for this class of cable. Work at Brookhaven on laminar taped insulation impregnated by supercritical helium indicates the impulse levels appropriate for the class equipment meeting AEIC standards can be met (5). Operating stresses of about 10 MV/m are feasible although the economic appeal of higher stresses is undeniable and this may justify higher operating pressures for the helium 'go' stream. Typical characteristics of a flexible cable ($\varepsilon_r = 2.2$) with unity surge impedance load are shown in Table 1. Ratings for gas-insulated superconducting cables show that the low operating stress results in a cable with low J_s for unity SIL, or to put it another way, the series inductance, $\overline{Z}_L$, is high for useful values of J_s, resulting in poor regulation. This design factor contributed to the unfavorable showings of rigid gas-insulated cables in systems studies.

Table 1

CHARACTERISTICS OF FLEXIBLE CABLE WITH UNITY SIL

$\varepsilon_r = 2.2$, E = 10 mV/m, $J_s = 40$ A/m, $\overline{Z}_0 = 1.0$

System Voltage kV	Current A	Power MVA	Conductor Dia, cm	Cable Diameter cm
138	4,000	950	3.1	7
230	6,500	2,600	5.2	10
345	9,800	5,900	8.0	15

SUMMARY OF MAJOR DEVELOPMENT PROJECTS

Table 2 gives a summary of active projects throughout the world in 1976. After tests on a 5 m cable (6) the CERL project was phased out. Similarly the program in Germany was run down after tests on a 15 m cable at AEG and a 35 m cable at Siemens (7). In contrast the project at the Institute for Low Temperature Research in Graz, Austria, is still very active. This is probably the oldest project, having started in 1965. At present a single-phase test cable is being fabricated for incorporation into a 60 kV system at the Arnstein power plant. When completed this will be the first test of a superconducting cable in actual utility service.

Table 2

SUPERCONDUCTING POWER TRANSMISSION PROJECTS

Institution	Location	Type of System
Europe		
Central Electricity Research Laboratories	Leatherhead, England	Flexible ac cable, NbZr conductor
Siemens	Erlangen, Germany	Flexible ac cable, Nb conductor
Allgemeine Eletrizitats Gesellschaft (AEG)	Frankfort, Germany	Flexible dc cable, Nb_3Sn conductor
Institute for Low Temperature Research	Graz, Austria	Flexible ac cable, Nb conductor
Soviet Union		
Kzhizhanovsky Power Engineering Institute	Moscow	Rigid ac cable, Nb_3Sn conductor
All-Union Scientific Research Institute of Direct Current	Leningrad	DC superconducting cable
All-Union Research Institute of the Cable Industry	Podolsk	Flexible ac cable, Nb_3Sn conductor
United States		
Brookhaven National Laboratory	Upton, New York	Flexible ac cable, Nb_3Sn conductor
Linde Division of Union Carbide	Tarrytown, New York	Rigid ac cable, Nb conductor
Los Alamos Scientific Laboratory	Los Alamos, New Mexico	Flexible dc cable Nb_3Sn or Nb_3Ge conductor

At the Kzhizhanovsky Power Engineering Institute in Moscow tests have been performed on 8 m cables for several years. Construction has started on an outdoor test at the Mosenergo substation which will initially comprise a 3-phase rigid cable operating at 15 kV about 100 m long with the capability of extension to 1000 m. The flexible cable under development at Podolsk has been evaluated for thermal performance at low temperature in a length of 50 m; current tests are imminent.

In the U.S. the projects at Los Alamos Scientific Laboratory and at Brookhaven National Laboratory are still very active although the competitive position of dc systems is a complex problem. There is no doubt that conventional cables can handle substantial power levels using dc transmission, this may lead to a de-emphasis of superconducting dc systems. It is not improbable that successful trials of the 138 kV cable at Brookhaven described above may lead to utility interest as the room-temperature components for this rating could be designed without great difficulty, i.e., transformers and circuit breakers. It has been decided not to continue the rigid cable design under development by the Union Carbide Corporation. This step was taken in the light of unfavorable projections of the future economic viability of this particular approach. It should be emphasized that the decision to close down a project based on economic forecasts must be made with great care. Generally speaking, analysis of the forecast indicates what programmatic changes are necessary to optimize the design, although even with these changes the general design may not be viable. This judgement is a great art which must be frequently exercised by responsible officials in funding agencies. The problems involved have received some attention (8).

The major reason cited for the discontinuance of superconducting power transmission projects in Europe is that the power level at which these systems become economically attractive is higher than anticipated circuit needs. At the same time most projects complete the demonstration phases with some unresolved technical problems. Although these problems have not received much public discussion they probably reinforce the decisions made officially on economic grounds. Neither reason is completely justified at this stage of development: it would be more logical to refine the project goals in the light of the analysis rather than shut down completely.

THE BROOKHAVEN PROJECT

When development began a major problem to be solved was the design of a conductor. The initial study (1) had shown the potential economic appeal of a flexible cable installed in lengths of several thousand feet between splices. The study also showed that the overall system efficiency would greatly benefit from the use of niobium-tin as the superconductor because both the tolerable temperature rise and mean temperature of a cooling loop would be higher than those necessitated by the use of niobium, at that time the material most commonly proposed for superconducting power transmission applications (2). The choice of niobium-tin posed significant problems which had to be solved if the potential of this material was to be realized. For example the ac losses of commercially made Nb_3Sn were very high. Early work showed that much of the loss was due to extra material laminated to the superconductor. These extra components had little effect when the tape was used to wind magnets; the intended function, but they had to be removed or modified when the tape was designed for 60 Hz applications (9). In addition Nb_3Sn was made at Brookhaven by a new method which resulted a very pure form of the compound (10). These samples exhibited very low losses and served as a benchmark for the improvement of commercially-made tape. At the same time the design of the complete cable conductor proceeded. The superconductor required strengthening so that the tape would withstand the rigors of high-speed winding. This was achieved by the addition of a thin stainless-steel layer, which had to add very little to the ac losses. A normal metal layer is also necessary to provide a current path in the event the superconductor is quenched, such a layer is called a stabilizer. A further refinement to the conductor which became apparent during the development was a winding pattern in the form of double-helices (11, 12). These improvements are incorporated in a 10 m cable tested in the laboratory at Brookhaven (13).

