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TRANSMISSION SYSTEM

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SYSTEM

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SYSTEM

INTRODUCTION

Numerous studies involving cost estimates have been performed for superconducting power transmission systems.¹⁻³ As these systems were usually aimed at providing transmission from large clusters of generation the base power rating of the corridor was very high; in the case of the most comprehensive study it was 10,000 MVA.³ The purpose of this study is to examine a system which is very closely based on the prototype 1000 MVA system which was operated at Brookhaven National Laboratory over a four year period.⁴ The purpose of the study is to provide cost estimates for the superconducting system and to compare these estimates with a design based on the use of advanced but conventional cable designs. The work is supported by funding from the Office of Energy Research's Industry/Laboratory Technology Exchange Program. This program is designed to commercialize emerging technologies. The technical design of the superconducting system was prepared by the BNL staff, the design of the 800 MVA conventional cable system was done by engineers from Underground Systems Incorporated. Both institutions worked on the cost estimate of the superconducting system. The description and cost estimate of the conventional cable system is given in the Appendix.

TECHNICAL DESIGN OF THE SUPERCONDUCTING SYSTEM

The design closely follows the prototype at BNL. This consists of rigid cryogenic enclosure with flexible superconducting cables employing Nb₃Sn conductor. Some small technical changes have been made; the cable dimensions have been reduced slightly reflecting the smaller power rating of this study.

The operating 60 Hz stress for the electrical insulation has been reduced from 10 kV/mm to 9 kV/mm. The conceptual design of the cryostat has been slightly revised to reduce the heat leak. Previous studies had indicated the heat leak of the present design, which was based on the requirements of the PEC Study,³ would be too high for a much lower power system.⁵ The operating voltage of the system is 138 kV and the Surge Impedance Load (SIL) is 640 MVA, a value chosen to match the scenario of load growth over the life of the system; the characteristics are summarized in Table 1.

System Design

The system consists of one three-phase circuit 25 miles in length. Connections to the network are only made at each end. No reactive compensation is required. A sketch of the system layout is shown in Fig. 1. The system is cooled by two main refrigerators located approximately at the 1/3 and 2/3 points. Two small refrigerators cool the gas used to cool the leads of the terminations; one is located at each end. The various joints are shown as types A, B, and C in Fig. 1. The spacing is based on an average pull of 4000 ft. A description of these components follows:

Type A Manhole

Total of thirty. Provides simple cable to cable splice. It is assumed there is little increase in the radial dimensions at the splice. A design of the manhole is shown in Fig. 2.

Type B Joint

Total of two. This joint provides the main feeder joints to the two large cooling refrigerators. The joint is gas cooled so that one loop can run warm and one cold (without electrical excitation, i.e., no electrical connection to the outside).

Table 1

The Parameters of the 138 kV Superconducting Cable System

Rated Power	:	800 MVA
Rated Voltage	:	138 kV
Rated Current	:	3.33 kA
Inner Conductor Linear Current Density	:	442 A/cm
Maximum rms Dielectric Stress	:	9 kV/mm
Surge Impedance Load	:	640 MVA
$Z_0 (\epsilon_r = 2.2)$	:	30 Ω
Diameter of Inner Conductor	:	2.4 cm, 0.945"
Diameter of Outer Conductor	:	5.0 cm, 1.970"
Cable O/D (Not Including S/S Jacket)	:	5.47 cm, 2.155"
Cryogenic Inner Pipe Dia.	:	16 cm, 6.3 in
Cryogenic Outer Pipe Dia.	:	34.3 cm, 13.5 inch
Per Unit* Series Reactance	:	$2.3 \times 10^{-3} \text{ km}^{-1}$
Per Unit Shunt Reactance	:	667 km
Per Unit Series Reactance fo 40 km	:	0.093
Per Unit Shunt Reactance for 40 km	:	16.7
Specific Current Dependent Loss at 442 A/cm	:	98 $\mu\text{W}/\text{cm}^2$
Specific Dielectric Loss Tangent	:	50 $\mu\text{Radians}$
Heat In-leak (Referred to 7 K)	:	0.326 W/m

*All Per Unit on 138 kV, 800 MVA Base.

