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Superconducting Cable System

Summary Report for the Period
November 1971—August 1975

Date Published—May 1977

Work Performed Under Contract
No. E(49-18)1420
and EPRI EL-402-SY

Union Carbide Corporation
Tarrytown, New York

Energy Research and
Development Administration

Division of Electric Energy Systems
and
Electric Power Research Institute

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**Robert Meyerhoff
Hiroshi Morihara**

**Union Carbide Corporation
Tarrytown, New York**

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ABSTRACT

In the opinion of EPRI and ERDA this 46 month program to develop an ac superconducting power transmission line was unsuccessful in meeting most of its specific objectives. The report does outline the technical and economic problems pursued. Unforeseen difficulties were encountered with power losses in the superconductor, eddy current losses, and heat leak. Fault current testing was never attempted. Major dielectric problems were encountered preventing operation of this system at 138 kV.

Ac loss data on small samples of electroplated niobium and a preliminary cost estimate by the contractor indicated that this type of cable system might be attractive for moving large blocks of power if an overall system could be developed that would meet utility system needs. Based on R&D to date, a conceptual design was generated for the rigid conductor, rigid cryogenic enclosure, helium-spacer insulated superconducting cable system.

The design parameter values that are included in this report and the cost estimate represent values that the contractor believes could be achieved with continued development; they are based on the results of full-scale laboratory tests or extrapolations from smaller scale laboratory tests. None of these values have been demonstrated to be valid in a full-scale rated power test. The test data on the voltage withstand of the dielectric spacers in pressurized liquid helium were unacceptably low, a factor of 3 to 4 below the anticipated value.

FOREWORD

This summary of the Final Report is one part of the final report covering the work performed under the U. S. Energy Research and Development Administration - Electric Power Research Institute sponsored Superconducting Cable System Program (EPRI Project RP7807-2, Government Contract E(49-18)-1420) during the period November 1, 1971 to August 31, 1975. The summary is intended to highlight the main report, presenting an overview of the work performed under the program and the results to date. The design concept is described and estimated performance values and cost information are given for a 40-km long, 3400 MVA cable system. The main portion of the final report contains the bulk of the information on experimental procedure, apparatus and data from which the design concept was derived.

This project is part of the comprehensive U. S. Energy Research and Development Administration and Electric Power Research Institute's underground transmission research and development program. The project steering committee consisted of Dr. D. P. Hartmann, Banneville Power Authority; Mr. C. Hoogerhyde, Public Service Electric and Gas Company; Dr. M. J. Mulcahy, Boston Edison; Dr. M. Rabinowitz, Electric Power Research Institute; Mr. R. Settembrini, Consolidated Edison Company; Mr. W. G. Smith, Energy Research and Development Administration; and Mr. A. Zanona, Chairman, Commonwealth Edison Company.

The work reported was performed at the Tarrytown, New York and Tonawanda, New York facilities of the Linde Division of Union Carbide Corporation.

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Part II	Systems, Conductors, Dielectric and Terminations
Part III	Cryogenic Enclosure, Refrigeration and System Costs
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Appendix 1B	Method for Calculating Envelope Heat Leak
Appendix 2A	Gibbs & Hill #1
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Section I

INTRODUCTION

This is the final report summarizing the work directed toward the development of an underground AC superconducting cable system, SCS, carried out in the 46 month period, November 1, 1971 - August 31, 1975. Originally a 3 1/2 year program was funded by the Edison Electric Institute, EEI, and the U. S. Department of the Interior, USDI, but during this period, the responsibility for the program was transferred to the Electric Power Research Institute, EPRI, and the U. S. Energy Research Development Administration, ERDA. At the end of 3 1/2 years, a 4 month extension was approved to permit the completion of experiments in progress.

Guidance and monitoring of this program was by a steering committee, chaired by Mr. A. Zanona. The remaining committee members included representatives of EEI/EPRI and USDI/ERDA. The contracting officer for this program, which was conducted as Government Contract Number E(49-18)-1420 and EPRI project RP7807-2 was Mr. F. F. Parry.

The objectives of this program as stated at the time of contract award were to demonstrate that:

- I. All losses--conductor, dielectric, thermal insulation, and mechanical--are sufficiently low that the superconducting cable and its attendant refrigerating system are competitive with non-superconducting cables.
- II. Predicted emergency loading can be sustained without upset. Fault conditions can be undergone without damage to the conductor and with the conductor returning to the superconducting state upon removal of the fault current.

- III. Voltage transients, can be sustained without any permanent damage or excessive aging of the insulation.
- IV. While meeting the above criteria, the predicted total cost of the superconducting line would provide an incentive for its adoption over non-superconducting competitors.

The general concept for the superconducting cable system, SCS, which is being developed to meet the above objectives is described below. This design concept is the culmination of the work carried out under this program. It is yet to be demonstrated that this concept meets all of the requirements for a SCS.

The presently conceived design, based on a rigid conductor and cryogenic envelope, employing pressurized helium as both the refrigerant and principal electrical insulation, is illustrated in Figure 1. The conductor and shields are niobium-copper-Invar tricomposites in which niobium is the superconducting component. Copper is used to provide a low resistance shunt to protect the cable during faults or sudden thermal excursions. Invar is employed to control thermal contraction and expansion on cool down and warm up. Each of the three conductors, one for each phase, is mounted coaxially within its shield using post spacers. Eddy current losses in the copper and Invar components of the conductor and shields and in the cryogenic enclosure are eliminated by the niobium on the OD of the conductors and the ID of the shields, which confines the magnetic flux to the annular space between each conductor and its shield.

Pressurized helium is used to support the electric stress between each conductor and its shield. Two types of electrically insulating spacers are employed. Post spacers are used to maintain the coaxial geometry and "strong" spacers are used to transmit the tensile force of the conductors to the shields which in turn are anchored to the earth by means of their attachment to the cryogenic envelope. This keeps the conductor length essentially constant during cool down.

The three conductor-shield assemblies are contained within an evacuated super-insulated, multishielded cryogenic enclosure. The enclosure concept is illustrated in Figure 2. The cryogenic enclosure system consists of factory assembled and evacuated pipe section 18-30 meters long which are joined in the field by means of factory assembled and evacuated superinsulation to minimize conduction, con-

Figure 1. Rigid Conductor-Shield, Rigid Cryogenic Enclosure AC Superconducting Power Transmission Cable Concept

Figure 2. Cryogenic Enclosure Concept Showing Insulation System and Sleeve Joints

vection, and radiation heat transfer through the enclosure. Even though super-insulation is the most effective insulation for cryogenic applications, it is still desirable, in the case of equipment for liquid helium temperature operation, to incorporate some means of intercepting the heat leak at one or more intermediate temperatures. For this reason, six multishields are stationed within the insulation space. These shields are cooled by bleeding a small quantity of helium from the enclosure through tubes at each end of each pipe section and one end of each sleeve section. This helium is then collected at ambient temperature and returned to the refrigerators for reliquefaction. A major reason for the use of both the cryogenic pipe-sleeve joint concept and the multishields is to eliminate the need for any vacuum tight field welding of either the cryogenic envelope or cryogenic lines used for cooling of intermediate temperature shields.

Helium at a temperature of 4.6 - 5.1 K and a pressure of 400-600 kPa (4-6 atm) is provided by refrigeration stations located at ~ 8km intervals along the length of the cable. Each refrigeration station contains three refrigerators, each sized to accommodate a 4-km cable section. This provides one spare refrigerator unit in each refrigeration station for increased reliability. It can also be used to decrease cool-down time when putting the cable in service, to handle increased refrigeration requirements if the line is operated above its rated current level during system contingencies, and to provide refrigeration during scheduled or unscheduled refrigerator maintenance. Helium is supplied from the refrigerator to the cable system through a vacuum insulated pipe within the cryogenic envelope. The helium then returns the 4 km to the refrigerator through the remaining space within the envelope except for the small quantity which is used to maintain the multishields at their operating temperatures.