The ability of a superconducting cable to carry heavy currents is only half the story. Although the voltages for a given power are lower than conventional cables they are still substantial and system studies indicate the acceptable range of electric stress is quite narrow. As the cable under development are flexible the dielectric insulation is applied in the form of many layers of thin tape. The constraints of low dielectric losses at the acceptable operating stress dictated the choice of a polymer such as polyethylene or polypropylene as the material. The commercially available tapes made from these materials are too weak to allow satisfactory cable bending. Methods of improving this situation include extra laminates and orientation. Under a contract from Brookhaven a team at Battelle Columbus Laboratories produced a prototype highly-oriented polyethylene tape with a tensile modulus of about 10^6 psi. Many other constraints on the dielectric material must also be considered (14). The tape itself is only part of the dielectric insulation: supercritical helium coolant permeates the insulation and it is this combination which must satisfy all the high-voltage requirements (5).

As mentioned above the technical aspects of the Brookhaven program have been under continuous review by means of systems studies. In all cases the studies are based on an actual situation under investigation by utility companies using, of course, more conventional transmission equipment. Meeting the same boundary conditions imposed by the utility engineers for their study provides a fair test of the ability of the helium-cooled version to integrate into the system. These conditions include real and reactive power flow under normal and contingency operation, transient phase stability margins and surge levels to be expected. By using an actual route, it is possible to include realistic installation costs which allows for such factors as type of soil and rock structure, number of road and river crossings and the provision of distribution power for the refrigerator stations.

The first study was carried out in cooperation with the Lond Island Lighting Company (LILCO) and covers a transmission line which is actually under construction (15). A nuclear generating station is being built at Shoreham on the north shore of Long Island. In the next fifteen years, it is planned to build two more in the same general area, leading to the need for a transmission corridor with an ultimate capacity of 4800 MVA. The plans selected by LILCO call for a mix of overhead and pipe-type underground cables at a voltage of 345 kV. The route to a main substation at Ruland Road, where interconnection to other parts of the 345 kV network around New York City can be made, is 43 miles. This application is a situation which appears to be typical, namely, underground penetration to a load center through a fairly well built-up urban or suburban region. This example may also simulate the case in which long-distance overhead transmission is forced underground as the load center is approached, either due to lack of right-of-way for high-voltage overhead lines or due to zoning restrictions. Three different plans were considered, each of which provided the opportunity to determine the sensitivity of the total cost to various technical alternatives. The plans have been described in detail (15) and here a brief summary is given in Table 3.

Table 3

FLEXIBLE SUPERCONDUCTING CABLES: BASIC DESIGN PARAMETERS (LILCO STUDY)

	Plan 2	Plan 3A	Plan 4
Voltage, kV	138	345	345
No. of Circuits/Single Circuit Normal MVA (Continuous Contingency MVA)	2/1300 (2100)	2/2400 (4800)	3/1600 (2400)
Length of Circuit, Miles	22	42.9	22
Inner Conductor Radius, Ins.	1.06	1.19	0.72
Outer Dia. of Cable, Ins.	3.19	4.88	4.74
Max. Electrical Stress, kV/cm	100	100	100
Mean rms Stress, kV/cm	86	71	55.2
Normal Current, kA	5.5	4.0	2.67
Dielectric Constant of Insulation (Mean)	2.2	2.2	2.2

The plan numbers in Table 3 refer to the various routes, or portions of routes, which are shown in Fig. 1. 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 full-scale demonstration system now under construction at Brookhaven which is described below is also designed for 138 kV but at a rating of 1000 MVA. If the trials are successful this may prove to be a useful power level for a 138 kV design.

Clearly, at the present time, it is not possible to assess the operating reliability of superconducting transmission systems. There seems to be every possibility that the cables will be extremely reliable as there is virtually no temperature change associated with load variations. The operating records of existing liquid nitrogen plants seem to indicate that refrigerators can be made

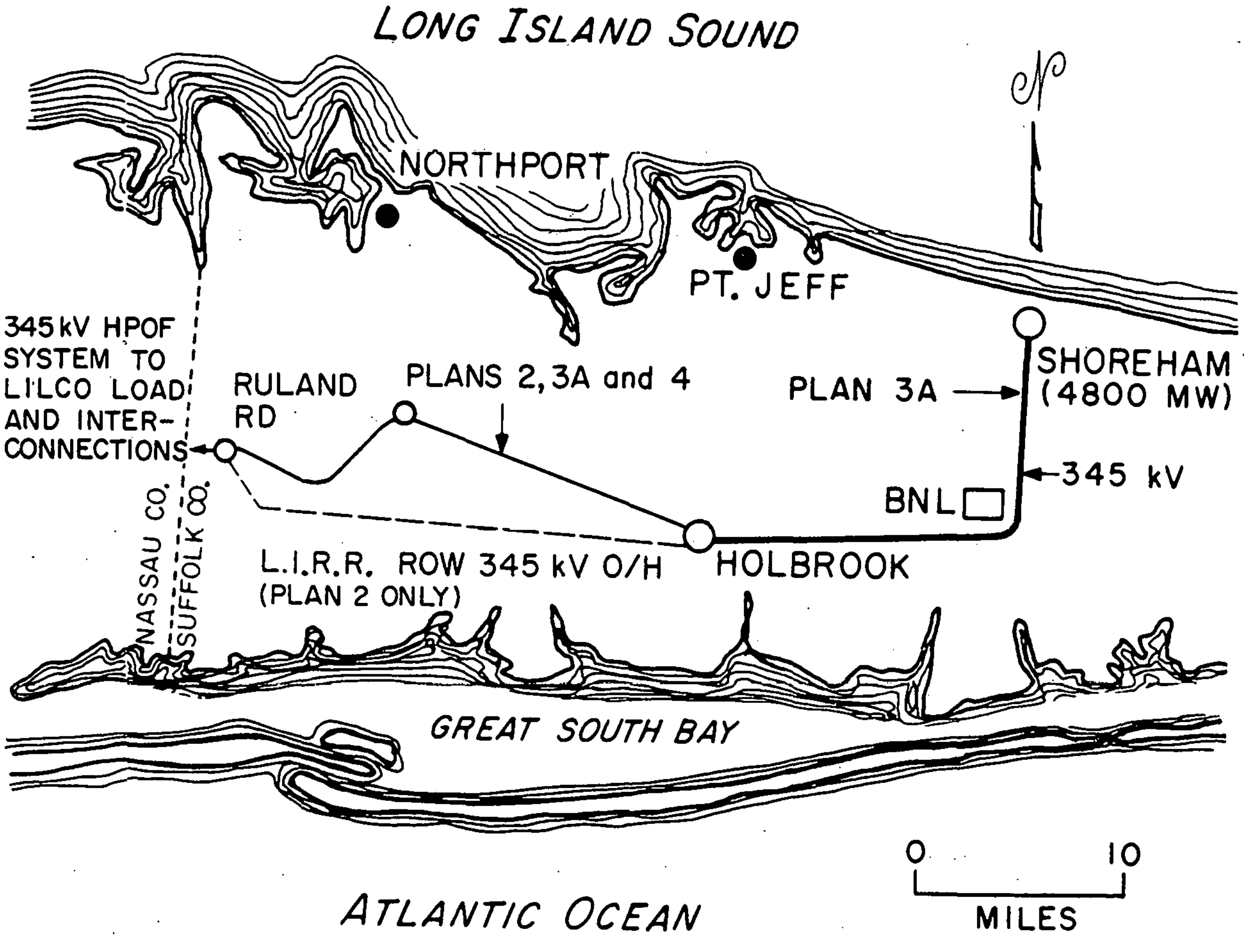

Figure 1. Transmission routes used in a study of a 4800 MVA system on Long Island.

with 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 4.

