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THE TECHNICAL AND ECONOMIC FEASIBILITY OF SUPERCONDUCTING POWER TRANSMISSION: A CASE STUDY*

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ABSTRACT

The long-range plans of the Long Island Lighting Company include the installation of 4600 MW of generation capacity at nuclear sites on eastern Long Island by the 1990's. A single site, Shoreham, was chosen for this study which would require transmission facilities to the Ruland Road substation, 43 miles away. Conventional 345 kV overhead and underground circuits are planned for this service. For the case study three superconducting cable schemes have been investigated which reflect various technical options. The superconducting cables have been designed to meet acceptable normal and contingency load flow conditions and to withstand maximum short circuit faults. A cost analysis has been made of the complete installation, providing a valuable comparison of the estimated cost of this new technology with conventional methods. The most favorable cost comparison is a two-circuit 345 kV superconducting system, which appears to be about one-half the cost of an all underground 345 kV high pressure oil-filled cable system. No reactive compensation will be required for the superconducting system, whereas extensive compensation is required for HPOF cables over the same distance. The cost estimate for the two-circuit superconducting system is about twice that of 345 kV overhead transmission, which would consist of two double circuits and one single circuit, assuming right-of-way could be obtained.

INTRODUCTION

Power transmission using superconducting cables is an idea that has been studied for over a decade. However, it is only in recent years that detailed designs have been made for compressed gas insulated¹ and flexible cables² using conductors which will be cooled to within a few degrees of absolute zero. The general characteristics to be expected of superconducting transmission systems have been described³. The intent of the study is to provide detailed cost estimates for superconducting systems which meet the technical requirements for a specific utility application. In this way a direct economic comparison can be made with conventional transmission methods for that particular situation. This has allowed the potential economic feasibility of superconducting systems to be judged with much better accuracy than in previous studies of a sim-

ilar nature. Clearly this comparison may not be valid for some other site, but the percentage contributions of the major cost items will permit some extrapolation with suitable modification to reflect differing conditions.

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 this 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 a 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 can not 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.

General Description of Superconducting Transmission Plans

The three plans include one scheme which is completely superconducting and two requiring superconducting cables in combination with 345 kV overhead circuits. The original numbers assigned to all plans have been maintained, the plans discussed are #2, #3A and #4. These are presented in more detail below.

Common to all three plans are the conceptual designs of the superconducting cable, the thermally-in-

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Fig. 1. Model of Flexible Superconducting Cable Showing Major Components.

ulated pipe to contain the cable and the refrigeration systems. The transmission system under development at Brookhaven National Laboratory is analogous to conventional HPOF cable in many ways. The cable is designed to be flexible and reelable at room temperature. The cryogenic envelope is installed in a trench and jointed. At intervals of 3000 to 4000 feet the cable is pulled in and spliced in special manholes. The cable is a coaxial geometry with a full-current return shield, hence, each cable is an isolated-phase conductor. A model of 345 kV superconducting cable is shown in Fig. 1. The inner bore of the envelope is pressurized at approximately 1.5 MN/m^2 ($\sim 15 \text{ atm}$) with helium in the range 6 to 9 Kelvin, a suitable temperature for the niobium-tin superconducting material forming the conductor. The lapped tape insulating plastic is still the subject of extensive development and a definite choice has yet to be made. Three materials possessing some of the necessary properties are Kapton*, polysulphone and polyethylene⁴. The price of these materials covers a 10 to 1 range, polysulphone is in the middle and has been used in the cost analysis. All superconducting cable designs for this study have an operating stress of 100 kV/cm (250 V/mil) at the surface of the inner conductor.