This application requires a high refrigerator reliability. For this reason, we favor the use of centrifugal compressors because of their demonstrated high reliability and low maintenance in process industries. Generally, centrifugal compressors would not be used for low molecular weight gases like helium. However, the Linde developed LTR cycle, in which helium is mixed with a high molecular weight gas to achieve an average molecular weight comparable to air, should allow the use of centrifugal compressors.

Power is brought into or out of the SCS by means of terminations which must not only carry high currents and grade the voltage but must also provide the thermal

transition from ambient temperature to liquid helium temperature. These requirements are met by the termination concept illustrated in Figure 3. The principal feature of this concept is isolation of the thermal gradient in the high current lead from that of the voltage grading portion of the termination. This is done by incorporating a vacuum insulated sleeve between the current lead and the epoxy casting used to grade the voltage. The thermal heat in-leak due to both joule heating in, and thermal conductivity of, the high current lead is minimized by bleeding helium from the enclosure through the leads. This ambient temperature helium is then brought to ground potential through a voltage graded stanchion and returned to the refrigerator for reliquefaction.

Figure 3. Cryogenic Termination Concept

Section 2

SUPERCONDUCTING CABLE SYSTEM PARAMETERS

During the course of this program, designs were developed for 69, 138, 230, 345 and 500-kV cable systems having power ratings which range from a low of 1.1 to a high of 35.7 GVA. All of these designs have three things in common, namely, that the maximum electric stress at the surface of the inner conductor at the BIL level is 150 kV/cm, that the peak magnetic field at the conductor surface at the rated current is 0.1 T (1000 gauss), and that the ratio of the shield radius R to the conductor radius r is e ($e = 2.718$).

The specific parameters of a cable of given voltage are determined in the following manner. The dependence of the peak electric stress E_{BIL} on the V_{BIL} for a coaxial cable is given by:

$$E_{BIL} = \frac{V_{BIL}}{r \ln (R/r)} \quad (1)$$

Since $R/r = e$ the conductor radius is given by

$$r = V_{BIL}/E_{BIL} = V_{BIL}/150 \quad (2)$$

where r is in centimeters and V_{BIL} is in kV. Since the peak magnetic field at the surface of the conductor is 0.1 T the current rating is obtained from the relation

$$I = 2\pi rB / (\sqrt{2}\mu_0) = 3.536 r \quad (\text{kA}_{rms}) \quad (3)$$

where r is given by equation 2. The Power rating of the cable P is given by

$$P = \sqrt{3} I V_{\phi\phi} = 6.125 V_{\phi\phi} \frac{V_{BIL}}{E_{BIL}} \quad (\text{MVA}) \quad (4)$$

where I is in kA_{rms} and $V_{\phi\phi}$ is the phase-to-phase voltage in kV_{rms} and V_{BIL} and E_{BIL} have units of kV and kV/cm , respectively. Thus, the power rating depends on the current which is determined by the choice of E , B , and V_{BIL} where the value of V_{BIL} is chosen to be appropriate to the voltage rating, $V_{\phi\phi}$.

Design parameters for 69, 138, 230, 345 and 500 kV cable systems based on the relations discussed above are given in Table I. To date, the parameters relating to the cryogenic envelope and refrigeration system have been developed in detail only for the 138-kV system. The cryogenic parameters for the 138-kV system are also included in Table I. The basis for the choice of values of E_{BIL} , peak magnetic field, conductor loss, and cryogenic parameters are discussed briefly in the following sections of this summary and in detail in the main body of this report.

Table I

DESIGN PARAMETERS FOR SUPERCONDUCTING TRANSMISSION LINES^aBased on $E_{BIL} = 150 \text{ kV/cm}$

V_{ϕ} (kV rms)	69	138	230	345	500
V_{BIL}	400	600	870	1,200	1,650
r (cm)	2.67	4.00	5.78	8.00	11.00
R (cm)	7.26	10.87	15.71	21.75	29.90
I (kA/rms)	9.44	14.14	20.44	28.28	38.89
P (MVA)	1,128	3,380	8,143	16,898	33,680
V	56	113	188	282	408
$E_{peak\ ac}$					
peak ac (kV/cm)	21.0	28.2	32.5	35.3	37.1
Inductive reactance/km, p.u. 1.58×10^{-3}		3.96×10^{-4}	1.42×10^{-4}	6.33×10^{-5}	3.01×10^{-5}
on 100 MVA base					
Shunt capacitance	0.10	0.40	1.11	2.50	5.24
MVAR/km					
Cryogenic Envelope		50.8			
ID (cm)					
Cryogenic Envelope		68.6			
OD (cm)					
Nominal Section		18			
Length (m)					
Cryogenic Envelope		16.5			
Length (m)					
Sleeve length (m)		3.66			
Sleeve ID (cm)		74			
Sleeve OD (cm)		89			
Weight of Pipe Section		3550			
(kgf)					

Refrigeration load (all values expressed as watts/km equivalent at 5K)

Refrigeration from 5.1 to 4.6K:	
AC and dielectric dissipation	62
Heat leak through insulation	34
Joint conduction - helium	
convection heat leak	150
Refrigeration from 300K to 4.6K:	
Multishield bleed	105
Joint conduction bleed	68
Joint weld leak loss	18
Total Refrigeration Load (watts	
equivalent at 5K/km)	437 ± 17% ^a
Refrigeration efficiency ratio	
(watts RT/watts 5K)	540
Refrigerator spacing (km)	8
Number of operating	
refrigerators/station	2
Number of standby	
refrigerators/station	1
Total refrigeration capacity per	
station (watts at 5K)	5244
Reserve refrigeration capacity per	
station (watts at 5K)	1748
Input power per refrigerator (kw)	944
Ratio of refrigerator input	
power/km to line rating	0.007%

- a) The value of 437 W/km is based on a conductor plus dielectric loss of 62 watts/km and an equivalent thermal load for the cryogenic enclosure (heat leak plus bleed refrigeration) of 375 W/km. It does not include the refrigeration requirement for the terminations. The value of 62 W/km for the conductor plus dielectric loss is an estimate based on the lowest loss measured to date on a niobium-copper component conductor (36 watts/km) which we believe to be obtainable for a niobium-copper-Invar conductor. However, the best results obtained to date on the single full-size tricomposite conductor corresponds to 180W/km at 4.2K

Section 3

COST ESTIMATE RESULTS

A cost estimate was made for the 138-kV, 3400-MVA cable design. The cost figure represents the total price to a utility, exclusive of right-of-way, for an installed SCS. Because the values for the conductor-shield loss, cryogenic enclosure heat leak, and pipe section length have not been fully determined, the effect on system cost of changes in the value of these parameters has been calculated. The details of this cost estimate are given in the System Cost section of this summary. Figure 4 shows the cost of a single 40 km-long line in 1974 dollars assuming conductor plus dielectric losses of 62 or 217 W/km and pipe section lengths of 18 or 30 m. The cost of the cable system was evaluated for the 4 cases denoted by the points A, B, C and D in Figure 4. For other values of refrigeration load, pipe section length or power costs, equation 13 can be used to estimate the cost. The cost for the base case, as defined in Table 1, which assumes a conductor plus dielectric loss of 62 watts/km and a 18 m-long pipe section is $\$4.2 \pm 1 \times 10^6$ /km ($\$6.8 \pm 1.7 \times 10^6$ /mi) or $\$1245 \pm 300$ /MVA-km.

The lowest cost based on a conductor loss of 62 watts/km and a 30 m pipe section length is $\$1089 \pm 275$ /MVA-km. The estimated cost assuming a conductor plus dielectric loss of 217 watts/km and a 18-meter pipe section length is $\$1326 \pm 330$ /MVA-km. All of these values are within a 25% band. The estimated overall accuracy of these costs is $\pm 25\%$.