Table 4 shows that the costs of superconducting systems appear to be quite attractive; the capitalized loss for these plans is well below that of the conventional cables. Although a completely overhead 345 kV system is unlikely because of lack of right-of-way and environmental considerations, it has been

Table 4

COST FOR FLEXIBLE SUPERCONDUCTING CABLES COMPARED WITH THOSE FOR CONVENTIONAL CIRCUITS*
(1973 dollars)

	Plan 2		Plan 3A		Plan 4	
	SC	Conventional	SC	Conventional	SC	Conventional
Number of Circuits	2	Double Ckt OH + 2-345 kV HPOF	2	9-345 kV HPOF	3	9-345 kV HPOF
Installed Cost for System (see Table 4, Item 7)	$64,000,000	$65,600,000	$189,800,000	$344,200,000	$139,500,000	$178,200,000
Reactive Compensation	-	$ 1,400,000	-	$ 24,200,000	-	$ 12,200,000
Demand, Capitalized Energy and Maintenance	$ 2,500,000	$ 7,900,000	$ 13,000,000	$ 42,000,000	$ 5,200,000	$ 22,000,000
Transformation Required	$21,000,000	-	-	-	-	-
Circuit Breakers Required	$7,000,000	$ 4,200,000	$ 6,000,000	$ 11,200,000	$ 11,900,000	$ 16,100,000
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
Total MVA, Normal Load	2,600	NA	4,800	4,800	4,800	4,800
Dollars/MVA-Mile	$1,760	NA	$1,020	$2,070	$1,470	$2,160
Total MVA, Continuous Contingency Rating	4,200	NA	9,600	5,400	7,200	5,400
Dollars/MVA-Mile	$1,036	NA	510	$1,840	$980	$1,920

*This table is taken from Ref. 15, which should be consulted for details of the assumptions underlying the estimates.

estimated that such a system comprising five circuits 43 miles long would cost about $110 million, including the costs of breakers and capitalized losses. This figure may be compared to the cost of $209 million on line 7 (Table 4), for the superconducting version of plan 3A. This is a significant improvement in the cost differential for an underground system and represents an important step towards the goal set by the Electric Research Council of bringing overhead and underground transmission costs into line (16). If the cost analysis had been based on present worth, the financial advantage of superconducting schemes compared with high pressure oil-filled (HPOF) cables would have been less noticeable in this case-study. Conventional underground cable circuits could be installed to match the steady growth of generation capacity, but the smaller 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 under-utilized in the early years of operation. As mentioned above, the cryogenic envelope design used in the LILCO study was an elaborate affair with an intermediate temperature shield and insulated helium return pipes. For plan 3A, the total cost of cryostat was estimated to be about $80,000,000. The heat leak of the plan 3A cryostat was 55W/km; the refrigerators would be about 6 miles apart.

After this study the high cost of the cryogenic enclosure was reduced by means of an intensive development program at Brookhaven (17). It is probably true to say that no engineering breakthrough was required, rather a very complex optimization was achieved between adequate system performance and overall cost. In effect, the refrigerator and cryogenic enclosure must form an integrated system which maintains the electrical equipment at a suitable temperature under all conditions of loading. Both the capital and operating costs are greatly affected by the design chosen. For example, in the first LILCO study, a superior design was adopted for the cryostat which resulted in a low heat in-leak and thus relatively small refrigerators. However, when cost estimates were completed, it was found that the cryostat, delivered at the site, represented about 40% of the total cost, whereas the refrigerators were less than 12%. It was obvious that a cheaper cryostat was required with a thermal insulation performance somewhat inferior to the best that could be achieved. This study also resulted in a radical change of thinking at Brookhaven concerning the hydrodynamics of the cooling helium flow loop. The study was based on a conceptually simple scheme in which the cooling gas flowed through the cable and inner pipe of the cryostat for a sufficient distance to absorb enough heat to cause the maximum allowable temperature rise of $2^{O}K$. At this point, the cooling gas was removed from the cable and returned to the refrigerator using insulated pipes contained within the annulus between the inner and outer pipes of the cryostat. These pipes would be connected as each section of the cryostat is installed, an expensive operation which also increases the likelihood of leaks in the numerous welds. The improvement was to make the cable and enclosure a heat-exchanger forming part of the refrigeration system. An expansion engine is required at the end of the cooling loop but numerous computer-based studies have shown that this system is greatly superior to the original plan (18). The increased conductance of the helium flow channels permits greater spacing between refrigerators and an unexpected bonus turned up - smaller compressors are needed for the same heat load. The original plan and the one that evolved are shown in simplified form in Fig. 2.