The design of the cryogenic envelope for this study was provided by the Cryenco Division of Cryogenic Technology, Inc., who also estimated costs and installation man-hours for this equipment. The envelope consists of an outer and inner pipe, the annulus is evacuated and contains multilayer insulation. A shield operating at about 85 K is incorporated. The pipe also contains helium return ducts. The cables themselves have a hollow center conductor for the helium go stream. A view of the envelope is shown in Fig. 2. The outer carbon steel pipe has a corrosion protective coating of a layer of uncured butyl rubber followed by spiral wraps of extruded polyethylene or polypropylene film. Cathodic protection is included. Designs have also been made of feeder joints, manholes and potheads but will not be described in detail in this paper. The refrigeration systems have been designed at Brookhaven using computer programs to calculate pressure drop, temperature rise and other data. Costs have been estimated for machines with rotary compressors and expanders. The use of reciprocating engines in this class of service is unlikely. The refrigerators normally feed upstream and downstream loops. Thus with 6 km (3.7 mile) loops the refrigerator station separation is 12 km (7.4 mile). A separate refrigerator is provided for each circuit, placed in a station common to all circuits. A site of less than 3000 m² (0.75 acre) is required and power for the refrigerators is supplied by two independent underground feeders from the nearest distribution substation.

Plan 2

Two superconducting circuits connect Holbrook and Ruland Road. Transmission is overhead from Shoreham to Holbrook with three overhead circuits feeding into the superconducting circuits at Holbrook and two continuing overhead to Ruland Road via the Long Island Rail Road (LIRR) right-of-way. As each superconducting circuit has a normal load of only 1300 MVA the cables have been designed for 138 kV operation, requiring 345 kV/138 kV transformers at either end. In order to obtain the low impedance for proper power sharing, auto-

* Kapton is a DuPont trade name for a form of polyimide (Nylon).

Fig. 2. Isometric View of the Cryogenic Envelope

transformers are used at the Holbrook end (0.025 p.u.⁵) and low reactance 2-winding transformers at Ruland Road (0.047 p.u.⁶). The parameters of the cables for each plan are shown in Table I and the site of these plans is shown in Fig. 3.

Plan 3A

Two superconducting circuits connect Shoreham and Ruland Road. No conventional 345 kV circuits are included. Each circuit has a continuous rating of 4800 MVA, 345 kV, see Table I. The current density at the continuous contingency load of 4800 MVA is 426 A/cm and corresponds to surge impedance loading for this cable.

Plan 4

Three superconducting circuits connect Holbrook and Ruland Road. Overhead lines complete the corridor to Shoreham. Each circuit is rated for a continuous contingency power of 2400 MVA at 345 kV, see Table I.

SYSTEM ANALYSIS

The three superconducting designs have been investigated for satisfactory operation under normal, contingency, and fault conditions on the LILCO system. Available fault MVA at the Ruland Road substation will be approximately 25,000 MVA and typical reactance values were used for the four generators and transformers at the Shoreham complex.

The scope of this study did not justify the use of computer programs for rigorous solutions to fault conditions. Straightforward calculations of current division under the various conditions were made to give a general understanding of system performance with superconducting cables. No stability studies were performed, although previous studies of the planned conventional 345 kV overhead and HPOF system indicate the effect of the relative impedance values associated with the three superconducting schemes. In the three plans considered the impedance levels are equal or less than the reference impedance of the planned system. Stability studies have shown the planned system to be acceptable, hence it is not anticipated that superconducting

* 1200 MVA base, the continuous rating of the transformers is 2100 MVA.

Fig. 3. Map of Long Island With Routes of Plans 2, 3A and 4.

cables will lead to stability problems. In fact, the impedances of plans 3A and 4 are considerably less than the reference system. The calculated values of system parameters under normal, contingency and fault conditions are shown in Table II. Circuit breaker ratings are shown in Table III.

A summary of the cooling systems for each plan is shown in Table IV. The major heat loads are heat influx into the envelope, dielectric loss and hysteretic loss in the superconductor. The heat influx has been calculated by Cryenco based on the single-shield design. The dielectric loss is based on a dissipation factor for the insulation of 2×10^{-5} at the operating temperature. The hysteretic loss is based on measured characteristics of niobium-tin specially developed for use as a transmission line conductor⁵.

INSTALLATION

A detailed study has been made of the installation procedures for the flexible superconducting transmission system. A determination was made of many factors, such as angular bend of the envelope, pulling tension, sidewall pressure and manhole locations using LILCO route maps. A summary of the installation parameters is given in Table V.

Trenching - All three superconducting plans use LILCO right-of-way for the entire length of the circuit. No pavement removal and replacement is required except for street crossings, of which there are 69 in the Holbrook-Ruland Road route. Two borings are required under parkways where disruption of traffic is not permitted. To allow access to the pipes for inspection a bore size of 1.2 m (4 ft) is used for plan 2 and the single 345 kV circuit of plan 4. The two circuit 345 kV pipes of plans 3A and 4 require a 1.5 m (5 ft) bore.