Figure 4. The Installed Cost of 40-km Long, 3400-MVA Cable System - Includes Capital Cost and Capitalized Operating and Maintenance Costs. Estimated Accuracy $\pm 25\%$

Section 4 CONDUCTOR DEVELOPMENT

The decision to pursue the development of the rigid coaxial design described in the previous section is based on our belief that this design represents the most technically and economically viable design for an ac superconducting cable which can be fabricated using materials presently available and/or easily manufactured. Several other design concepts have been considered. The fully flexible cable concept, with both flexible conductor-shield and cryogenic envelope was considered but not pursued due to what we considered to be the difficulty of obtaining adequate envelope thermal performance at a reasonable cost. In addition, there may be a question of reliability resulting from the presence of a common vacuum over relatively long cable lengths. This still left open the choice of conductor-shield type. Both rigid and flexible conductor-shield types may employ either wrapped or pressurized helium electrical insulation. However, pressurized helium is preferred for the rigid concept and a wrapped insulation is preferred for the flexible concept. While the rigid conductor-shield concept requires more joints, these joints are easy to make since no insulation wrapping is required. Thus, there is a cost trade-off between a few complex joints or many simple joints. Since there are already envelope joints between each section, there is only a modest, if any, cost difference resulting from the conductor-shield joints.

Three types of superconducting materials can be used; pure niobium, solid solution alloys such as Nb-Ti and Nb-Zr, and A-15 materials such as Nb₃Sn and

Nb₃ Ge. The solid solution alloys are inferior to niobium for this application because their cost and ac losses are higher than that of niobium and they do not offer any advantage in operating temperature.

The choice between pure niobium and a higher T_c A-15 superconductor depends primarily on the trade-off between material costs and operating temperatures. Our major effort has been on a niobium system since, initially, its losses and cost were below that of the commercially available Nb₃ Sn. Moreover, it was not clear that Nb₃ Sn would offer a sufficient advantage in higher operating temperature to offset these disadvantages. As the losses and cost of A-15 materials are decreased and their operating temperature is increased, these materials become of greater interest for the rigid system. If the cost and losses of A-15 superconductors or other higher T_c superconductors which might be discovered in the future reach the level where they are more cost effective than niobium they could be utilized in this rigid conductor-gas insulated design. The fabrication technique, method of forming joints, and method of providing for fault protection would likely be different, however.

The conductor-shield assemblies must be able to handle both rated and fault current, have acceptable AC losses, and be able to be thermally cycled between ambient temperatures and liquid helium temperature without damage. Several methods of dealing with the problems associated with thermal cycling were considered. These included bellows, sliding joints, omega bends, and Invar cladding. We have chosen a solution based on the use of Invar. The conductor and shields will be niobium-copper-Invar tricomposite tubes which will be rigidly anchored to the cryogenic enclosure so that their length will not change when the system is cooled down. Invar is used to keep the total strain on cool-down below the elastic limit of the tricomposite, preventing plastic deformation which would cause buckling on warm-up. A thickness of Invar twice that of the copper layer was calculated to be adequate to satisfy this objective and include a suitable safety factor. This was confirmed experimentally for a 6-meter long, 1-cm diameter tricomposite conductor having niobium, copper, and Invar thicknesses respectively of approximately 0.08, 0.81, and 1.62 mm (3, 32 and 64 mils). This sample was cycled 40

times between room temperatures and 77K. The length was maintained constant by changing the force on the conductors as the temperature was changed. No damage to the tricomposite was observed and at the end of the test the length of the conductor had changed by less than 0.025 mm (1 mil) which corresponds to a length change of less than 0.43 cm/km (0.27 in/mile). This sample was cooled to 77K instead of 4.2K because ~ 90% of the cool-down strain has taken place by 77K, hence the higher cost of testing 4.2K was considered to be unjustified. The measured force on the 1-cm diameter conductor required to keep its length at 77K equal to that at room temperature agreed with the calculated force. The force calculated to maintain a constant length on cool-down to 4.2K for an 8-cm diameter tricomposite conductor is 53 kN (12,000 lbs).

Copper is incorporated between the niobium and Invar to handle through-faults as well as to provide a low resistance shunt to protect the system should a sudden thermal excursion occur. Theoretical calculations showed that a copper layer 0.08 cm (32 mils) thick would be adequate to allow the conductor to cool down following a through-fault which heated the niobium above its critical temperature. That is to say, the I^2R heating in the copper at the rated current following the fault is sufficiently low to allow the conductor to cool down and return to the superconducting state without the need for any current interruption following the through-fault. These theoretical predictions were confirmed experimentally in a number of experiments using the 1-cm diameter tricomposite conductor. In one experiment, for example, the 1-cm niobium-copper-Invar conductor described above, when operating at a steady state ac current of $2000 A_{rms}$, was pulsed to 8000 A for 18 cycles, a current sufficient to drive the conductor normal, and then brought back to its steady state current of 2000 amps. Within eight cycles after returning to rated current, the conductor returned superconducting. This corresponds to the recovery of a cable operating at 113% of its rating from a fault current 4.5 times its normal rating. If this fault recovery performance measured on the 1-cm diameter conductor scales linearly to a full size conductor, as we expect, this design could handle 6 cycle, 10X, 3- ϕ through-faults without current interruption. This is a significant advantage of this design concept and results from the direct heat transfer from the conductor to the helium and the ability of the helium to absorb large quantities of energy with a small temperature rise.

For the rigid system being developed, it is both desirable and possible to have the ac hysteretic losses in the conductors and shields small in comparison with the effective cryogenic envelope heat in-leak at the operating temperature. For

the 3400-MVA cable system, as it is presently conceived, the conductor-shield loss plus dielectric loss is projected to be 62 watts/km (100 watt/mi) which is 15% of the envelope heat leak. The dielectric loss is so small that it is difficult to measure but has been estimated to be no more than 6 watts/km. The value of 62 watts/km for the conductor-shield loss is an estimate based on our experience in fabricating conductors and on the ac loss measurements carried out in this program. It is about 45% greater than the lowest value obtained to date, 36 watts/km. The value is thought to be close to the economic optimum, and could be raised or lowered by decreasing or increasing the conductor fabrication cost. AC loss data for samples fabricated during this program are summarized in Table 2. Also included in this table are results obtained for three niobium tubes, samples 11, 12 and 13 studied in a previous program.

Based on the loss data, we have observed that there is a direct relationship between ac loss and surface roughness. In fact, the quality of the niobium finish plays a dominant role in determining the magnitude of the ac loss. We would expect that if the surface of these tubes were smoothed by mechanical or electropolishing techniques the ac loss could be substantially reduced. For example, Bogner¹ has reported an ac loss for niobium at a peak magnetic field of 0.1 T of $0.2 \mu\text{W}/\text{cm}^2$. This value is a factor of 17 lower than the lowest value given in Table 2. In Table 1 we have used a conductor-shield assembly loss value of 56 watts/km for the 138-kV, 3400-MVA cable design. This value corresponds to a loss in the niobium of approximately $5 \mu\text{watts}/\text{cm}^2$. The main emphasis of our work, however, was not to achieve extremely low loss values but rather to demonstrate that the tri-composite conductors can be produced commercially with losses adequately low for this application.

The first tricomposite conductor tested was 1-cm in diameter and showed a loss at 4.2K and 0.1 T of $180 \mu\text{w}/\text{cm}^2$. Previous measurements under the same condition for an as-received 1-cm diameter niobium-copper composite conductor gave a loss value of $57 \mu\text{w}/\text{cm}^2$ in the as-received condition and $3.5 \mu\text{w}/\text{cm}^2$ following swaging to improve the surface finish. Swaging of the 1-cm tricomposite conductor to obtain a surface finish comparable to that of the as-received 1-cm niobium copper conductor gave losses of $42 \mu\text{w}/\text{cm}^2$, a value comparable to that obtained for the as-received niobium-copper conductor. This same tube was also annealed to see how this would affect the ac loss. Annealing increased the loss by a factor of 4 and consequently should not be done following fabrication.