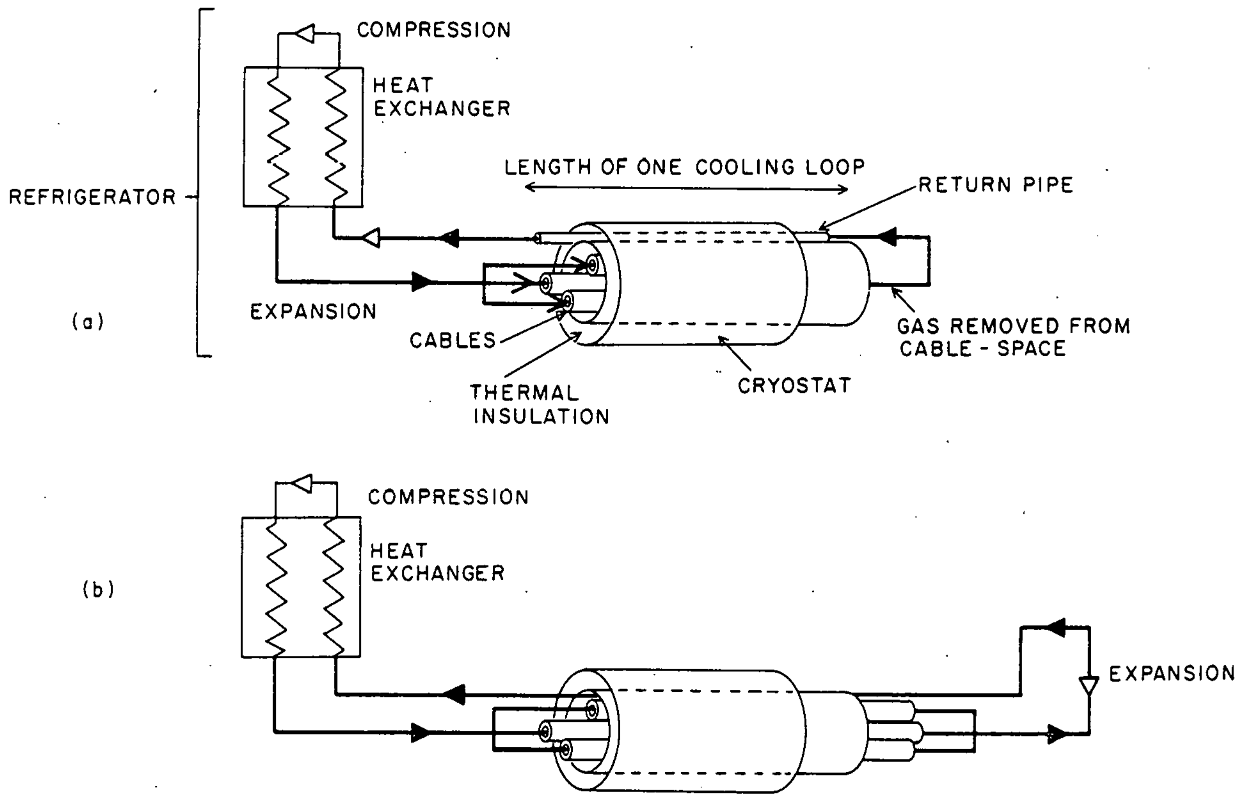

Figure 2. (a) Simplified diagram of a cooling loop using thermally-insulated return pipe. (b) A method of reducing cost by forming a counter-flow heat exchanger from the cable and cryostat.

It is well known that ac interconnections of more than a few hundred miles represent a difficult problem if the network is to remain stable, particularly under contingency conditions. The next study to be attempted investigated the possible use of helium-cooled cables in this situation. Engineers working for several Pennsylvania utility companies had looked at the transmission requirements for a hypothetical 10,000 MW generating station located near Lake Erie with the load on the Allentown-Philadelphia axis. This is simply a planning exercise at present, but the characteristics of the load end are well known. Several H.V. ac and one dc overhead (O/H) schemes were considered and analyzed to determine cost and efficiency. For comparison purposes, the superconducting system has been designed to replace a 3-circuit 1300 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. 3. A double circuit runs to the Alburtis Substation near Allentown and a single circuit to the Midsite Substation near Philadelphia.

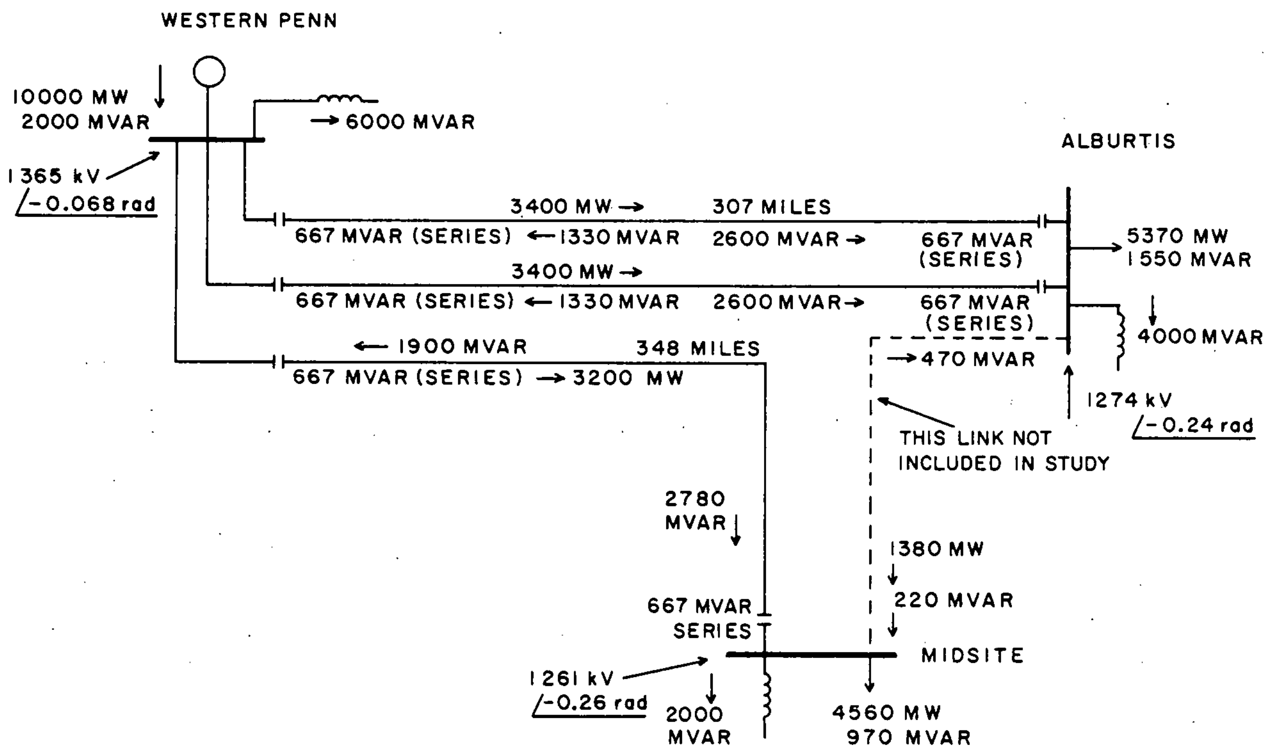

Figure 3. One line diagram for reference 1300 kV overhead system used in the Pennsylvania study.

The general area covered by the route is shown in Fig. 4, it must be emphasized the route was selected only for the purposes of preparing estimates. The helium-cooled designs are all for 500 kV, a convenient voltage as this avoids the use of transformers at the load end (19). A brief summary of each plan follows.