25 MILE STUDY. SYSTEM LAYOUT

Fig. 1.

Fig. 2. Cable splice design with common pressure vessel

Type C Joint

Total of one. This is the cooling loop turn-around. It permits cryogenic connection to the two expanders and connection of a N_2 -cooled heat exchanger for cooldown. The joint is gas-cooled so that one loop can run warm and one cold. There is no electrical connection to the outside.

Terminations

Total of two. These permit electrical connection to the outside. They also permit connection to the expander and to the small refrigerator for lead cooling.

Cable Design

In the Brookhaven program to build a prototype a flexible cable was chosen for development as this approach promised the most economical system and provided a means of accommodating the contraction produced at the operating temperature of approximately 7 K. At the start of the project none of the major cable components existed in a form suitable for direct application and considerable development was necessary. Niobium-tin was chosen as the most attractive superconductor for this application and over a period of about five years considerable progress was made in the development of commercial sources of niobium-tin tape of lengths up to 200 m with appropriate magnetic and electrical properties. The electrical insulation consists of a polymeric tape with low dielectric loss at the operating temperature and well-controlled mechanical properties at room temperature. These are imposed by the taping machine requirements and the need to reel and unreel the cable during manufacture and installation. The components mentioned above are placed on a metallic "core", the general construction of the cable is shown in Fig. 3.

Fig. 3. General assembly diagram of flexible superconducting power transmission cable design. The cable is pulled into the corrugated jacket during installation. In the design costed in this study the outer stainless steel tapes were omitted.

The taping diagram of the prototype cable at BNL is shown in Fig. 4. The construction data is given in Table 2. Apart from the small dimensional changes indicated in Table 1 the cable used in this study is identical except that an analysis of pulling forces during installation showed that the stainless steel tapes on the outside were not necessary as the pulling force would not exceed 4000 lbs; the inner core was designed to accommodate this force.

Cryogenic Enclosure

The design consists of an unshielded cryostat with vacuum barriers at each end of each section. The sections are 18m in length, the length is determined by shipping restraints. The diameter of the inner pipe is 16.01 cm and the outer pipe diameter is 34.34 cm. The design is the same as that used at the 1000 MVA test site.^{4,6} A diagram of the enclosure is shown in Fig. 5. The inner pipe is normally operated at 7 atms; about half the pressure in the cables. The cooling system uses the far-end expander design evaluated in the trials of the Brookhaven prototype.⁷

Cooling System

The helium refrigerator is designed as a system optimized for utility company service. To provide long periods of uninterrupted service it is essential to ensure each component provides the highest possible reliability. Selecting major components for the refrigerator system to satisfy the basic criterion of continued long-term operation is difficult when compared to operating requirements placed on present helium refrigeration systems. However, new types of equipment are available which have demonstrated long-term trouble-free operation. The principal components requiring special considerations are:

Fig. 4. Radial build-up of the layers forming cables

Table 2

Construction Data of Cable 1001/2

	Pass	Width In.	Thick- ness In.	Lay Angle °	Tension Lbs.	Pitch In.	Lay Direc.	Butt Cap In.	Out- side Dia. In.	Core Direc.	Date
PK II core (2 layer)	Prefab- ricated by Gen. Cable Co.	0.433	0.060	40.0	-	3.67	RH	0.010	0.965		12/79
		0.453	0.060	45.0	-	3.95	LH	0.010	1.005		10/80
Pre-formed high resistivity ratio copper stabilizer	1	0.243	0.015	42	7-8 lbs	3.97	RH	0.013	1.105	FWD	6/9/81
Pre-formed high resistivity ratio copper stabilizer	2	0.243	0.015	44	6-7 lbs	3.87	LH	0.013	1.143	FWD	6/15/81
Inner s.c.	3	0.254	0.004	42	2 7/8	3.97	RH	0.013	1.153	FWD	6/26/81
Inner s.c.	4	0.254	0.004	43	2 7/8	3.92	LH	0.013	1.165	FWD	7/15/81
2-wire axial	5	0.155	0.011	0	1 lb	-	Longi- tudinal	-	-	FWD	
(2) Carbon loaded paper bedding	5	7/8"	0.005 ea	76	1 3/4 lb	0.953	RH	0.050	-	FWD	
(2) Intercalated aluminized screen	5	7/8"	0.004 ea	76	2 1/2 lb	0.953	RH	0.050	-	FWD	
(6) Polypropylene Teflon treated dielectric	5	7/8"	0.004 ea	76 1/2	1 1/8 lb	0.953	RH	0.052	1.26"	FWD	8/15/81
(16) "	5	1"	0.004 ea	76	1 1/4 lb	1.076	LH	0.044	1.39"	FWD	
(16) "	5	1 1/8"	0.004 ea	75	1 3/8 lb	1.233	RH	0.070	1.532"	FWD	
(14) "	5	1 1/8"	0.004 ea	76 1/2	1 3/8 lb	1.233	LH	0.074	1.655"	FWD	
(8) "	6	1 1/4"	0.004 ea	76	1 1/2 lb	1.348	RH	0.058	-	FWD	
(8) "	6	1 1/4"	0.005 ea	76	1 5/8 lb	1.348	RH	0.061	1.800"	FWD	
(16) Polypropylene Teflon treated dielectric	6	1 3/8"	0.005 ea	75 3/4	1 3/4 lb	1.522	LH	0.100	1.942	FWD	10/22/81
(10) "	6	1 3/8"	0.005 ea	76 3/4	1 3/4 lb	1.522	RH	0.016	-	FWD	
(2) Intercalated aluminized screen	6	1 3/8"	0.005 ea	77	2 1/4 lb	1.522	RH	0.108	-	FWD	
(2) Carbon loaded paper bedding	6	1 3/8"	0.005 ea	77	2 lb	1.522	RH	0.109	2.075"	FWD	
2-wire axial probe	7	0.155	0.011	0	1 lb	-	Longi- tudinal	-	-	REV.	10/27/81
Outer s.c.	7	0.461	0.004	42.5	5 lb	7.26	LH	0.020	2.090"	REV.	10/27/81
Outer s.c.	8	0.461	0.004	42.3	4 1/2 lb	7.26	RH	0.020	2.110"	FWD	10/29/81
High resistivity copper stabilizer	9	0.472	0.015	42	6 1/2 lb	7.35	LH	0.020	2.145"	REV.	11/2/81
"	10	0.472	0.015	43	6 1/2 lb	7.20	RH	0.020	2.200"	FWD	11/5/81
(4) Kapton cover insul.	10	1 3/8"	0.005 ea	77	3 lb	1.522	RH	0.130	2.245"	FWD	11/5/81
Stainless steel compression tapes	11	1/2"	0.005	41	6 1/2 lb	8.5"	LH	0.060	2.255"	REV.	11/10/81
"	12	1/2"	0.005	41	6 1/2 lb	8.5"	RH	0.060	2.280"	FWD	11/12/81
(2) Mylar final protection tapes	12	1 3/8"	0.005 ea	77	3 lb	1.522	RH	0.136	2.300	FWD	11/12/81

Fig. 5. Design of the cryogenic enclosure. The re-entrant seals at each end permit a permanent vacuum space within the annulus of the enclosure

- 1) the compressor,
- 2) the expanders, and
- 3) the heat exchangers.

