AN ASSESSMENT AND STUDY OF EXISTING CONCEPTS
AND METHODS OF CRYOGENIC REFRIGERATION
FOR SUPERCONDUCTING TRANSMISSION CABLES

PROGRESS REPORT

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INTRODUCTION

This report covers the progress made in a six task program as outlined in Table 1. Task 01 and subtask 02.10 of the previous report period have been completed. The current report period includes most of the subtasks outlined under task 02. As shown in the schedule chart, Figure 1, task 02 for the current report period involves contacting of refrigerator users, review of APCI operations in the area of air separation plants, contacting of refrigerator manufacturers, and the initial phases of component manufacturer contacts.

WORK STATUS

Completion of Work From Previous Report Period

Before detailing the work carried out for the present report period, the most current summary of the refrigeration requirements for the BNL, Union Carbide-Linde, and LASL transmission lines is presented in Table 3. All of these designs are subject to change, but in particular, the LASL requirements are very preliminary. The summary chart of refrigeration requirements included in the previous progress report included three (3) different plans which were being considered by BNL in the designs formulated with LILCO. Since preparation of that report it has been learned that the most feasible choice for the proposed power line is probably plan 3A. Plan 3A is a two-circuit superconducting system, each circuit of which will have a continuous contingency capability of 4800 MVA at 345 KV. For the purposes of the present investigation Plan 3A

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will be considered representative of BNL's transmission line.

The requirements outlined in Table 3 for the LASL transmission line are based on the assumption that a bi-polar transmission line design will be used and that a refrigeration system similar to the one currently being used on the BNL cold neutron moderator experiment (reference 20 in helium refrigeration systems bibliography section) will be utilized. Until further studies are completed at LASL this is probably the most logical system choice. For the purposes of the present investigation a pressure of 10 atm is assumed in the transmission line, although this probably represents a lower limit with the eventual pressure probably being closer to 15 atm.

Table 2 gives an updated summary of contacts made at the major laboratories working on the superconducting power transmission lines, as well as the contact made at Fermilab in order to determine the refrigeration requirements of the proposed Energy Doubler program at Fermilab. The requirements for the Energy Doubler program have not been included in Table 3 since details are still not available on the revised system configuration.

Figures 2, 3, and 4 represent the flow schematics of the refrigeration systems for the Union Carbide-Linde, Brookhaven National Laboratory, and Los Alamos Scientific Laboratory transmission lines as presently conceived. Also given are the thermodynamic states of various points along the flow circuit. Note that the loading shown on the flow schematic for the Linde line and the Brookhaven line are based on the full distance between refrigeration stations,

whereas the Los Alamos flow schematic is based on half the distance between adjacent refrigeration stations. The most obvious options for these refrigerators are either to build a large refrigerator and split the flow as shown in option 1 of Figure 5, or use two adjacent half size refrigerators as shown in option 2 of Figure 5. The final configuration used will depend on trade-offs between overall system reliability, efficiency, and cost.

Criteria Used to Fix Helium Operating Temperatures, and Pressures:

In order to understand why the temperatures and pressures of the helium in power transmission lines are the values given in Table 3; and in order to understand what must be expected of a refrigeration system which must deliver this helium coolant, it would be helpful to summarize some of the many trade-offs which must be considered before the final temperatures and pressures as well as the allowable temperature rise and pressure drops are established. A good discussion of some of these tradeoffs is given in reference 32 of the superconducting power transmission line section of the bibliography. Most of the parameters which help to establish the operating pressures and temperatures fall into the category of electrical or thermodynamic considerations.