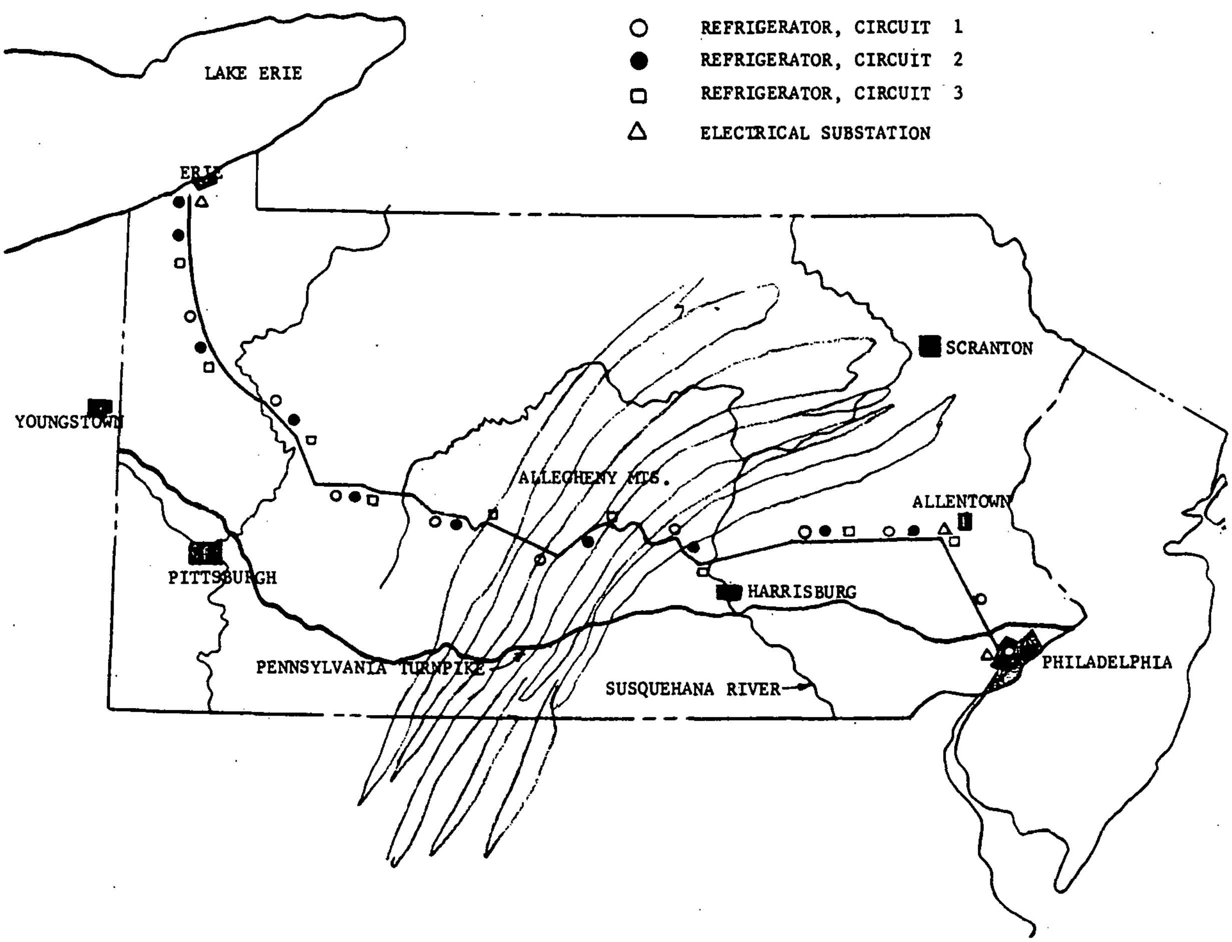

Figure 4. Route selected for the preparation of cost estimates for a 10,000 MW helium-cooled transmission system in Pennsylvania.

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 1300 kV O/H circuits. Because of heavy compensation, this scheme makes the most economic use of the cables.

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 undersirable subharmonic system resonances and has been blamed for turbine-shaft 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 5. In all cases, a base generation of 10,000 MW is assumed. The design parameters of cables for each plan are shown in Table 6. For the purposes of this study, transformer tap changes were not made. Reactor sizes were chosen instead to give good voltage regulation. Comprehensive computer simulations of the system under normal and contingency conditions did not disclose any transient response which was worse than the 1300 kV reference case. Breaker interruption was assumed to take place in 3 cycles, a very conservative period: it seems likely that 1 cycle breakers will be available by the time superconducting cables are developed to the prototype stage. Various technical factors forced a design to be adopted which resulted in relatively poor utilization of the superconductor. The cryogenic enclosure costs about $750,000 per mile cheaper than the design used in the first LILCO study, despite the fact that it is somewhat larger. The trade-off is reflected in the increased refrigeration; expressed in compressor power per MVA-mile, the LILCO study required 0.06 compared to 0.11 for the Pennsylvania system. Another factor which tends to offset the increased refrigeration of this design is the much longer spacing between refrigerator stations; 37 miles as compared to 6 miles in the original LILCO study.

Table 5

DESIGN OF CIRCUITS (10,000 MW GENERATION, BASE CASE)

Parameter		Mode of Operation	Generator to Alburtis	Generator to Midsite
Distance, km			498	563
	1,300 kV O/H			
Number of Circuits		Normal	2	1
MW			6,791	3,209
MVAR			2,658	1,931
	Plan 1			
Number of Circuits		Normal	2	1
MW			6,729	3,271
MVAR			5,043	2,698
Number of Circuits		Contingency	2	
MW		# 1	10,000	0
MVAR			2,412	-
Number of Circuits		Contingency	1	1
MW		# 2	5,285	4,715
MVAR			1,014	1,547
Number of Circuits		Contingency	2	1
MW		# 3	6,128	3,872
MVAR			5,394	1,910
	Plan 2			
Number of Circuits		Normal	2	0
MW			6,787	3,213
MVAR			7,994	4,442
Number of Circuits		Contingency	2	0
MW		# 1	10,000	-
MVAR			5,608	1
	Plan 3			
Number of Circuits		Normal	2	2
MW			5,200	4,800
MVAR			6,359	7,324
Number of Circuits		Contingency	2	1
MW		# 1	6,768	3,232
MVAR			5,529	3,211
Number of Circuits		Contingency	1½	1
MW		# 2	5,912	4,088
MVAR			2,313	2,329

Table 6

CABLE DESIGN (PENNSYLVANIA STUDY)

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
Hysteretic loss, rated power, W/km	67	56	50
Hysteretic loss, continuous contingency power, W/km	127	69	76
Relative dielectric constant of insulation	2.2	2.2	2.2
Dissipation factor	1×10^{-5}	1×10^{-5}	1×10^{-5}
Dielectric loss, nominal operating voltage, W/km	140	200	152
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
Operating temperature, K	6.5-8.0	6.5-8.0	6.5-8.0

Some of this improvement may be attributed to the greater hydraulic conductance of the 500 kV cables used in the later study but mostly it is due to the better technical features associated with far-end expansion. The total power consumption of the refrigerators results in a transmission loss of about 3.0% for the Pennsylvania system, this is somewhat more than the reference 1300 kV O/H case, but less than for any other overhead schemes which were considered. In the case of the LILCO study, the helium-cooled design was the most efficient.