Of course, this does not minimize the importance of other more conventional components included in the total system. Similar design requirements were placed on these components as well. The components included in this group are as follows: gas control stations, control valves, mechanical pumps, vacuum systems, heat rejectors, water chiller, air compressors, air driers, and helium storage tanks.

Another important requirement often ignored or considered unnecessary is adequate inspection and testing of equipment prior to installation. Very high standards of inspection and QC are essential. The plant layout reflects the physical features of a small chemical processing plant. The helium refrigerator plant layout is arranged such that a minimum distance is provided between connected components while allowing adequate distances for operation and maintenance. Of course, it is also desirable from a cost standpoint to move the equipment together in order to minimize the interconnecting piping and wiring.

The refrigerator is essentially a Claude cycle at the high temperature end and a Brayton cycle at the low temperature end. A simplified flow diagram of the refrigerator is shown in Fig. 6.

Each of the main refrigerators has a cryogenic cooling capacity of 13.1 kW at 7 K. The design is based on the Brookhaven prototype employing screw compressors.⁸ Based on an efficiency of 225 W/W, each refrigerator station requires 3.25 MW of distribution power: this includes 10% excess power over the compressor input. Cool-down employs portable nitrogen-cooled heat exchangers. Each loop can be cooled separately. Although the idea has not been examined in detail it should be possible to store the helium from one loop in the adjacent loop, should a warm-up be necessary for repairs.

Fig. 6. Simplified flow diagram of the supercritical helium refrigerator

Table 3

Low Temperature Superconducting Transmission Line

1 Circuit 800 MW - 25 Mile

Material Costs

<u>Item</u>	<u>(\$/Unit)</u>	<u>(\$/ft)</u>	<u>(K\$/Mile)</u>	<u>Total (M\$)</u>
1. Cable	86.25/ft	258.75	1366.2	34.2
2. Cor. St. Steel	11.70/ft	35.10	185.0	4.6
3. Cryo. Enclosure	322.50/ft	322.50	1703.	42.6
4. Normal Joints (A)	25,000 ea		30.0	0.8
5. Feed Joints (B)	100,000 ea		8.0	0.2
6. Feed/Stop Joint (C)	100,000 ea		4.0	0.1
7. Termination Assy	1,150,000 ea		92.0	2.3
8. Main Refrigerators (incl He Tanks, etc.)	6,900,000 ea		552	13.8
9. Gas Expanders	120,000 ea		19.2	0.5
10. Helium (11.8 M cu ft @ 1 atm 60F)	.057/cu.ft		26.9	0.7
			<hr/>	<hr/>
TOTAL			3986.4	99.8
Present Worth (x 1.54)				153.7

Fig. 6. Simplified flow diagram of the supercritical helium refrigerator

Table 4

Low Temperature Superconducting Transmission Line

1 Circuit 800 MVA - 25 Mile

Installation Costs:

	<u>(\$/A)</u>	<u>(K\$/Mile)</u>	<u>Total (\$ Mil)</u>
1. Trench, Backfill & Manholes* Trench 24" x 50"***	345	1822	45.540
2. Lay & Weld Enclosure (Incl. Materials)	45	240	6.000
3. Pull Cables & St.St. Tubes St.St.: 33 x \$13 K/Pull Cable : 99 x \$13 K/Pull	13	69	1.716
4. Splice Cable (Incl. Welding, Etc.) 30 Type A x \$50 K/3 Phase 3 Type A&B x \$100 K/3 Phase	13.64	72	1.800
5. Terminate Cables & Install Term. Cooling: 2 x \$375 K Ea.		30	0.750
6. Install Main Refrigerators		50	1.250
TOTAL		<hr/>	<hr/>
		2283	57.056
Present Worth (x 1.54)			87.866

* Includes removal of rock over 25% of route.