Table 2
60 Hz AC LOSSES OF TUBE SAMPLES

Sample No.	Sample Description	$\mu\text{W}/\text{cm}^2$ at 4.2K and 0.1 T	Cond-Shield ^a Loss for 3400 MVA Design (watts/3 ϕ -km)
10	1 cm electroplated niobium	10	100
11	3 cm welded commercial niobium	30	310
12	1 cm welded commercial niobium	65	670
13	1 cm plasma-sprayed niobium	3600	37,000
14	1 cm Supercon Nb-Nb Ti-Cu	80	820
15	1 cm Supercon NbTi-Cu	1300	13,000
16	1 cm Supercon Nb-Cu	57	580
17	1 cm Supercon Nb-Cu-Invar	180	1,800
18	Same as 17 following swaging	42	430
19	Same as 18 following annealing	170	1,700
20	Same as 16 following swaging	3.5	36
21	8 cm INCO Nb-Cu-Invar	17	180

- a) Conductor-shield ac loss for 3400 MVA design, PL, derived from loss per unit area (p) using the formula

$$\begin{aligned}
 PL &= (p) (\text{conductor circumference}) (\text{length of cable-cm}) (3 \text{ phases}) \times \\
 &\quad (1 + 1/e^2) (1.2) \\
 &= 10.27 (p) \text{ watts/km when } p \text{ is in } \mu\text{W}/\text{cm}^2
 \end{aligned}$$

1.2 factor converts loss from 4.2 to 4.7K

Because of the importance of demonstrating that a full size tricomposite conductor can be fabricated, an 8-cm diameter, 12-meter long tube was ordered from the International Nickel Co. (INCO). Loss measurements on this tricomposite conductor in the as-received condition extrapolated to a peak surface magnetic field of 0.1 T, gave a value of $17 \mu\text{w}/\text{cm}^2$. This is the lowest value obtained for any of the commercial niobium tubes studied in the as-received condition. Based on the quality of the surface finish of the full size tricomposite tube, we anticipate that its ac loss could be reduced to a value comparable to that obtained for the swaged niobium-copper tube if its surface finish were improved. As a result of the experience gained in fabricating this first full-scale tricomposite conductor, INCO believes that a better surface can be obtained with the same processing methods by making minor adjustments to the tube reducer. If the surface finish obtained after making these adjustments does not result in a reduction from 17 to $3.5 \mu\text{w}/\text{cm}^2$, mechanical polishing can be employed to obtain the desired surface finish and hence the desired loss level. This assumed that the presence of the Invar does not effect the ac losses.

One of the major accomplishments of this program was the development of the processes which can be used for the commercial fabrication of the tricomposite conductors and shields. The process developed for fabricating the conductors is to insert a set of concentric niobium, copper and Invar tubes into a steel container. After evacuation, it is reduced by means of hot extrusion. The outer steel shell is then removed chemically from the extruded billet which is then reduced to the final size in a single pass through a tube reducer. An optional final polishing step may be added if required to achieve the desired surface finish.

The tricomposite shields are fabricated in the following sequence. Tricomposite plate is made by explosively welding a copper plate to an Invar plate and then explosively welding a niobium sheet to the copper side of the copper-Invar composite. This tricomposite plate is then cold-rolled to the desired thickness of 1.25 mm (0.05 mm niobium, 0.4 mm copper and 0.8 mm Invar). The cold-rolled tricomposite sheet is then slit to width, roll formed and longitudinally seam welded with a partial penetration weld of the Invar.

The tricomposite conductors and shields would be joined in the field by explosively welding as illustrated in Figures 5, 6a and 6b. The conductor sleeves are welded first. Following this, the shield sleeves are welded in place. The ends of the conductor, shields, and their sleeves are prepared so that following welding each

NOT TO SCALE

(ONLY ONE CONDUCTOR-SHIELD ASSEMBLY FOR SIMPLICITY)

Figure 5. Cable Joining Concept

Figure 6a . Conductor Joint for Explosive Welding

Figure 6b. Shield Joint for Explosive Welding

of the three layers of the tricomposite is connected through the joint area. We have made tricomposite welds using flat tricomposite sheet with the envisioned end preparation. These welding studies indicated the feasibility of employing the field joining process described above, however; no joints were made with tubular tricomposite conductors or shields.

Section 5

DIELECTRIC DEVELOPMENT

A prerequisite for the rigid design concept discussed above is the ability of helium to support the required operating and transient voltage levels. At the inception of this program, this ability was uncertain since the only breakdown data available for liquid helium was taken at smaller gaps and lower voltages than those required for the cable system. Hence, the first task pertaining to the development of the dielectric system was to obtain data for the breakdown strength of helium with gap sizes and at voltage levels comparable to those required for the cable system.

In order to simplify the initial experiments, the first data were taken in boiling helium. The electrodes consisted of a 25-cm diameter polished brass sphere mounted above a horizontal polished brass ground plane. Figure 7 summarizes the ac, dc, -dc, switching surge ($200 \times 2000 \mu\text{sec}$), and lightning impulse ($1.5 \times 40 \mu\text{sec}$) data obtained with these electrodes. These data show that the average breakdown voltage of helium increases nearly linearly with gap size over the range of gap sizes studied. Similar measurements were made using a 25-cm diameter niobium sphere and a niobium ground plane in order to be certain that the breakdown characteristics of helium using niobium electrodes would not be anomalous. These results were similar to those for the brass electrodes and are summarized in Table 3. In boiling helium at 4.2K, the average ac and dc breakdown fields were $\sim 160 \text{ kV/cm}$, and the switching surge and lightning impulse breakdown fields were 180 and 272 kV/cm respectively. In helium at 4.2K, slightly pressurized to eliminate boiling, the breakdown field for the three slower wave forms is increased by a factor of one-third. On the basis of this initial data, a peak stress of 150 kV/cm at the BIL level was chosen. This was done so that work on other system components such as spacers, conductors and envelopes could be started since the size of these components depends on the E_{BIL} value. Additional breakdown studies carried out to determine the validity of this choice of E_{BIL} are discussed in the main body of this report. They do not provide adequate support to justify the use of the value of 150 kV/cm for E_{BIL} and additional studies will be required to un-

Figure 7. Breakdown Voltage of Boiling Liquid He at 4.2K and 1 Atmosphere as a Function of Gap Length

Table 3
BREAKDOWN ELECTRIC FIELD (kV/cm) FOR A 5-mm GAP
BETWEEN A NIOBIUM SPHERE AND GROUND PLANE

	<u>Boiling Helium 0 psig</u>	<u>Nonboiling Helium 2 psig</u>
1.5 x 40 μ sec	272	272
200 x 2000 μ sec	180	238
DC	154	210
AC (peak)	165	228

derstand the dielectric behavior of helium. Low breakdown voltages were obtained for helium in horizontal coaxial electrodes which may be due to impurities, spacers, or some property of helium in this geometry.

Once the value of E_{BIL} was chosen, conductor-shield dimensions were calculated and the work was started on the development of spacers. The first task in developing the spacers was the screening of a number of materials to find those having the required dielectric strength, mechanical strength, thermal expansion and loss tangent.

The dielectric breakdown strength of filled epoxies was measured in boiling helium using cylindrical spacers 4.8 cm in diameter and 4.1 cm long. These test spacers supported ac and dc voltages, respectively of 60 kV_{rms} and 150 kV. There were no flash overs through the helium as all of these spacers ultimately failed internally in the epoxy. The withstand electric stress for the epoxy was found to be in excess of 470 kV_{rms}/cm, a value more than 10 times greater than the stress on the epoxy at operating voltage in the 138-kV design. As a result of these measurements, we chose a filled epoxy, Emerson and Cuming 2850 FT Blue, for initial fabrication of test spacers. Based on spacer field plots and tests in liquid nitrogen, we developed the design for a full-scale spacer for the 138kV system shown in Figure 8.