Following this study the LILCO system was re-examined using the latest design for the cryogenic enclosure. At the same time the economic advantage of higher operating stress was investigated (19). These studies laid the groundwork for the most advanced investigation to be attempted: a comparative analysis of sixteen designs made by the Philadelphia Electric Company (PEC) under the sponsorship of the Department of Energy. This involved the detailed design of a 66 mile (106 km) underground transmission network. In the past comparisons have been difficult to make because different routes, power levels, security conditions and many other technical factors have been used in cost studies. Also these studies often omitted the cost of auxiliary but necessary apparatus such as compensating reactors and transformers. In the PEC study all technologies met a minimum standard of feasibility set by the company engineers and included the cost of all necessary equipment as well as the capitalized cost of losses. This then permits a comparison of the total cost of each design which meets the requirements. Such a study is immensely complicated and this one took close to two years to perform (20). The very broad technical characteristics of the system are shown in Table 7. The range of technologies considered is shown in Table 8. A final report has been issued which discusses the technical designs and cost estimates (20). A summary of cost estimates is shown in Table 9.

Table 7

PHILADELPHIA ELECTRIC COMPANY STUDY - GENERAL SYSTEM REQUIREMENTS

Corridor length	:	66 miles (106 km)
Corridor power	:	10,000 MVA
Rating with first contingency	:	10,000 MVA
Rating with second contingency	:	7,500 MVA

Table 8

CATEGORIES OF UNDERGROUND TRANSMISSION SYSTEMS EVALUATED

General Type	Comment
Cable with lapped insulation	4 systems at 500 kV 2 systems at 765 kV 1 600 kV dc system
Gas insulated cables (All 500 kV)	2 rigid designs 1 flexible design
Cryogenic	2 cryoresistive 2 superconducting (ac) 1 superconducting (dc)

Table 9

COST ESTIMATES PREPARED BY THE PHILADELPHIA ELECTRIC COMPANY

Underground Systems	Acronym	Adjusted Grand Total-$K*
500 kV HPOPT Cellulose-insulated cable	500 kV HOPOT-C	1,879,191
500 kV HPOPT PPP-insulated cable	500 kV HPOPT-PPP	1,562,674
765 kV HPOPT PPP-insulated cable	765 kV HPOPT-PPP	1,682,270
500 kV force-cooled HPOPT PPP-insulated cable	500 kV HPOPT-F/C	1,766,735
765 kV force-cooled HPOPT PPP-insulated cable	765 kV HPOPT-F/C	1,761,224
500 kV AC self-contained oil-filled cable	500 kV SCOF-AC	1,364,795
600 kV DC self-contained oil-filled cable	600 kV SCOF-DC	1,422,628
500 kV single-phase, SF_6, GITL, rigid system	500 kV GITL-R1	1,538,853
500 kV single-phase, SF_6, GITL, flexible system	500 kV GITL-F	1,417,960
500 kV three-phase, SF_6, GITL, rigid system	500 kV GITL-R3	1,338,707
500 kV resistive cryogenic cable	500 kV RC	2,694,461
345 kV resistive cryogenic cable-rigid system	345 kV RC-R	not costed
230 kV superconducting cable	230 kV SC	1,294,881
230 kV superconducting cable-rigid system	230 kV SC-R	2,628,303
300 kV DC superconducting cable	330 kV SC-DC	1,695,831
500 kV aerial/underground system (60 miles overhead)	500 kV aerial	667,850

Acronyms used in the table are defined as follows: HPOPT-high pressure oil-filled pipe-type; C-cellulose insulation; PPP-Paper polypropylene laminate insulation; F/C-force-cooled; SCOF-self-contained oil-filled; CITL-gas-insulated transmission line; R1-one-phase rigid; F-flexible; R3-three-phase rigid; RC-resistive cryogenic; SC-superconducting; AC-alternating current; DC-direct current.

*These data are taken from Ref. 20.

It should be borne in mind that a generous tolerance must be placed on these estimates; particularly for untried technologies. The flexible superconducting ac cable design submitted by Brookhaven is the lowest cost system but the 3-phase gas-insulated cable and self-contained 500 kV cables have substantially the same cost. All these designs appear to be about three times more expensive than a 500 kV overhead transmission system with comparable ratings. Work is now proceeding at Brookhaven on ways to reduce the cost of the design without compromising performance.

A considerable amount of work is going into the construction of an outdoor test facility which will be capable of testing 100 m of 3 phase cable rated for 138 kV service at 4 kA, or about 1000 MVA (21). The supercritical refrigerator has been operated for periods of 4 to 5 days on several occasions. Performance for such an advanced machine has been satisfactory (22). Five sections of cryogenic enclosure providing a total length of 100 m have been installed, jointed and leak-tested. Transfer lines from the refrigerator have been installed and tested. It is planned to conduct a full thermal test of the refrigerator and cryogenic enclosure in the summer of 1979. Electrical tests of a cable should be performed in late 1980 or early 1981. The general arrangement of the Test Facility is shown in Fig. 5. Most of the termination design has been verified