Both circuits are placed in one trench in plans 2 and 3A. Two trenches are used for the three circuits of plan 4. A 4 inch free-poured concrete slab is placed in all the trenches to reduce the chances of an accidental dig-in. No special back-fill is required. The cryogenic envelopes have vacuum gauges and relief valves in each section which must be inspected periodically. Consideration has been given to placing the pipes in a concrete trough the entire length of the line. The cost of the trough, plus the need for pipe anchors in each 18.3 meter length, made this too costly.

Instead a valve box allows the necessary access at the end of each section.

Installation of Cryogenic Envelope - Handling and alignment of the cryogenic envelope is similar to that for gas-spacer cable pipe. Assembly of the sections can be done above the trench, and the sections lowered as assembly is completed. The basic steps in installation are as follows:

- Unload and position pipes so that inner stainless steel liners butt. Positioning jigs will probably be required.
- Weld the stainless steel liners and weld couplings on refrigerant return pipe. Test weld integrity. (Helium mass spectrometer test.)
- Wrap cryogenic insulation.
- Position and weld carbon steel outer sleeve.
- Test weld integrity. (Gas bubble test, X-ray)
- Evacuate area between stainless steel and carbon steel pipes. Test weld integrity. (Helium mass spectrometer.)
- Apply corrosion coating in weld areas.

The overhead right-of-way has gentle horizontal bends of approximately 10° , with a minimum radius of 240 m (790 ft). Cryenco indicates that each joint in the envelope can allow a 1° deflection, and a further 1° can be tolerated in the 18.3 m length of pipe, so that a bellows-type cryogenic envelope is not required for horizontal bends. Vertical dips are 1.2 m in 30 m at the worst, for which a bellows section may be required. To allow for these dips and other unanticipated deflections, one flexible section has been inserted after nine lengths of rigid envelopes. Each flexible section is 3 m long, and can be used for a 20° , 5.2 m radius bend, although a radius of not less than 25 m would be used to prevent cable damage in pulling. The average pipe section length is then $16.8 \text{ m} : (9 \times 18.3 \text{ m} + 1 \times 3 \text{ m}) / 10$. This length is used for costing the installation of pipes. As in traditional practice, the pipes between splicing manholes are copped, evacuated, and filled with nitrogen until the cable is pulled.

Cable Installation - The low weight of the cables, few bends and dips, and low coefficient of friction of stainless steel on stainless steel will allow long section lengths. The maximum pulling length for straight sections, assuming that two cables carry the full tension, is over 3350 m (11,000 ft) for the 138 kV cables, and over 1430 m (4700 ft) for 345 kV cables. A section length of 1220 m (4000 ft) has been assumed for 138 kV (Plan 2) to allow a sufficient factor of safety. For the 345 kV design (Plans 3A and 4) the reelable length is the determining factor. A drum width extension of 24 cm (2 cable wraps) over the standard 345 kV design allows a section length of 915 m (3000 ft). Handling and pulling of the cables is similar to normal practice for NPOF cables, except tension is applied to the stainless steel skid and armor ribbons instead of the conductor.

As a lapped tape insulation is used the construction of a splice will follow normal practice. However, the compression joint for the center conductor must be made with very low resistance and the superconducting shield must be extended over the splice. Special splices are required at feeder joints located at the ends of cooling sections. Helium is removed from the

Table 1

Flexible Superconducting Cables Basic Design Parameters

	Plan 2	Plan 3A	Plan 4	Reference 345 kV MPOF
Voltage, kV	138	345	345	345
No. of Circuits/Single Circuit Normal MVA. (Continuous Contingency MVA)	2/1300 (2100)	2/2400 (4800)	3/1600 (2400)	2/450-650 (450-650)
Length of Circuit, km. (Mile)	35.6 (22)	68.4 (42.5)	35.6 (22)	-
Inner Conductor Radius, cm. (Inches)	2.68 (1.06)	3.01 (1.19)	1.83 (0.72)	2.3 (0.91)
Radius of SC Shield, cm. (Inches)	3.61 (1.42)	5.83 (2.30)	5.44 (2.14)	4.95 (1.95)
Outer Dia. of Cable, cm. (Inches)	8.1 (3.19)	12.4 (4.88)	12.04 (4.74)	11.0 (4.33)
Max. Electrical Stress, kV/cm. (V/Mil)	100 (254)	100 (254)	100 (254)	115 (292)
Mean rms Stress, kV/cm. (V/Mil)	86 (218)	71 (180)	55.2 (140)	78 (198)
Normal Current, kA.	5	8	4	0.83
Dielectric Constant of Insulation.	2.2	2.2	2.2	3.5