A. Electrical Considerations

1. The upper limit in temperature for any of the type I or type II superconductors is set by the critical or transition temperature of the superconductor being considered. Among the current superconductors being tested, niobium has a transition temperature of about 9.3°K and niobium-tin has

has a transition temperature of about 18.3°K. At these temperatures, the superconductor may revert to its normal state through the application of an external magnetic field or through a self-induced magnetic field generated by current flowing in the superconductor. If this magnetic field strength exceeds a certain limiting value called the threshold field, the superconductor will switch back to its normal state. Allowing for the expected self induced magnetic field which will appear around a superconductor, and also, taking into account the possibility of carrying fault or overload currents, the realistic upper limit for temperature of the helium coolant in contact with the superconductor is about 5°K for the niobium line and about 8.75°K for the niobium-tin line if both are used in AC power transmission. For transmission of DC power, the upper limit of the temperature of the niobium-tin line is about 13°K.

2. From an electrical standpoint, the pressure of the helium cooling the line should be as high as possible. The reason for this is that in many cases the helium coolant is also to double as the dielectric insulation. The dielectric properties of helium are such that the dielectric strength increases with pressure. Another advantage of high pressure, related to dielectric strength, is that for pressures above the critical pressure of helium (2.24 atm) the formation of low density vapor bubbles is unlikely - a low density bubble could very well lead to a high voltage breakdown.
3. It should also be mentioned in this section that for the coaxial type design in which the central superconducting element is separated, from the outer conductor which surrounds it, by a dielectric material (either

a solid dielectric or helium), the central helium flow channels are fairly well fixed by optimizing the electrical properties of the superconductor and dielectric. This optimization will generally give a fixed geometry and size. It generally follows that this type of electrical optimization will more than likely not be optimum from a cooling standpoint.

B. Thermodynamic Considerations:

1. Although there is no lower limit on the temperature of the superconductor from an electrical standpoint, huge penalties must be paid from an overall thermodynamic efficiency standpoint for temperatures which approach absolute zero. Low efficiencies can be equated with very large required energy inputs in order to operate the refrigerator. This point is illustrated very clearly by looking at the ratio of the work required to operate an ideal Carnot refrigerator (W_c) divided by the heat removed from the cold end (Q_c) at temperature T_c :

$$\left(\frac{W_c}{Q_c} \right)_{\text{CARNOT}} = \frac{T_{\infty} - T_c}{T_c}$$

where T_{∞} is the ambient temperature.

It is evident that as T_c decreases the ratio (W_c/Q_c) increases. Thus, from a refrigerator systems standpoint one would like to keep the allowable temperature rise of the helium coolant to a fairly low value - typically about a $2^{\circ}\text{K } \Delta T$ for the niobium tin superconductor and about $0.5-0.25^{\circ}\text{K}$ for the niobium line (a $2^{\circ}\text{K } \Delta T$ for niobium which has an upper temperature limit of only 5°K would be prohibitive).

2. Another important consideration which has an effect on temperature and pressure level is the specific heat of the coolant. From a specific heat standpoint one would like to operate at a thermodynamic state for which the specific heat is large - this would reduce the mass flow rate of helium required for a given heat removal rate and a given allowable ΔT (this of course would mean greater distances between refrigerator stations because of reduced pressure drop). Unfortunately, operation near the transposed critical line (maximum specific heat line) is an inherently unstable region to operate in from a thermodynamic and fluid mechanical standpoint; hence, one should try to operate as close to this line as possible without entering into the unstable regions.

In the case of niobium, because the heat capacity of helium in the 4.4° to 5°K range decrease with an increase in pressure, it is advantageous to avoid a high inlet pressure; by the same token, the pressure drop should not be so high as to drop the pressure below the critical pressure.