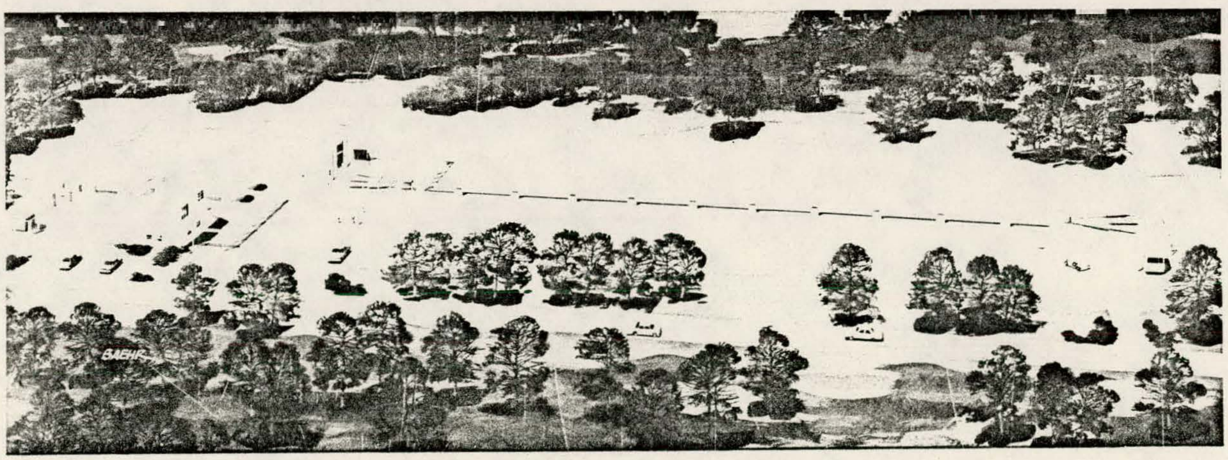

Figure 5. Impression of the 138 kV, 1000 MVA Superconducting Cable Test Facility.

by building three-quarter scale models for laboratory testing, shown in Fig. 6. Design of the terminations for the Test Facility has started.

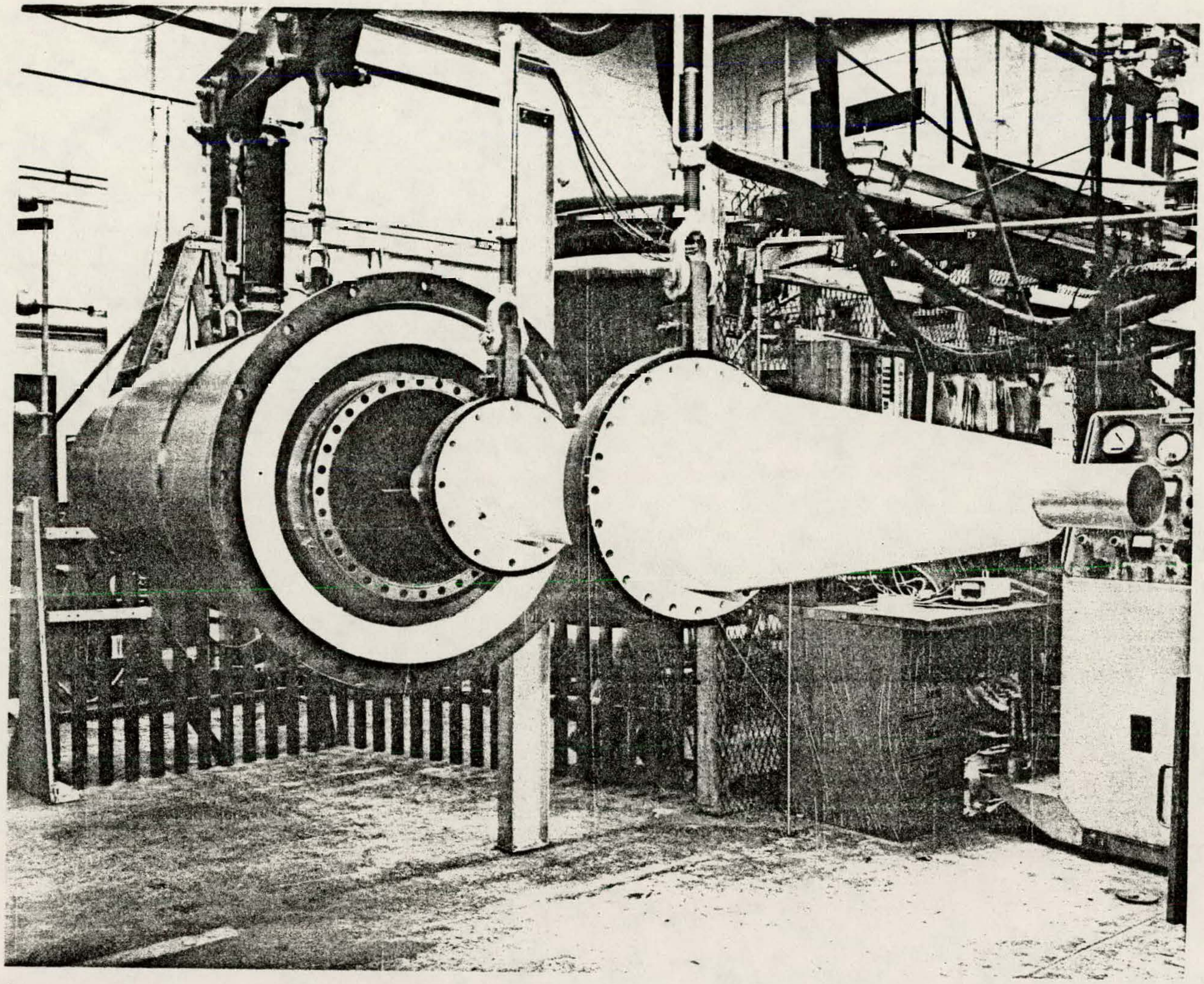

Figure 6. Epoxy bushing used in temperature transition section of cryogenic cable termination.

The work at Brookhaven has resulted in the development of a good deal of supporting equipment and techniques. A short length of taping machine has been assembled with payoff and take-up reels. Sections of experimental cable can be fabricated with a maximum of 64 tapes applied in one pass. The machine has been specifically modified to tape polymeric tapes: acceleration and deceleration are carefully controlled and the minimum tension may be adjusted to 0.2 kg. This facility is shown in Fig. 7.