center conductors and returned to the refrigerator. A short length of helium-insulated cable will be introduced to accomplish this, an operating stress of 20 kV/cm (50 V/mil) has been used in the design of this joint.

Terminals - These are a trifurcating manifold at each end of a superconducting circuit. The terminal accomplishes the usual task of grading the electric field so that an external connection can be made to the cable. In addition a thermal gradient exists between room-temperature and the operating temperature. As the temperature rises within the terminal the superconductor gives way to a normal metal. The sheaths are also brought out at the terminal. The portion of the terminal at room temperature uses a conventional bushing for the center conductor. The terminal will incorporate evacuated multilayer thermal insulation and for costing purposes it has been assumed each terminal will be cooled by a separate refrigerator, not the main coolant stream for the cable.

Cooldown and Maintenance - Evacuation of the completed line is especially critical since at helium temperatures all other gases are solid and must be filtered at the refrigeration stations. A ten-day evacuation period, with vacuum pumps at 8 locations on the 35.6 km line, has been assumed. A further three weeks are required for helium filling and cooling to the operating temperature.

Routine maintenance of the envelope consists of periodic inspection of the vacuum gauges and replacement of gaskets on the relief valve gaps. Corrosion

is prevented by a standard cathodic protection system. The refrigerators will be designed for 10,000 hours or more mean time before failure. Components will be in a modular form to permit speedy replacement without shutting down the line. The enormous heat storage of the helium in the cable will allow up to 24 hours of operation without refrigeration.

It is anticipated that the incidence of electrical faults will be small, especially since the cable will operate at a relatively constant temperature, and therefore will not be as subject to mechanical stresses during normal operation as are pipe-type cables.

In the event of an electrical failure, the 6 km refrigeration loops would be emptied to allow repairs to proceed. Several possible methods of storing the helium have been investigated in detail. Repairs to the cable itself would probably follow MPOF practices. There is no technical problem with having a buried splice in the system to avoid replacement of a cable section. The time to repair and restore the cable to service, including evacuation and cooldown, will probably be 4 to 10 weeks.

COST ANALYSIS

Cost estimates for different items in this study were provided by the participating institutions and outside consultants. The standard methods used by LLCO to cost similar projects were applied during this study. The cost of materials in a form ready for cable fabrication was prepared by Brookhaven. The actual

Table II

Calculated Values of System Parameters

Plan	System Condition	Power thru 1 SC ckt (MVA)	Current in Cable (Amps)*	Cable Current Density† (Amps/cm)	Cable System Impedance (p.u.)**	System Impedance Shoreham to Ruland Rd (p.u.)**	Load Division U/G to O/H
2	Normal	1,320	5,500	324	jo.060	jo.054	0.55/0.45
"	OM Line Out - Shoreham to Ruland Rd.	1,750	7,300	432	jo.060	jo.070	0.73/0.27
"	SC Cable Out	2,080	8,700	512	jo.120	jo.069	0.43/0.57
"	1-OM Lines Out - Shoreham to Rul. Rd.	2,400	10,000	592	jo.060	jo.099	1.00/0
"	OM Line Out - Shoreham to Holbrook	1,200	5,000	296	jo.060	jo.060	0.50/0.50
"	1Ø Fault at Ruland Rd. (Cable)	2,640	11,000	648	-	-	0.55/0.45
"	1Ø Fault at Holbrook (Cable)	5,770	24,000	1,408	-	-	0.46/0.54
"	1Ø Fault at Ruland Rd. (OM Lines)	2,640	11,000	648	-	-	0.55/0.45
"	1Ø Fault at Shoreham (Rul.Rd.Line)	3,200	13,400	792	-	-	0.55/0.45
"	1Ø Fault at Holbrook (OM Line)	3,400	22,500	1,320	-	-	0.43/0.57
"	1Ø Fault at Shoreham (Holbrook Line)	3,200	13,350	784	-	-	0.55/0.45
3A	Normal	2,400	4,000	210	jo.068	jo.068	-
"	SC Cable Out	4,800	8,000	420	jo.136	jo.136	-
"	1Ø Fault at Ruland Rd.	6,900	11,450	600	-	-	-
"	1Ø Fault at Shoreham	9,250	15,400	820	-	-	-
4	Normal	1,600	2,670	230	jo.019	jo.066	1/1
"	SC Cable Out	2,400	4,000	350	jo.029	jo.076	1/1
"	1Ø Fault at Ruland Rd. (Cable)	3,890	6,450	360	-	-	1/1
"	1Ø Fault at Holbrook (Cable)	6,950	11,550	1,000	-	-	1/1
"	1Ø Fault at Holbrook (OM Line)	6,950	11,550	1,000	-	-	1/1
"	1Ø Fault at Shoreham (OM Line)	4,950	8,250	720	-	-	1/1