**1. Alternate 24" wide x 30" deep trench \$215/ft (\$1135 K/mile) 28.380 mil.

Table 5

Present Worth of Cost of Losses Over 40 Yr. Life of Superconducting System

<u>Annual Loss Factor</u>	<u>Energy Charge \$/kW hr.</u>	<u>Demand Charge \$/kW</u>	<u>Cost \$/Mile</u>	<u>Total, \$ M</u>
0.7	0.03	0	754,100	18.9
0.7	0.03	1200	1,066,000	26.6
0.7	0.03	2000	1,274,000	31.8
0.7	0.05	0	1,257,000	31.4
0.7	0.05	1200	1,569,000	39.2
0.7	0.05	2000	1,776,000	44.4
0.7	0.08	0	2,011,000	50.3
0.7	0.08	1200	2,323,000	58.1
0.7	0.08	2000	2,530,000	63.3
0.5	0.03	0	664,600	16.6
0.5	0.03	1200	976,400	24.4
0.5	0.03	2000	1,184,000	29.6
0.5	0.05	0	1,108,000	27.7
0.5	0.05	1200	1,419,000	35.5
0.5	0.05	2000	1,627,000	40.7
0.5	0.08	0	1,772,000	44.3
0.5	0.08	1200	2,084,000	52.1
0.5	0.08	2000	2,292,000	57.3
0.2	0.03	0	530,400	13.3
0.2	0.03	1200	842,200	21.1
0.2	0.03	2000	1,050,000	26.2
0.2	0.05	0	884,000	22.1
0.2	0.05	1200	1,196,000	29.9
0.2	0.05	200	1,404,000	35.1
0.2	0.08	0	1,414,000	35.4
0.2	0.08	1200	1,726,000	43.2
0.2	0.08	2000	1,934,000	48.4

COST ESTIMATE

The cost estimated for materials and installation of the superconducting system are shown in Table 3 and 4. All costs are shown as "present worth cost" (P.W.C.), calculated in accordance with standard practices,^{9,10} as follows:

$$P.W.C. = K Y$$

where K = capital cost

f = fixed or carrying charge annual rate (covers minimum acceptable return, depreciation, taxes and insurance).

d = annual discount rate (covers cost of borrowing)

y = year

Y = cable life in years

for Y = 40 years, d = 0.1155, f = 0.18, P.W.C. = 1.54 x K

Therefore, all capital costs have been increased by the factor 1.54 to obtain their present worth. The cost of losses has been calculated for various operating conditions. the common assumptions are:

- 1) Load is 800 MW at 0.98 power factor.
- 2) Load end reactive power is 815.69 MVA (3.4 kA at 138 kV, 3 phase).
- 3) Charging current losses are negligible.
- 4) Dielectric and heat in-leak are fixed losses of 139.8 kW circuit mile based on a cooling system efficiency of 225 W/W.
- 5) Circuit length of 25 miles.

The cost of losses are shown in Table 5, based on the following calculations:

Cost of Losses = PWFe x 8760 x e.r. + PWFd x d.r.

where e.r. = energy rate, \$/kWh

d.r. = demand rate, \$/kW

$$PWFe = \sum_{y=1}^Y [1 + i]^Y / (1 + a)^Y \times We_y$$

$$PWFd = \sum_{y=1}^Y [(1 + i)^Y / (1 + d)^Y \times (Wt_y - Wt_{y-1})]$$

Y = cable life

Wt_y = peak loss in Year y, see below

We_y = effective or average loss in Year y, see below

i = inflation rate per year

d = discount rate per year

The cost estimate of the materials for the cable is based on the following assumptions:

- 1) The cable factory exists.
- 2) Continuous core is supplied.
- 3) The cable is manufactured in single pass.
- 4) 105 reels exist, with 4000 ft. of useable cable to be put on each reel.
- 5) 5 ft. per minute winding speed.
- 6) 1,068 pads of proper tape materials exist ready for mounting on the factory machines.
- 7) There are no factory malfunctions.