In order to develop statistics for the ac and lightning impulse withstand voltage of these spacers, a group of spacers purchased from Permali was tested in boiling

Figure 8. Cross Section of Full-Size Spacer

liquid nitrogen between vertical spheres and in a vertical coax. These spacers employ a proprietary Permali epoxy which has properties comparable to those of the 2850 FT Blue. These spacers have a size 60% of that of the full size spacers shown in Figure 8, a size chosen to be small enough so that we could be confident of determining their withstand capability using our high voltage equipment and yet large enough to reasonably extrapolate their performance to that of full size spacers. The lowest ac breakdown value in the sphere-sphere tests of these sub-scale Permali spacers was $200 \text{ kV}_{\text{rms}}$, and the highest flash over voltage was $265 \text{ kV}_{\text{rms}}$. Lightning impulse withstand voltage in this sphere-sphere geometry was $\sim 600 \text{ kV}$. In the sub-scale vertical coax with three spacers, ac flash overs occurred between 150 and $254 \text{ kV}_{\text{rms}}$, voltages corresponding to a peak stress at the inner conductor of 88 to 150 kV/cm . In the same coaxial geometry, a series of lightning impulses showed the impulse withstand level to range from 400 to 568 kV corresponding to stresses at the surface of the inner conductor of 167 to 237 kV/cm . The observed differences in both ac and impulse withstand in these two geometries can be accounted for by the difference in the field enhancement factors, i. e., the peak field at the breakdown voltage is approximately the same for both geometries.

Following these promising results in liquid nitrogen and the earlier results in liquid helium with the cylindrical test spacers, a series of tests of subscale and full-scale 138-kV coaxial cables 6 meters long both with and without spacers was carried out using the test dewar and termination shown in Figure 9 and illustrated schematically in Figure 10. The results of these tests were very surprising in that while the performance of the spacerless coaxial cables was comparable to what was expected on the basis of the sphere-plane helium tests, the performance of the coaxial cables with either subscale Permalloy or full-scale Westinghouse spacers was far below that which had been expected on the basis of the earlier tests. In fact, the ac withstand of the spacer cables was as much as a factor of 3.5 below that of the spacerless cables. The results of these spacerless and spacer tests are summarized in Table 4. It should be pointed out that in one of these sub-scale

Table 4
SUMMARY OF VOLTAGE BREAKDOWN MEASUREMENTS IN
HELIUM USING HORIZONTAL COAXIAL GEOMETRY^a

<u>Experiment</u>	<u>Initial AC Flashover</u>	<u>Maximum Achieved AC Withstand</u>	<u>Maximum Achieved Impulse Withstand ($1.5 \times 40 \mu s$)</u>
Subscale cable, ^b no spacers He at 450 kPa (4.4 atm)	140 kV rms (85 kV peak/cm)	160 kV rms (96 kV peak/cm)	442 kV (188 kV/cm) No flashover
Full scale cable, no spacers He at 450 kPa (4.4 atm)	180 kV rms (64 kV peak/cm)	180 kV rms (64 kV peak/cm)	494 kV ^c (124 kV/cm)
Subscale cable, ^b Permalloy spacers He at 450 kPa (4.4 atm)	40 kV rms (24 kV peak/cm)	130 kV rms (77 kV peak/cm)	381 kV (162 kV/cm)

a Crest electric stress at surface of the conductor given in parentheses.

b Subscale cable 60% of full scale for 138-kV design.

c Cable damaged in previous tests.

spacer experiments, following an initial ac flash over at 40 kV_{rms} (24 kV/cm peak stress at the inner conductor) the withstand was increased to 130 kV_{rms} (77 kV/cm) following a series of re-applications of successfully higher voltages. This stress of 77 kV/cm, which is nearly 3 times the intended ac operating stress for the 138-kV

Figure 9. Large Cryogenic Test Enclosure and High Voltage Terminations

Figure 10. Configuration for Testing Two Coaxial Samples in Large Dewar

design, is comparable to the breakdown stress measured for the subscale spacerless tests in helium. It is also more than a factor of 3 greater than the initial ac breakdown stress. The fact that this coax could be conditioned to withstand a stress more than 3 times greater than initial flashovers probably indicates that the low breakdown voltages are caused by contamination or surface irregularities. These stress enhancers could be removed by repeated flashovers. The acceptable breakdown voltages which were obtained after conditioning suggest that the basic spacer design would be adequate in a clean system.

At this time we do not know whether this poor performance was due to gross contamination or whether these spacers are especially sensitive to any contamination as a result of one or more of the following: shape, material and surface finish. It is clear that additional work is required to find a solution to this unacceptable performance of the spacers in helium. Decreasing the ac electric stress is not a viable solution since this increases the cable diameter which in turn raises the heat in-leak and the overall system cost.

It is important to note that while the spacer results to date are unacceptable, there is no clear evidence indicating that acceptable performance can not be obtained within the present design framework.

Section 6

TERMINATION

A major accomplishment of this program was the success of a cooperative sub-contracted program with the Westinghouse Electric Corp. to design and construct terminations for the SCS. These terminations are unique as compared with conventional cable terminations in that they must have a much higher current rating and must be able to not only grade the voltage but also accommodate the large difference between ambient temperature and the operating temperature of the system.

One of two 138-kV, 14,000-A terminations constructed for this program is shown in Figure 11 and illustrated schematically in Figure 3. The voltage is graded with an epoxy casting which extends into the cryogenic enclosure from the grounded flange. The ambient temperature region of the termination is insulated with SF_6 . Since these terminations were to be used indoors, the SF_6 in the ambient temperature region is contained within a fiberglass tube. The length of this tube is such that its replacement with a porcelain weather shed would make the termination suitable for outdoor use.

The high current is transported from the top of the termination to the cable by means of a vapor-cooled lead. This lead is contained within a vacuum insulated sleeve which thermally insulates it from the epoxy casting and the SF_6 .

Following the fabrication of these terminations, they were tested at room temperature by Westinghouse and withstood 190 kV rms for 6 hours and 335 kV_{rms} for 1 minute. They also withstood 650 kV lighting impulses at both room temperature and with the lower end immersed in liquid nitrogen. Following their delivery to Tarrytown, they have been used extensively for testing at both liquid helium and liquid nitrogen temperatures. To date, we have carried out some 20 termination-thermal cycles and have operated in liquid helium routinely at ac voltages up to 265 kV_{rms} and lighting impulse voltages up to 600 kV. Thus, this termination design appears to be fully adequate for the voltage levels and thermal gradients associated with the 138-kV, 3400-MVA cable system.

Figure 11. High Voltage Termination

The 14-kA high current leads which are made up of a Nb₃Sn superconducting section and a vapor-cooled copper section were purchased from American Magnetics. These leads have performed well up to the highest current, 2 kA, used to date.

Section 7

CRYOGENIC ENCLOSURE

The cryogenic enclosure being considered in this program consists of vacuum insulated pipe sections 18-30 m long which are joined together using vacuum insulated sleeves about 4 m long. Both the pipe sections and the sleeves are pre-fabricated in the factory, shipped, and assembled in the field using standard assembly welding techniques. These welds do not intersect the vacuum space and do not have to be vacuum tight.

The vacuum space of the enclosure is filled with superinsulation to reduce radiation heat transfer and six copper multishields to absorb heat at temperatures intermediate between 5K and ambient. The design of the cryogenic insulation system is shown in Fig. 2. The multishields are held at their operating temperature by bleeding a small quantity of helium from the interior of the pipe through bleed lines thermally anchored to the multishields. The bleed lines enter the vacuum space at each end of the pipe sections and exit at the sleeve section weld shoulder. The helium then returns to the refrigerator via a separate helium return line at room temperature.