3. Another thermodynamic property to consider is the Joule-Thomson (J-T) coefficient. In some temperature and pressure ranges of operation, the J-T coefficient can be negative, in which case any pressure drop in the helium circuit will cause an increase in fluid temperature and therefore create additional heat load. If the J-T coefficient is positive, pressure drop could actually cause a temperature drop in the fluid.
4. Another consideration, which was mentioned above, is the problem of density wave propagation down the transmission line. This type of flow instability

is especially severe in the immediate vicinity of the helium critical point. Some of the regions on a temperature-entropy chart of helium somewhat removed from the critical point and lying in the supercritical fluid region are less apt to cause flow stability problems; unfortunately, not all of the regions around the supercritical zone of the helium vapor dome have been investigated for the L/D ratio being contemplated in the design of the major transmissinn lines. The L/D ratio used here refers the flow channel length divided by the fluid hydraulic diameter. One region which has been investigated is that portion of the temperature-entropy chart which is below the critical temperature and above the critical pressure. No oscillations have been observed in this region - this region approximately corresponds to the zone of operation of the Linde niobium transmission line. The region of the T-S chart corresponding to the temperature range 6.75 to 8.75°K (niobium-tin) and pressures higher than 10 atm (probably on the order of 15 atm), although not investigated thoroughly for density wave behavior, should be reasonably free from oscillations. NBS is planning to run stability tests in most of the regions of interest around the critical point to determine zones of oscillatory flow behavior for the L/D ratios being investigated.

5. An upper limit on system pressure level, other than the physical pressure limitations of the equipment, is the fact that at high pressure levels the helium inventory in the system is tremendous. This is prohibitive from a practical standpoint, that is, if the line must be emptied in an emergency, vast amounts of helium would have to be put into temporary storage or otherwise disposed of.

Establishment of the Distance Between Refrigerator Stations:

Within the framework of the numerous trade-offs which must be considered in light of the preceding discussion, the maximum allowable distance between refrigeration stations along a superconducting power transmission line may be computed. The prime controlling limitation on the distance between stations is the temperature rise of the helium coolant. For a given combination of coolant mass flow rate, transmission line heat load, effective heat transfer coefficient, and flow circuit length, the superconductor should not exceed the upper temperature limit which has been set for it; armed with the pertinent heat transfer equations and heat transfer coefficients one may calculate the conductor length for which the limiting temperature is reached.

The other primary limiting factor on the distance between refrigeration stations is the pressure drop in the transmission line. The pressure drop should not be such that the refrigerator cycle efficiency drops to too low a value. Also, the pressure drop should not cause the helium coolant to move into a thermodynamic state which would permit density wave oscillations or an appreciable reduction in the dielectric strength of the helium.

Taking all of these factors into account, the major transmission line development laboratories have found that the best choice for the distance between refrigeration stations falls within the range of about 8 to 12 kilometers.

Visits to Refrigerator Users

The work done by Dean on the reliability of a hypothetical refrigeration system to be used on a superconducting transmission line (reference 40, Superconducting Power Transmission Lines Section of Bibliography) showed that the overall reliability of a refrigerator using reciprocating as opposed to rotating equipment was so poor that the likelihood of using reciprocating expanders and to a lesser extent, reciprocating compressors, on future transmission lines was very remote. Based on mean time between failures (MTBF) obtained by Strobridge et al of NBS (reference 20 in Helium Refrigeration Systems Section of Bibliography) in a survey of the reliability of reciprocating and turbine expanders in helium service, Dean used a mean time to failure of 6000 hours for reciprocating expanders and 20,000 hours for oil lubricated expanders. It was also stated in Dean's report that gas bearing turbines were expected to have a MTBF two or three times greater than the oil lubricated turbines. Based upon these findings it was decided to concentrate our efforts on visiting or contacting refrigeration users whose systems are made up of turbo-expanders either gas or oil lubricated. It is believed that we have now either visited or gathered information pertaining to most of the major helium refrigeration equipment in the U.S.A. Due to the difficulty of scheduling visits to the main refrigeration users in Europe (because of vacation schedules) these visits have been delayed probably until early or mid August. Table 4 summarizes the helium refrigeration systems for which information has been gathered either through visits or other means. Detailed summaries of the findings of these visits will not be given until all the information has been gathered. Also appearing in Table 4 is a listing of the refrigerator users

and manufacturers who will probably be visited in Europe.

APCI Operations Review

The review of APCI experience in large air separation plants is not complete at this time. A summary of the findings of this review will be included in the next progress report.