* Current at 138 kV for Plan 2 and 345 kV for Plans 3A and 4.

† Current per unit circumference of inner conductor.

** MVA Base for p.u. quantities: Plan 2, 1200 MVA; Plan 3A, 4800 MVA; Plan 4, 2400 MVA.

cable fabrication costs were prepared by Power Technologies Inc. The cost of the cryogenic envelope and helium, for the construction site, was prepared by the Cryenco Division of Cryogenic Technologies Inc. This company also estimated the labor to join these envelopes. Brookhaven provided basic refrigerator and cable terminal costs. All other estimates were provided by LILCO and Power Technologies Inc.

All prices are in 1973 dollars and no escalation or inflation factor has been included, normal wastage and contingency charges have been included. In the case where the item is not available at present, such as the cable itself or the cryogenic envelope, it has been assumed a factory exists with an annual output of about twice the amount needed for this job and half the annual factory overhead has been included in the estimates. The analysis is presented as a total investment cost. It is recognized that a present worth analysis would also reflect the scheduling of the work so that transmission facilities match the installation of generators, unfortunately time and money did not permit this depth of analysis.

Limitations of space do not permit a full listing of the many items which were considered in producing the cost estimates. The relative contributions made by the many components of the system can be assessed by the following percentages. The following shows the cost of materials for plan 3A.

Materials

Cryogenic envelope:	57%
Cable on reels at site:	18%
Splices:	1%
Terminals inc. refig.:	1%
Helium:	3%
Misc: alarms, monitoring, cathodic protection:	negligible

The total costs of materials for all three plans are shown in line 1, Table VI. Similarly, the percentage contributions to the installation costs for plan 3A are shown below, the list does not include construction of the refrigeration stations.

Installation

Trenching and backfilling:	26.5%
Street crossings:	2.0%
Parkway borings:	1.5%
Stream crossings:	1.5%
Valve boxes:	12.5%
Pipe handling and positioning:	11.0%
Cryogenic envelope joints:	14.0%
Manholes:	8.5%
Cable pulls:	3.5%
Splicing:	9.0%
Terminals:	1.0%
Misc., alarms, protection:	1.5%
Evacuation, cooldown, proof test:	1.0%
Contingency on above:	6.5%

* Includes material costs.