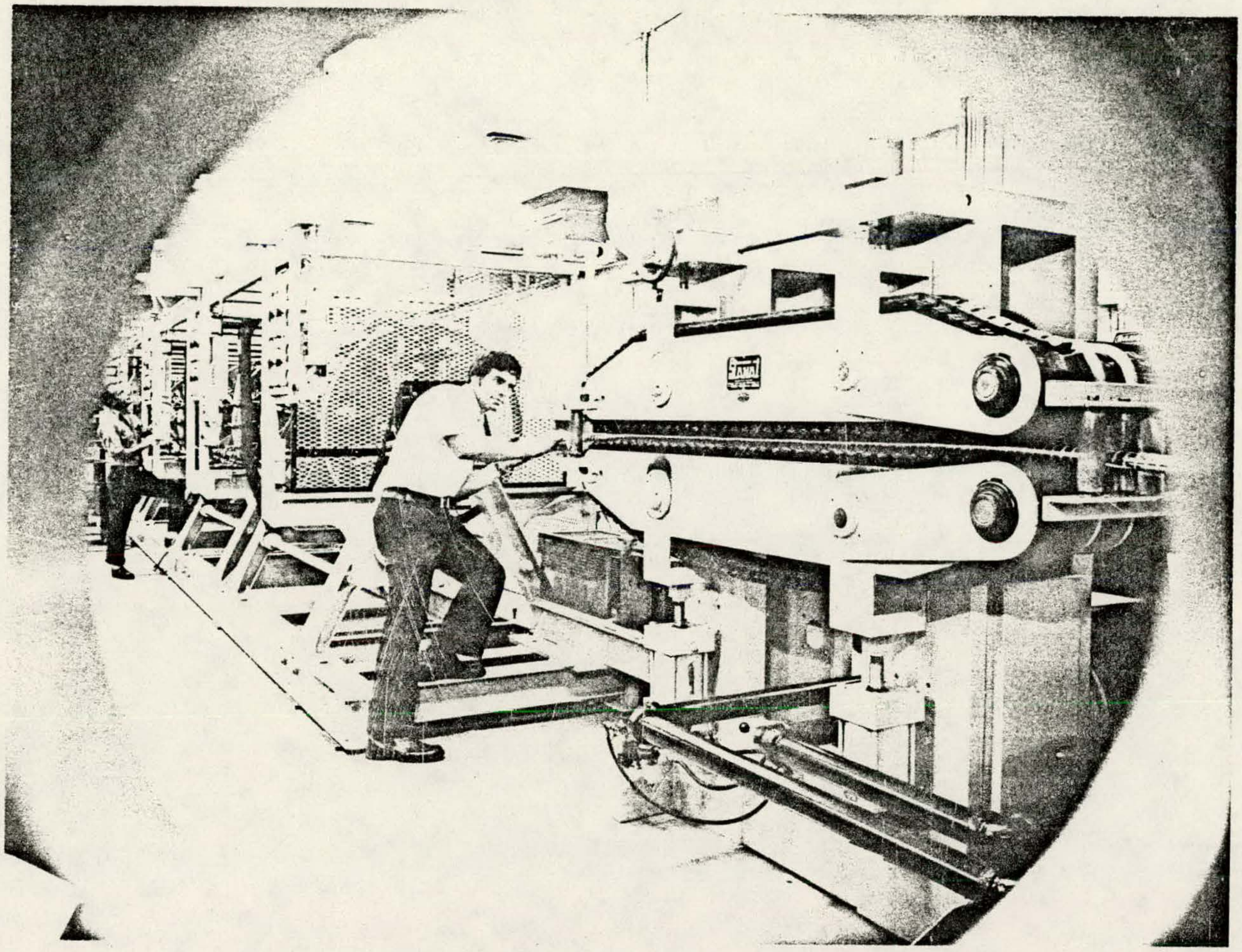

Figure 7. Experimental cable taping line at Brookhaven.

A find-focus x-ray system has proved to be invaluable for the investigation of bending performance (24). This apparatus has been used at electric utility sites to measure the integrity of paper-oil cables and has recently discovered deep-seated damage to paper-oil cables caused by thermomechanical cycling.

THE OUTLOOK

At Brookhaven the results of various systems studies, culminating in the Philadelphia Electric Co. study have been most useful in providing "mid-course corrections" to the development program. We are confident this iterative process to arrive at the most cost-beneficial design will continue to influence our work. In about a year we hope to energize the first single phase cable at the 100 m Test Facility. On a three-phase basis the ratings correspond to a 1000 MVA circuit capacity. When this is running the economic projections will rest on a much firmer foundation. These projections may indicate that the

1000 MVA rating is competitive with other methods in some situations. In this case the commercial introduction of superconducting power transmission will be brought much closer than previously thought.

In Europe only the Austrian project is still active; although this is a true pioneering effort no economic analysis of the particular technical design has been published and the future is uncertain after the test at Arnstein. It is ironic that the project under Professor Klaudy in Graz has survived longer than others in Europe even though the funding has been more modest. Compared to the savings and technological advantages which may be reaped when applied to an electric utility transmission system the amounts expended so far on all the projects are not large and the termination of the British and German programs appears premature. The decision appears to have been based on one study (25), which is unfortunate as experience at Brookhaven indicates several studies are necessary to identify expensive components of the design and before an interation process leads to an optimized design. Efforts in the U.S.S.R. appear to be well staffed and are proceeding under the direction of two ministeries (26). Experience in the U.S. seems to indicate that the rigid cable design made at the Kzhizhanovsky Power Engineering Institute would be economically unattractive by western standards. The flexible cable made at Podolsk does not possess a true cryogenic dielectric insulation but Nb_3Sn tape made for this cable and tested at BNL is surprisingly good. It seems likely that this active and diverse program will be maintained in the U.S.S.R. for some time.

The system studies have given some indication of the likely applications of superconducting ac power transmission systems. For short routes compressed gas insulation and paper-oil cables (sometimes forced-cooled) are already established technologies. For routes of less than 10 miles the reactive power generation and relatively high losses of paper-insulated cables are not considered to be detrimental factors. For distances above 10 miles the characteristics of superconducting ac cables appear very favorable, however, many are shared by compressed gas cables which have not been widely accepted by utility companies because of high costs associated with the rigid design and the relatively wide trench which is required.

Although successful operation of the 138 kV cables at the 100 m Test Facility at Brookhaven will be a most significant step forward in this technology it must be stressed that many problems remain. At a practical level a field joint design must be developed for splicing cable sections. Longer systems of several miles will raise problems not tackled on the 100 m scale associated with pulling forces and cool-down techniques. Larger scale installations require standard operating, maintenance and repair procedures to be established if the cables are to be operated by electrical utility companies. Ph.D's are remarkable thin on the ground in the operations and maintenance crews of utility companies: although these cables will represent a practical application of one of the most esoteric phenomèna discovered by modern physicists, the equipment and procedural practices must be reduced to something that is easily understood. Finally a most important problem facing designers of novel transmission systems is to nurture an industrial competence to design and install them. Only a few very large companies will have the financial base needed to build these enormous and complicated systems. These companies must increasingly participate in the development of equipment so that they are in a position to realistically assess the profit potential at the time when prototypes are successfully tested.

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