The amounts and weights of material required for the cable are as follows:*

Core

Performed Mandrel	OD:	0.905"
	ID:	0.825"
Material Thickness:		0.04" (2 layers) (0.02 x 2)
Material Type:		Cu
Weight:		0.42 lbs./ft
Total length required:		396,000 ft.
Wastage (11%)		<u>44,000</u>

Stabilizer

Inner	OD:	0.935"
	Thickness:	2 layer each 0.015"
	Material :	Cu
	Weight :	0.33 lbs./ft.
Outer	:	2.0"
	Thickness:	2 layers each 0.015"
	Material :	Cu
	Weight :	0.73 lbs./ft.

*Weights/ft. refer to one cable.

Insulation (Includes screens)

ID:	9.945"
OD:	1.970"
Material :	Oriented PE Tape
Thickness:	0.004" x 128 = 5125
No. of Layers:	128
Weight :	0.85 lbs./ft. (includes 7% butt gaps)
Total Weight:	336,000 lbs. (3Ø, 25 mi.)

Superconductor

Composite tape as per prototype cable, the three layers are:

Copper:	0.002"
Nb ₃ Sn :	0.001"
Stainless Steel:	0.001"
Total Thickness:	0.004-0.005" (variation depends on solder thick- ness)

Inner and outer conductors compromise 2 layers wound left and right handed.

Inner Conductor:	0.086 lbs./ft. (includes both layers)
Outer Conductor:	0.18 lbs./ft. (includes both layers)

Weight of Nb ₃ Sn:	0.068 lbs./ft.
Weight of Cu :	0.14 lbs./ft.
Weight of S/S :	<u>0.065 lbs./ft.</u>
Total :	0.27 lbs./ft.
Total for System:	107,000 lbs.
Cost inc. 10% Wastage:	\$6.4 M (slit tape)

Misc.

Bedding, screens, protective tapes, etc.

For costing purposes the core and stabilizer were combined.

The cost of the corrugated jacket was supplied by Kabelmetal based on the following dimensions:

Length	:	75 miles
O.D.	:	2.8 inch
I.D.	:	2.5 inch
Wall Thickness	:	0.025 inch

The cost estimate for the cryogenic enclosure was prepared in cooperation with the MVE company, who manufactured the prototype installed at the 1000 MVA test site.

The following assumptions went into the cost estimate:

1. $\$2.5 \times 10^6$ up front money required for material and assembly building.
2. Total cost shown in Table 3 includes engineering field visits to construction site and 10% increment for contingency.
3. Approximately one section in ten is flexible to facility installation.
4. Cost of inter-connecting section approx. $\$6 \times 10^6$.
5. Delivery rate 10-20 section/week. Production rate 20/week.
6. Shipping cost \$4,500.00/load. Ten sections per truck load.
7. Design changes in the Cryogenic envelope have produced an overall heat leak of 0.264 watts/meter. These changes include new pant leg configuration for interconnecting sections. Radiation heat leak improved by better multi layer insulation application techniques.

The cost of the main refrigerator was estimated by Koch Systems Inc. based on a rating of 13.1 kW at 7 K.

Table 6

Cost Estimate: High Pressure Oil-Filled Pipe Type System With PPP InsulationMaterial Costs

<u>Item</u>	<u>Unit Cost</u>	<u>Quantity</u>	<u>Total Cost (M\$)</u>
Cable	\$ 45/ft ¹	396,000 ft	17.820
Filling Oil Cable	\$ 3.90/gal	210,000 gal	0.819
Cable Pipe	\$ 15.6/ft	132,000 ft	2.059
Oil Return Pipe	\$ 12.0/ft	132,000 ft	1.584
Splices	\$ 8000/ea	38	0.304
Terminals	\$100,000/ea	12	1.200
Trifurcators/ Riser Pipes	\$ 10,000/ea	4 sets	0.404
Oil Pressurization & Expansion Tanks		1 2x20,000 gal	0.420
Reactors	\$ 5,000,000/ea	3x200 MVAR	15.000
Total Materials (1989):			<u>39.446</u>
Present Worth (Above x 1.54):			60.747

¹Copper = \$ 1.50 per pound.