Table III

Breaker Duty Under Various System Conditions

Plan	System Condition	Maximum Symmetrical Current in Breaker (Amps)*	Breaker Location	Symmetrical Fault Power (MVA)
2	Normal	2,200	Cable System	-
"	OH Line Out - Shoreham to Ruland Rd.	2,920	Cable System	-
"	SC Cable Out	3,470	Cable System	-
"	2-OH Lines Out - Shoreham to Rul. Rd.	4,000	Cable System	-
"	OH Line Out - Shoreham to Molbrook	2,000	All Breakers	-
"	3 ϕ Fault at Ruland Rd. (Cable)	53,500	Ruland Rd. - Cable System	31,965
"	3 ϕ Fault at Molbrook (Cable)	31,700	Molbrook - Cable System	19,010
"	3 ϕ Fault at Ruland Rd. (OH Lines)	54,250	Ruland Rd. - OH Line	32,440
"	3 ϕ Fault at Shoreham (Rul. Rd. Line)	42,800	Shoreham - Rul. Rd. Line	26,220
"	3 ϕ Fault at Molbrook (OH Line)	32,700	Molbrook - OH Line	19,640
"	3 ϕ Fault at Shoreham (Molbrook Line)	44,500	Shoreham - Molbrook Line	26,695
3A	Normal	4,000	Cable System	-
"	SC Cable Out	8,000	Cable System	-
"	3 ϕ Fault at Ruland Rd.	53,300	Ruland Rd. - Cable	31,900
"	3 ϕ Fault at Shoreham	44,000	Shoreham - Cable	26,370
4	Normal	2,670	Cable System	-
"	SC Cable Out	4,000	Cable System	-
"	3 ϕ Fault at Ruland Rd. (Cable)	54,800	Ruland Rd. - Cable System	22,750
"	3 ϕ Fault at Molbrook (Cable)	44,500	Molbrook - Cable System	26,700
"	3 ϕ Fault at Molbrook (OH Line)	52,000	Molbrook - OH Line	31,050
"	3 ϕ Fault at Shoreham (OH Line)	48,250	Shoreham - OH Line	28,970

* At 345 kV for all plans.

Table IV

Summary of Cooling System Characteristics

Plan #	Dielectric Loss, W/km*	Hysteresis Loss at Normal Load, W/km*	Hysteresis Loss at Continuous Contingency, W/km*	Heat Influx of Cryogenic Envelope, W/km*	Heat Load of Shield, W/km*	No of Refrig's per Circuit/NP of Each Refrig'r	Power Req for Each Refrig Station, all Circuits**	Refrig Station Site Size m ² (acre)
2	59	35	127	29	690	3/1300	1940 kW	2000 (0.5)
3A	165	8	42	55	775	6/1693	2526 kW	2000 (0.5)
4	100	< 1	7	55	775	3/1288	2883 kW	3000 (0.75)

* Value at operating temperature of 6-9 K, per circuit

* At a temperature of ~ 85 K

** Continuous contingency operation

Table V

Installation Parameters of Flexible Superconducting Cables

	Plan 2	Plan 3A	Plan 4	Reference 345 kV HPOF
Voltage, kV	138	345	345	345
Number of Circuits	2	2	3	2
Length of Circuit, km, (mile)	35.6, (22)	68.4, (42.5)	35.6, (22)	-
Outer Cable Dia., cm, (ins)	8.1, (3.19)	12.4, (4.88)	12.0, (4.74)	11.0, (4.33)
Cable Weight, kg/m, (lbs/ft)	4.69, (3.15)	11.0, (7.37)	10.7, (7.2)	20.1, (14.0)
Inner Pipe Dia., cm, (ins)	19, (7.5)	28.5, (11.2)	28.5, (11.2)	26, (10.2)
Outer Pipe Dia., cm, (ins)	40.6, (16)	50.8, (20)	50.8, (20)	-
Trench Size, Width x Depth, cm x cm, (ft x ft)	137 x 147 (4.5 x 4.8)	163 x 152 (5.3 x 5.0)	163x152, 81x152* (5.3x5.0), (2.7x5.0)	152 x 137 (5.0x4.5)
Pulling Length, m, (ft)	1,220, (4000)	914, (3000)	914, (3000)	-
No. Splices/ckt	29	75	39	-
No. Refrig'n Sta./ckt	3	6	3	-
Jam Ratio	2.34	2.30	2.33	2.38
Clearance to Pipe "D", cm	2.1	2.4	2.8	3.4
Weight Corr'n Factor, W_c				
Cradled Config.	1.74	1.79	1.76	1.44
Triangular Config.	1.48	1.57	1.52	1.52
Average	1.61	1.68	1.64	1.48
Coef. of Friction, K_o	0.07	0.07	0.07	0.20
$K = K_o W$	0.11	0.12	0.12	0.30
Total Maximum Pulling Tension, kg, (lb)	2,360 (5,200)	4,350 (9,600)	4,470 (9,850)	21,800 (48,000)
Max. Sidewall Pressure, (for 30 m radius bend) kg/m, (lb/ft)	90 (60)	150 (100)	150 (100)	714 (400)

* Two trenches are used in plan 4.