The principal low temperature structural member of the pipe sections is the inner pipe which is made of Invar. The shields of the three coaxial conductor shield assemblies are mechanically anchored to this Invar pipe. During fabrication, the inner Invar pipe is flanged at each end and superinsulation and heat shields are wrapped around its exterior surface between the flanges. A composite tube at each end of the pipe section attaches to the inner and outer pipes forming a vacuum barrier. Heat leak across this gap is minimized by using a composite wall design comprising a 0.2mm (8 mil) thick, 1-m long stainless steel vacuum barrier supported structurally by a low thermal conductivity fiberglass-epoxy liner. This pipe joint end design is illustrated schematically in Figure 12.

Figure 12. Details of Pipe Joint End Design

The sleeve section is insulated similarly to the pipe section, however, it differs mechanically in that the inner pipe of the sleeve is not a structural member. It consists of two tubes formed of stainless steel sheet welded to either side of a bellows located at the center of the sleeve. The outer ends are welded to the outer carbon steel flanges which are attached to the casing of the sleeve. The annular space between the vacuum barrier of the pipe section and the inner tube of the sleeve is a source of heat in-leak and will be discussed below.

The very low ac loss in superconductors when operated below their critical temperature is partially offset by the power requirements for low temperature maintenance. Approximately 540 watts of input refrigeration power are required to remove one watt dissipated in the cryogenic envelope at helium temperature. Heat in-leak into the envelope arises from conductor-shield ac loss, dielectric loss and heat leak through the insulation of the cryogenic envelope.

The heat leak through the cryogenic envelope was determined for the design described above by analytical techniques and by measurement using the test unit shown in Figures 13 and 14. The test unit was 13 meters long and 36 cm (14") inner diameter with a joint in the middle and with the ends well insulated. This unit simulates one pipe section together with its joint. Initial tests with this unit with liquid nitrogen showed that there was a large heat leak at the joint caused by convection in the joint annulus between the inner wall of the sleeve and the outer wall of the pipe section. At this point a polyurethane foam was placed in this annulus space and the total heat in-leak of the test unit was measured using liquid helium as shown in Figure 15. The upper curve gives the measured heat leak as a function of annulus pressure and the lower curve gives the calculated heat leak assuming only conduction heat transfer in the joint annulus. At low joint annulus pressure the agreement between the calculated and measured heat leak is good but at higher pressures the measured heat leak is much greater indicating the failure of this urethane foam to suppress helium convection.

A convection seal development program was undertaken immediately to identify a joint design with acceptable heat losses. Plastic foam materials were sought with cryogenic properties superior to the materials of the initial test and which have low helium porosity. Two (bench scale) testers smaller than the prototype tester were designed to assist in evaluation of a larger number of candidate materials than could be processed in the larger tester. One was designed to measure the restriction to helium flow and the mechanical resiliency of seal materials

Figure 13. Cable Enclosure Concept and Simulation

Figure 14. Cryogenic Test Envelope System

Figure 15. Predicted and Actual Heat Load into the Conductor Space With Joint Annulus Pressurized

at liquid nitrogen temperature. The other tester, shown in Figure 16, was a small 20-cm (8 inch) diameter seal annulus to test seal candidates on a smaller scale. After more than 30 plastic foam materials were screened using these bench testers, two were chosen for testing in the large test unit, a composite of Norton PVC and urethane and a composite of Insolyte Type I and fiberglass matting. Figure 17 shows the Norton PVC and urethane seal wrapped around the pipe end and ready for assembly.

As a result of this test program we have concluded that the joint annulus should be operated at a reduced pressure of 1.4 atm. The total heat leak as a function of annulus pressure, extrapolated to the 138-kV, 3400-MVA design with 18-m pipe sections is given in Table 5. These projections are based on data taken with the 20-cm (8-inch) bench tester. Higher losses than these (about 20% higher) would have been projected from the large tester results but these are felt to be erroneous due to the existence of liquid helium in the convection suppressor material during the test. An annulus pressure of 140 kPa (1.4 atm) can be maintained by adding a split sleeve in the joint as shown in Figure 18. This sleeve would be welded in place with high quality but not vacuum tight welds. Any helium which leaks

Table 5
PREDICTED CRYOGENIC ENCLOSURE PERFORMANCE ANNULUS
PRESSURE FOR 3400 MVA DESIGN WITH 18 m PIPE SECTIONS

	ANNULUS PRESSURE (ATM)	Q INSULATION	Q MULTISHIELD BLEED	Q JOINT	Q JOINT ANNULUS BLEED	Q TOTAL (WATTS/Km)
1	0	34	173	171 ³		224
2	1	34	173	264 ¹		471
3	1.4	34	173	150 ³	18	375
4	1.4 ²	34	173	345 ⁴	—	552
5	2.7	34	173	880 ¹	—	1067
6	3.7	34	173	1652 ¹		1859
7	5.0	34	173	2839 ⁴		3046

¹ JOINT HEAT IN-LEAK VALUES ARE BASED ON DATA TAKEN ON CONVECTION SUPPRESSION MATERIALS USING 8 INCH DIAMETER BENCH TESTER.

² RECOMMENDED ANNULUS PRESSURE OPERATING VALUE.

³ JOINT IN-LEAK VALUES MEASURED IN 14 INCH DIAMETER TEST MODEL.

⁴ VALUES ESTIMATED ON THE BASIS OF THE QUADRATIC RELATION NOTICED BETWEEN PRESSURE AND HEAT LOSS IN THE 8 INCH DIAMETER TESTER.

Figure 16. Helium Convection Seal Bench Tester

Figure 17. Norton PVC/Urethane Foam Composite Seal Installed on the Enclosure OD

Figure 18. Low Pressure Annulus Joint Design

through leaks in this sleeve will be collected at each joint and returned to the refrigerator via the bleed system return line. This modification requires that the bleed system be operated at a pressure of 140 kPa (1.4 atm) instead of 500 kPa (5 atm). An equivalent heat load of 18 watts/km (30 watts/mi) has been added to the heat in-leak to account for the reliquefaction of the helium which leaked through the sleeve and for the power to recompress the bleed helium from 1 to 5 atmospheres.

Two goals must be attained before we can be fully confident that the reduced annulus pressure joint concept will result in acceptable heat leak values. First, the preliminary design which has been outlined here and shown in Figure 18 must be completed and the loss measured in a full-scale test facility. Second, a helium convection suppressor material and seal design having low losses and reproducibility must be developed and tested. PVC foam material in the joint annulus of the 14-inch test enclosure cracked during testing, thereby degrading the seal's performance. We intend to duplicate or improve performance values by using a seal material that doesn't crack or by using a segmented seal design which allows thermal movement.

Based on the data obtained with the bench testers and the 14-inch test unit we estimate the total cryogenic heat leak for a 138-kV, 3400-MVA cable to be 375 watts/km (603 watts/mi). The distribution of this load into five components is given in Table 6. In addition to the heat leak from the cryogenic enclosure an additional load of 62 watts/km (200 watts/mi) has been assumed for the conductor-shield loss and from dielectric losses in the spacers and helium. This gives a total load equivalent at 5K of 437 watts/km (703 watts/mi) for the refrigerators.

Table 6
REFRIGERATION LOAD FOR 138-kV
3400-MVA CABLE DESIGN

	<u>5K equivalent watts/km</u>	<u>5K equivalent watts/mile</u>
<u>Refrigeration from 5.1K to 4.6K:</u>		
Heat leak through insulation in pipe and sleeve sections	34	54
Joint conduction plus helium convection heat leak	150	241
AC loss in conductor-shield- dielectric assembly	62	100
<u>Refrigeration from 293 to 4.6K:</u>		
Multishield bleed for pipe and sleeve sections	105	169
Joint condition bleed	68	109
Joint weld helium leak loss and total bleed recompression	18	30
Total Refrigeration Load	<u>437⁺¹⁹⁰₋₁₁₅^a</u>	<u>703⁺³⁰⁵₋₁₈₅^a</u>

^a Value given is estimate of refrigeration load for the design that was costed. Uncertainty in value includes contributions resulting from experimental error, probable error in using models for extrapolation from experimental conditions to those in the cable, error in scaling values to the 138 kV cable, and variation due to manufacture and assembly.