Table 7

Cost Estimate: High Pressure Oil-Filled pipe Type System with PPP InsulationInstallation Costs

<u>Item</u>	<u>Unit Cost</u>	<u>K\$/Mile</u>	<u>Total (\$ Mil)</u>
1. Trench, Pipe, Backfill and Manholes ²	\$538/ft	2840	71.016
2. Cable Pulling	\$13K/pull x 40	21	.520
3. Oil Filling	\$ 3/ft	16	.396
4. Cable Splicing	\$ 50K/splice x 38	76	1.900
5. Terminating		13	.320
6. Install Pumping Plant, Tanks		5	.125
7. Install Reactor Station		<u>48</u>	<u>1.200</u>
Total Installation:		3019	75.477
Present Worth (Above x 1.54):			116.234

²Includes manhole and backfill material and removal of rock over 25% of route, trench 24" wide x 60" deep.

Table 8

Present Worth Cost of Losses Over 40 Yr. Life of HPOF System Including Reactors

<u>Annual Loss Factor</u>	<u>Energy Charge \$/kW hr.</u>	<u>Demand Charge \$/kW</u>	<u>Total Cost \$/M</u>
0.7	0.03	0	15.687
0.7	0.03	1200	19.877
0.7	0.03	2000	24.005
0.7	0.05	0	22.811
0.7	0.05	1200	29.001
0.7	0.05	2000	33.129
0.7	0.08	0	36.497
0.7	0.08	1200	42.688
0.7	0.08	2000	46.815
0.5	0.03	0	11.220
0.5	0.03	1200	17.412
0.5	0.03	2000	21.539
0.5	0.05	0	18.702
0.5	0.05	1200	24.893
0.5	0.05	2000	29.019
0.5	0.08	0	29.922
0.5	0.08	1200	36.112
0.5	0.08	2000	40.240
0.2	0.03	0	7.571
0.2	0.03	1200	13.761
0.2	0.03	2000	17.889
0.2	0.05	0	12.619
0.2	0.05	1200	18.809
0.2	0.05	200	22.936
0.2	0.08	0	20.190
0.2	0.08	1200	26.380
0.2	0.08	2000	30.507

Table 9

Design Characteristics of High Pressure Oil-Filled Pipe Type System

Conductor Size: 1750 kcmil Compact Segmental Copper

Insulation Wall: 0.850"

O.D.: 3.42"

Pipe Size: 8-5/8" O.D. x 1/4" Wall (80 Mils Butyl + Extruded Exterior Coating).

Pipe Oil: 1.41 Gal/Ft.

Charging mVAR = 30/Mile

Mode of Operation: Oil Circulation (Max. Operating Temp: 85°C).

Ambient Earth Temperature: 25C.

Earth Thermal Resistivity: 90 DegC-cm/watt.

Depth of Burial: 48" to Pipe Center.

Trench: 24 in Wide x 60 in Deep Backfilled to Within 1 Ft of Surface With Thermally Stable Material.

Load Power Factor: 0.98 (Inductive).

Insulation Material: Paper/Polypropylene/Paper Laminate.

Table 10

Cost Comparison of Superconducting and HPOF Transmission Systems
for 800 MW - 25 mile circuit

	<u>Superconducting</u>			<u>Conventional HPOF</u>		
	<u>Mat'l</u>	<u>Install</u>	<u>Total</u>	<u>Mat'l</u>	<u>Install</u>	<u>Total</u>
	(Cost in \$ Mil)					
Cable/ Splices:	35.3	3.5	38.8	18.1	2.4	20.5
Enclosure	47.2	51.5	98.7	3.6	71.0	74.6
Terminals/ Cooling:	17.3	2.0	19.3	17.8	2.1	19.9
	—	—	—	—	—	—
Total:	99.8	57.0	156.8	39.5	75.5	115.0

For comparison purposes the cost estimates for the high pressure, oil-filled cable system described in the Appendix are shown in Table 6, 7 and 8 for materials, installation and losses respectively. The materials costs are based on the design characteristics shown in Table 9. The cost of losses for the high pressure oil-filled system includes an allowance for charging current losses, which depends on the power factor, load, loss factor, capacitance and the length of the line.