Contact Refrigeration and Component Manufacturers:

Based upon the flow schematic information given in Figures 2, 3, and 4, specifications for systems and components are being prepared and will be sent to equipment manufacturers. They will be asked to supply information pertaining to equipment which they presently have or are in the process of developing which will meet these specifications. Information supplied by them should include approximate cost, component efficiency, and MTBF based on equipment in the field. Comments on the current state-of-the-art and the probable direction of future improvements is being solicited. In addition, manufacturers are being asked to comment on any recurrent problems which have become evident from the refrigerator users visits.

WORK PLAN FOR NEXT REPORT PERIOD

The next report period covers the initiation and/or completion of the following tasks:

02.20 Completion of APCI review

Completion of refrigerator user contacts

Contacting of refrigerator and component manufacturers

02.30 Evaluation of refrigerator data

TABLE 1

STUDY OF EXISTING CONCEPTS AND METHODS OF CRYOGENIC
REFRIGERATION FOR SUPERCONDUCTING TRANSMISSION CABLES

TASK 01.00	TRANSMISSION LINE SURVEY
01.10	Literature Survey - Transmission Lines
01.20	Visit Program Centers (Transmission Lines)
TASK 02.00	REFRIGERATOR SURVEY
02.10	Literature Survey - Refrigerators
02.20	Contact Refrigerator Users
	APCI Operations Review
	Contact Refrigerator Manufacturers
	Contact Component Manufacturers
02.30	Evaluate Refrigerator Data
TASK 03.00	DEVELOPMENT PROGRAM
03.10	Review of Equipment Vs. Requirements
03.20	Develop Optimization Criteria
03.30	Component Evaluation
03.40	Recommend Development Programs
TASK 04.00	SYSTEM RELIABILITY
04.10	Evaluate Component Reliability, Efficiency
04.20	Redundancy, Reliability, and Backup
TASK 05.00	SELECT BEST CURRENT SYSTEM(S)
TASK 06.00	REVIEW OF BUSINESS FACTORS

TABLE 2

SCHEDULED VISITS

DATE	COMPANY OR LABORATORY VISITED	INDIVIDUALS INVOLVED	TOPICS COVERED
25 April	Union Carbide- Linde	H. Morihara	Linde Transmisstion Line Program
1 May	Brookhaven Nat- ional Lab.	E. Forsyth J. Jensen	Brookhaven Transmission Line Program
12 May	Fermilab	B. Strauss	Helium Refrigeration Requirements Paralleling Superconducting Trans- mission Line Requirements
13 May	Los Alamos Scientific	F. Edeskuty J. Dean W. Keller D. Taylor	Los Alamos Transmission Line Program
15 May	National Bureau of Standards	T. Strobridge M. Jones W. Parrish D. Daney	Discuss work done by NBS relating to transmission line development

TABLE 3

Development Group	Superconductor Electric Mode of Power Transmission	Power Rating per Circuit and Voltage	Heat Load per Circuit at Superconductor	Temperature Range of Cable	Helium Pressure in Central Cable	Load on Shield Per Circuit and Temperature Range	Mass Flow Rate of Helium in Central Cable	Mass Flow Rate of Helium in Shield	Length of Circuit upon which Loads Based	Distance between Refrigerator Stations	Compressor Power (KW) per Circuit
Brookhaven National Lab.	Niobium-Tin 30, AC										
Plans formulated with Lilco :											
Plan 3A ^Δ		4800 MVA* 345 KV	3600 watts*	6.75-8.75°K	15 atm	11,200 watts @ 75°-100°K	312 g/s	80 g/s	12 km	12 km	1263.2
Union Carbide - Linde	Niobium 30, AC	3400 MVA 138 KV	662 watts	4.75-5°K	5 atm	667 watts + @4.7°K 4.57°-300°K	200-400 g/s	7.1 g/s	4 km	8 km	696 kw
Los Alamos Scientific Lab.	Niobium-Tin or Niobium Germ. D.C.	2-10 GW + 100KV	2500 watts [≠]	11°-13°K	10-15 atm		190 g/s [≠]	-	5 km [≠]	10 km [≠]	970 kw

Δ Most feasible plan

* Continuous contingency requirement per circuit

+ Equivalent refig. at 4.7°K

≠ Based on possible bipolar design configuration with an assumed heat leak of 0.25 w/m- these values subject to change since final superconductor configuration not determined yet.