Section 8

HELIUM REFRIGERATOR

For the superconducting cable application one of the most important requirements to be met by the refrigeration system is high reliability. The approach of using gas cooled multishields in the cryogenic enclosure is in part due to the desire to reduce the complexity of the refrigeration system by having only one refrigerant. Approximately half of the refrigeration power is used to reliquify the ambient temperature bleed gas and half to cool the 5.0 K helium contained in the enclosure.

Refrigeration system reliability is achieved by having three refrigerators in each station, two of which are operating at rated capacity. Such a station is illustrated schematically in Figure 19. This permits one refrigerator in each station to be down for scheduled or unscheduled maintenance. If three refrigerators are available at either of two adjacent refrigerations, then two refrigerators could be shut off with no loss in required refrigeration capacity. The 50% reserve capacity is also useful for cooling the line down initially, or after system repair, from ambient temperature, for cooling it down after a long duration through-fault and for operation of the line above rated capacity should that be required to meet immediate system needs.

The refrigeration cycle which we prefer is the Linde "mixed refrigerant" cycle (LTR). This cycle is preferred over conventional single fluid, cascade or precooled cycles because using the mixed refrigerant cycle one can use state-of-art turbo-machinery for both compression and expansion. Turbo-machinery has a demonstrated superiority over reciprocating machinery because of its better reliability and lower maintenance requirement. Centrifugal compressors have not previously been used for helium compression because only a small compression can be achieved per stage due to helium's low molecular weight.

LEGEND

① COLD BOX (3)	⑦ HELIUM RECYCLE COMPRESSOR (3)
② HELIUM RECOVERY STORAGE	⑧ HELIUM OIL REMOVAL SYSTEM (3)
③ HEAT REJECTION SYSTEM (AIR COOLED)	⑨ ADSORBER REGEN. BLOWER (3)
④ CONTROL ROOM	⑩ ADSORBER REGEN. HEATER (3)
⑤ HELIUM GAS STORAGE	⑪ HELIUM EXPANDER CONSOLE (3)
⑥ HELIUM RECOVERY COMPRESSOR (1)	

Figure 19 Helium Refrigerator Station for Superconducting Cable

In the Linde LTR cycle, helium is mixed with a high molecular weight gas so that the mixture formed has an average molecular weight comparable to that of air. Although this cycle has not been fully developed we anticipate that its advantages will be the proven reliability, good efficiency and low maintenance of centrifugal compressors as well as compact size and lower cost (10-15% reduction) as compared to conventional reciprocating machines.

Although we anticipate that the LTR cycle will ultimately be less costly and more reliable than conventional cycles we have not costed the system based on the LTR cycle. This is because the process is not fully developed and reliable cost data do not yet exist. Costing was done assuming the use of the "single fluid" cycle with reciprocating compressors. These compressors require relatively frequent maintenance but they are the only units available with the proper capacity for the application. Oil-flooded screw compressors were also considered but were not chosen because of their lower efficiency, limited size availability and relatively short field experience. "Cascade" systems using several refrigerants and "precooled" systems using liquid nitrogen and hydrogen were also evaluated. These systems were found to be more complex, more unreliable and more costly for this application than the conventional single fluid or the LTR cycle.

Section 9

SYSTEM COST

Although not all of the required technology is developed to the point that an optimally designed cable system could be built, we have made a cost estimate for the 138-kV, 3400-MVA cable system. This cost estimate is the selling price to a utility for a 40-km (25-mi) long cable system exclusive of right-of-way. The estimate is in terms of 1974 dollars and those associated with the cryogenic enclosure assume a fabrication rate of 48 km/year (30 miles/year). The estimated accuracy of these figures is $\pm 25\%$.

The cost was calculated for a base case in which we assumed a pipe section length of 18 m and a total thermal load on the refrigerators of 437 watts/km, 375 watts/km due to the cryogenic enclosure and 62 watts/km due to the conductorshield-dielectric losses. We also estimated the sensitivity of the base case cost to small variations in the values of pipe section length, heat load and power cost. These cost estimates are calculated as perturbations about the base case rather than being independent calculations. The purpose of these calculations is to determine the effect on the system cost of small variations in these parameters. It does not assume any change in the basic design of the system and hence, should not be used to determine the cost for a major deviation from the base case. As an example, the effect of pipe section length on cost considers only changes in installation cost, pipe fabrication cost and heat load. The difficulty of transporting longer lengths is not considered. Table 7 gives the cost breakdown for the components making up the SCS. The first column gives the installed system cost for a line 40 km long. The second column shows the cost division in \$/MVA-km, and the third column gives the percent of the total cost for each component. The cost for the base case system is $\$4.3 \pm 1 \times 10^6$ /km ($\$6.9 \pm 1.7 \times 10^6$ /mi). For this 3400-MVA rated system this cost corresponds to $\$1253 \pm 300$ /MVA-km.

The line is assumed to have six refrigeration stations placed at 8 km (5 mi) intervals along the line. All of the refrigeration stations contain three refrigerators since the heat load from the three terminations at each end of the line are expected to be nearly equivalent to 4 km of line. Cost data for the cryogenic envelope,

Table 7
COST OF 3400-MVA, 138-kV SUPERCONDUCTING
CABLE SYSTEM 40-km-LONG

Component	System Cost \$ x 10 ⁶	\$/MVA-km	Percent of Total
Installation ^a	54	400	32
Cryogenic Envelope ^b	36	266	21
Refrigerator System ^c	32	238	19
Conductor Shield ^d	16	121	10
Helium and Terminations	7	48	4
Capitalize Operating and Maintenance ^e	25	180	14
TOTAL	170	1253	100

- a) The installation cost was estimated by Gibbs and Hill. It assumes installation of a straight section of cable in a 50% suburban-50% rural area; cost of acquiring right-of-way is not included. Pipe length is 18-m (60ft) long, increasing pipe section length to 30 m (200 ft) decreases total system cost by 12 %.
- b) Estimate based on factory production of 48 km (30 mi) of cable per year. Factory amortized over 25 years at a rate of 10% and tooling at same rate over 5 years.
- c) Assumes a single fluid helium refrigerator cycle using state-of-art reciprocating compressors and a total refrigeration load equivalent at 5.0 K of 437 watts/km (703 watts/mi). Increasing heat load to refrigerators by 50% increases total system cost by about 10%.
- d) Cost of tri-composite conductors and shields is based in part on information supplied by International Nickel Company. This item also includes manufacturing cost of spacers.
- e) Operating and maintenance costs were capitalized assuming cost of money of 12% and a 40 year period, (multiplier is 8.24). Sixty percent of operating and maintenance costs are for electrical power for refrigerators (20 mils/kwh) and 25% is for professional, full time maintenance crew and maintenance supplies. Annual refrigerator maintenance cost assumed to be 3% of refrigerator cost.

refrigerator system, and operating and maintenance are based on Linde's experience in designing, building, installing and operating large air separation plants and in manufacturing vacuum insulated pipes and tanks. It should be noted that our cost estimate for the refrigerator system is a factor of 3 to 5 times higher than other estimates for large helium refrigerators designed for superconducting systems. Although the full reason for this difference is not known, we anticipate that it is due, in part, to our inclusion of all of the anticipated costs associated with installing a refrigerator system in a remote, non-industrial location. For example, items which have been included are: refrigeration station buildings that blend in with the surrounding area, substation and redundant power to the refrigerators, helium storage and recovery facilities, and a maintenance shop stocked with spare parts.