The current varies with distance X from the load as follows:

$$I_x = I_L \cos\theta + j (I_L \sin\theta - I_c X)$$

where: I_L is the load current; $\cos\theta$ is the load power factor; $\sin\theta > 0$ for inductive loads; and I_c = charging current per unit length

$$I_x^2 = I_L^2 \cos^2\theta + I_L^2 \sin^2\theta + I_c^2 X^2 - 2I_L \sin\theta I_c X$$

The peak loss per phase for line length L, including the dielectric loss W_d , is given by:

$$W_t L = \int_0^L (I_x^2 r + W_d) dx$$

where: r is the effective resistance, including the pipe and shield return resistance computed per Ref. 11.

The average peak loss per unit length for a 3-phase circuit is:

$$W_t = 3 I_L^2 r + r I_c^2 L^2 - 3 r I_c L I_L \sin\theta + 3 W_d$$

The second and third terms above are the correction to the losses for charging current. The maximum loss occurs for resistive or capacitive loads ($\sin\theta < = 0$).

Since the load current has an associated annual load factor (L_f) and loss factor (L_{sf}) the effective or average annual loss is:

$$W_e = 3 I_L^2 r L_{sf} + r I_c^2 L^2 - 3 r I_c L I_L \sin\theta L_f + 3 W_d$$

Discussion of Cost Comparison

The material and installation costs of the superconducting and conventional HPOF systems are compared in Table 10. The material costs of the superconducting system are higher than the HPOF system. The cost increase of

the superconducting system is driven almost entirely by the cost of the cable and cryogenic envelope. The cost of the cooling system is about the same as the cost of the reactive compensation required for the HPOF system.

Installation costs of the superconducting line are estimated to be lower than the HPOF system. In this category substantial savings are gained by the smaller trench and elimination of any special backfill.

The cost of losses is shown with various combinations of the cost of electrical energy and the loading produced by the demand charge, which varies from zero to \$2000/kW. In addition the costs are shown for three different loss factors. The losses of the superconducting system (see Table 5) are higher than the HPOF pipe-type cable system (Table 8). In part this is due to the relatively high specific value used for current-dependent losses. In addition the heat in-leak is a constant loss, regardless of load.

Conclusion

In the scenario used in this study the superconducting system was more expensive both to build and operate than an HPOF pipe type system using advanced cable insulation with reactive compensation. This conclusion is in accordance with many other systems studies which predicted breakeven costs for superconducting transmission systems in the range 1000 to 3000 MVA.¹² The study points the way to the R&D that must be done in order to decrease the breakeven power rating. Clearly the current dependent losses are an important contribution to the operating cost. The losses in the Brookhaven prototype were greatly increased by edge effects.¹³ R&D on conductor design could reduce this loss, for example the tape in the Brookhaven cable did not have niobium-tin edges. The onerous effect of heat in-leak at lower power ratings has been discussed.⁵ Designs of the cryogenic envelope which produce less heat in-leak and lower manufacturing costs are clearly needed - R&D on plastic spacers currently underway for the cryostats of the RHIC and SSC accelerators may well be of benefit for the transmission system cryogenic enclosures.

Although trenching costs for the superconducting cable are lower than the HPOF pipe-type system for the reasons mentioned above they are still a significant cost component. Serious thought should be given to methods of avoiding trenching altogether - a superconducting system does not need a heat-sink around the enclosure. This involves questions of security beyond the scope of this study.

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