The total costs of installation for the three plans are shown in line 2 of Table VI. The breakdown for the refrigeration stations for plan 3A is as follows:

Refrigeration	
Refrigerator, install'n, housing:	82%
Real estate and distribution supply:	13%
Land preparation, foundation:	3%
Controls, alarms, misc.:	2%

Comparison with Conventional Circuits - Table VII summarizes the complete cost of conventional systems to accomplish the same transfer of 4800 MVA. Note the conventional equivalent of plan 2 uses a combination of overhead and underground lines, thus the cost in dollars per MVA-mile does not offer a meaningful comparison to an all-underground system, especially on the basis of continuous contingency rating.

CONCLUSION

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.

The use of transformers in plan 2 clearly introduces technical problems and a substantial cost penal-

ty. 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.

No transient overvoltage or overcurrent analyses were performed during this phase of the study. Such studies are desirable in the future to examine the performance of the system and its capabilities during transient surge conditions. These runs, using a model simulation, would provide necessary information for the design of adequate protection for the cable system. A transient analysis would also shed some light on the possible need for insulation between the superconducting shield and the armor. The magnitudes of the dc and low-frequency components of the short-circuit current waveform are also important when optimizing the design of the cable conductor.

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

Table VI

**Flexible Superconducting Cables Cost Summary
Without Circuit Breaker and Transformer Costs**

		Plan 2	Plan 3A	Plan 4
1.	Material Cost	\$47,800,000	\$140,000,000	\$104,300,000
2.	Installation Cost	5,800,000	14,600,000	11,800,000
3.	Refrigeration Station Cost	5,900,000	15,700,000	8,800,000
4.	Engineering and Supervision	900,000	1,500,000	1,300,000
5.	TOTAL INSTALLED COST	\$60,400,000	\$171,800,000	\$126,200,000
6.	Estimated Time and Interest Charged During Construction	1 yr.	1-1/2 yr.	1-1/2 yr.
		4,200,000	18,000,000	13,300,000
7.	TOTAL COST	\$64,600,000	\$189,800,000	\$139,500,000
9.	MVA Total, All Circuits, Normal Rating	2,600	4,800	4,800
9.	Length, Miles	22	42.5	22
10.	Dollars/Circuit-Mile	\$1,470	\$2,230	\$2,110
11.	Dollars/MVA-Mile, For Installed System	\$1,130	\$930	\$1,320
12.	Add Demand, Capitalized Energy and Maintenance Charges to Item 7	\$2,500,000	\$13,000,000	\$5,200,000
13.	TOTAL COST	\$67,100,000	\$202,800,000	\$144,700,000
14.	Dollars/MVA-Mile, Including Capitalized Charges	\$1,170	\$990	\$1,370
The superconducting cable system is designed for a continuous rating higher than that shown above, to allow full load to be carried if one cable is out of service. The cost in dollars per MVA-mile for the maximum continuous rating is shown below:				
8a.	MVA Total, All Circuits, Continuous	4,200	9,600	7,200
11a.	Contingency Rating			
	Dollars/MVA-Mile	\$700	\$470	\$890
14a.	Dollars/MVA-Mile Including Demand and Capitalized Energy and Maintenance Charges	\$730	\$490	\$910

Table VII

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 ON + 2-345 kV NPOF	2	9-345 kV NPOF	3	9-345 kV NPOF
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	\$ 6,200,000	\$ 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	4,200	NA	9,600	5,400	7,200	5,400
Contingency Rating						
9a. Dollars/MVA-Mile	\$1,036	NA	\$ 510	\$1,840	\$ 980	\$1,920

there is virtually 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 shut-down 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 VII.

Table VII 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. Careful attention should be given to the design of this equipment to optimize the performance and the effect on total cost. 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 \$10 million, including cost of breakers and capitalized losses. This figure can be compared to the cost of \$209 million on line 7, Table VII, 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 Council⁶ of bringing overhead and underground transmission costs into line. If the cost analysis had been based on present worth the financial advantage of superconducting schemes compared with 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 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 under-utilized 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 costs 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.

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