The total system cost assuming parameters different from the base case is given by

$$C_1 = I_1 + CE_1 + R_1 + CS_1 + HT_1 + OM_1 \quad (5)$$

where C_1 is the total cost and the terms on the right hand side of Equation 5 are the component costs as listed in Table 7. The new component costs are related to the base case costs, denoted by sub zeroes, and are given by

$$\text{Installation:} \quad I_1 = I_0 \left[0.545 + (0.455) (18/L_1) \right] \quad (6)$$

$$\text{Cryogenic Enclosure:} \quad CE_1 = CE_0 \left[1.142 - (0.142) (L_1/L_0) \right] \quad (7)$$

$$\text{Refrigerator:} \quad R_1 = R_0 \left[0.347 + 0.653 (H_1/H_0)^{0.7} \right] \quad (8)$$

$$\text{Conductor-Shield:} \quad CS_1 = CS_0 \quad (9)$$

$$\text{Helium-termination:} \quad HT_1 = HT_0 \quad (10)$$

$$\text{Operation and Maintenance:} \quad OM_1 = OM_0 \left[0.1 + 0.28 (R_1/R_0) + 0.62 (PC/20) (H_1/H_0) \right] \quad (11)$$

where H refers to the total heat load on the refrigerators in watts/km, PC is the electrical power cost in mills/kwh, and L is the pipe section length in meters. The total refrigeration load is given by

$$H_1/H_0 = (1/437) \left\{ 34R (Q \text{ ins.}) + 105 R (Q \text{ multi-shield}) + 62 R (Q \text{ cond.}) + \right. \\ \left. \left[68 R (Q \text{ joint cond.}) + 150 (Q \text{ joint bleed}) + \right. \right. \\ \left. \left. 18 R (Q \text{ leak bleed}) \right] (18/L_1) \right\} \quad (12)$$

where the R's are ratios of new to base case values for heat loads as given in Table 6. Substituting equations 6 through 11 into 5 and simplifying we get

$$C_1 = 808.8 + 182.0 (L_0/L_1) - 37.8 (L_1/L_0) + 188.3 (H_1/H_0)^{0.7} + \\ 111.5 (PC/20) (H_1/H_0) \quad (13)$$

where H_1/H_0 is given by equation 12 above and C_1 is in dollars per MVA-km.

This formula can be used to calculate the cost of the four cases shown in Fig. 4 to a precision of about 1%. The base case value assuming $H=437$ watts/km and a pipe section length of 18 m is \$1253/MVA-km. Letting $L_1 = 30$ m and keeping the conductor loss at 62 watts/km the total heat load is 343 watts/km and the cost becomes \$1101/MVA-km a 12% reduction from the base case. If the base case performance values are assumed except for the conductor loss which is increased by a factor of 3.5, the total refrigeration load becomes 592 watts/km, a 35% increase, and the cost becomes \$1337/MVA-km, a 7% increase above the base case cost. The remaining point given in Figure 4 is for $L_1 = 30$ m and for a conductor-shield loss of 217 watts/km. The refrigerator load for this case is 498 watts/km and the system cost is \$1188/MVA-km, 5% less than the base cost. These examples show that for even fairly large changes in the conductor loss or joint heat leak the system cost is changed by less than the estimated absolute accuracy of the base case cost value. This is, in part, due to the fact that 33% of the total cost is for installation. The reduction in cost in increasing the pipe section from 18 to 30 m, 12%, does not consider any increased cost due to difficulty in transporting 30-meter-long-sections from the factory to the installation site. We do not consider it feasible to transport pipe sections longer than 30 meters, except possibly in special circumstances for sites convenient to the factory.

Section 10

SYSTEMS ANALYSIS

The objective of the systems analysis work of this program was to evaluate several likely future applications of the SCS and to develop reasonable estimates for the cable system parameters required for these applications. This is an ongoing objective since the anticipated needs of the utilities and the desired cable parameters for these applications change as these future requirements become better defined. Several likely applications for the SCS in the period 1985-2000 have been identified by meeting with electric utility system planners. Four of these applications are; the transmission of bulk power from an outlying generator station or overhead line loop to a major suburban or urban substation serving a large urban area; links in overhead transmission lines in areas where overhead right-of-way cannot be obtained; interties between overhead systems in areas where an overhead intertie is not practical; and use in an urban area transmission ring. We have devoted most of our attention to the generator lead application since the planners indicate that there will be a great need for high power underground cables for this application and because the SCS should be well suited to meet the requirements of this application.

Cable system parameters which have been examined for the generator lead application include emergency ampacity, fault current levels, switching surge and lightning impulse levels, system voltage, power rating, line length, load factor and surge impedance. As a result of the first series of meetings with utility system planners the cable parameters given below were developed.

Power rating: 2,000 - 5,000 MVA

Voltage level: 138 - 345 kV

Length: 5-130 km. Typical length for a land based plant of 30 km and 8 km for an off-shore plant.

BIL: An 800-kV BIL would be acceptable for a 230-kV generator lead and possibly by the 1980's for a 345-kV generator lead.

Fault rating: 15,000 - 50,000 MVA. A reasonable upper limit of 35,000 MVA was seen for the 1980's.

Emergency ampacity: None required for this application.

Redundancy: Complete redundancy for a single contingency, necessitating a two-cable line.

Load factor: 40% for a two-cable line.

Using the cable design parameters given above as well as theoretical and experimental work completed in this program, several preliminary cable system designs were developed. The characteristics of those cable systems were provided to several electric utilities near the end of the second year of this program with the request that they look at specific new transmission lines planned for the late 1980's and determine which of the lines best meet their requirements. Participating in this effort are Consolidated Edison, Commonwealth Edison, Pacific Gas and Electric, Public Service Electric and Gas, and Southern California Edison. This work is still in progress and this type of activity will need to be continued throughout the development of superconducting cable systems. Only in this way can it be assumed that the system being developed will meet the anticipated technical requirements and that the costs developed properly reflect the costs of all the components such as transformers, reactors, and phase shifters required by specific system applications.

Section II

CONCLUSION

At the onset of this program ac loss data on electroplated niobium and a preliminary cost estimate indicated that this type of cable system would be attractive for moving large blocks of power if an overall system could be developed which would meet utility system needs and be technically feasible and economically competitive. As a result of the work carried out during this 46-month program, a conceptual design was generated for the rigid conductor, rigid cryogenic enclosure, helium-spacer insulated superconducting cable system described in this report. This system provides what is believed to be a design which can meet all of the requirements which must be met by a high power cable system such as reliability, voltage rating, impedance values, and fault, switching, and lightning overloads.

The design parameter values which are included in this report and the cost estimate represent values which we believe can be achieved with continued development and are based on the results of full-scale tests or extrapolations from smaller scale tests. None of these values has been demonstrated to be valid in a full-scale, rated power test. The results which have been achieved to date indicate that most, if not all, of the cable requirements can be met within the existing design framework. However, the test data on the voltage withstand of the dielectric spacers in pressurized liquid helium were unacceptably low, a factor of 3 to 4 below our anticipated value. The cause of these low breakdown voltages must be identified and a solution found for this concept to be viable. At this time, the mechanisms triggering these low breakdown voltages are not fully understood but the result that the spacers could be conditioned to withstand acceptably high voltages implies that the low values may be due to contamination of the spacers and/or helium.

Experimental data to measure the performance of the cryogenic enclosure agreed well with a computer simulation of the heat leak with the exception of a heat in-leak at the joints caused by helium convection in the annular space between the pipe and sleeve sections. This loss can be reduced to an acceptable level by

operating the joint annulus at a reduced pressure and by putting a helium convection suppressor material in this region. There is still an incentive, however, for developing a more efficient convection seal. In fact, if a sufficiently effective seal were developed it may be possible to operate the joint annulus at full pressure.

The overall approach which has been taken in this program has been to design a system which would be fabricated using existing commercial equipment and techniques. Several of the components such as the terminations and conductors came close to meeting all of their design specifications even though they had been first-of-a-kind items. Much additional work will need to be done before this cable system is fully developed. As has been outlined in previous reports, we would expect that additional work will be required in order for a technically sound, economically competitive superconducting cable system to be installed. The progress during this program represents one positive step toward that objective.

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