TABLE 4

REFRIGERATION SYSTEM USER	ADDRESS	TYPE OF EQUIPMENT	DATE OF VISIT OR CONTACT
McGill University Magnet Lab.	Montreal, Canada	Helium system with Sulzer oil lubricated turbo-expanders and Sulzer labyrinth seal compressors	12 June 75
Brookhaven National Lab.	Upton, New York	H ₂ system used on large bubble chamber Sulzer oil lubricated turbo-expanders 3500 watt Sulzer system used on cold neutron moderator experiment. Sulzer oil lubricated turbo-expanders with Sulzer labyrinth seal compressors Oil lubricated helium screw compressor modified from Freon unit.	1 May 75
Los Alamos Scientific Lab.	Los Alamos, New Mexico	H. Sixsmith externally pressurized gas lubricated turbo-expander refrigeration system.	13 May 75
Fermilab	Batavia, Illinois	CTI 4000 helium liquefier with re- ciprocating expansion engines and horizontal dry lube reciprocating compressor.	12 May 75
Argonne National Lab.	Argonne, Illinois	Airco helium liquefier using BOC externally pressurized gas lubri- cated turbo expander and 3-stage dry lube Pennsylvania compressor.	23 June 75
Lawrence Livermore Lab.	Livermore, California	Airco helium liquefier with BOC externally pressurized gas lubri- cated turbo-expander and dry lube vertical 2-stage Rix compressors.	25 June 75
Lawrence Berkley Lab.	Berkley, California	Discussion of rotary compressors	25 June 75
Stanford High Energy Physics Lab.	Palo Alto, California	Sub λ point refrigerator with re- ciprocating expanders and Sulzer labyrinth seal compressors.	26 June 75
Stanford Linear Accelerator Lab.	Palo Alto, California	Large helium purifier and Gardner/ Denver horizontal 2-stage, double acting, oil lubricated compressor.	26 June 75

TABLE 4 (continued)

RIGERATION TEM USER	ADDRESS	TYPE OF EQUIPMENT	DATE OF VISIT OR CONTACT
Keyes Helium Plant	Keyes, Oklahoma	Two helium expanders/oil lubricated. Two reciprocating helium expanders. Three reciprocating, 3-stage, helium compressors.	TAKEN
Phillips Greenwood Plant	Elkhart, Kansas	Two helium turbo-expanders/oil lubricated. Two nitrogen turbo-expanders. Two wet reciprocating helium expanders. One helium dry lube reciprocating compressor.	from STROBRIDGE and SINDT REPORT - REFERENCE
Cities Service Jayhawk Helium Plant	Satana, Kansas	<u>NEW EQUIPMENT</u> Two helium turbo-expanders/oil lubricated. One two-cylinder wet helium reciprocating expander. One five-stage dry lube reciprocating compressor. <u>ORIGINAL EQUIPMENT</u> Two helium turbo-expanders/oil lubricated. One Reciprocating four-stage dry lubri- cated helium compressor.	21 IN HELIUM REFRIGERATION SYSTEMS SECTION OF
National Helium Corp.	Tiberal, Kansas	Two reciprocating helium compressors.	BIBLIOGRAPHY
Kansas Refined Helium Co.	Otis, Kansas	Two helium turbo-expanders/oil lubricated. One two-cylinder wet helium reciprocating expander. Two four-stage dry lubricated helium compressors.	
Central Elect- rical Research Lab.	Leatherhead, England	BOC turbine system with externally pressurized bearings.	August

TABLE 4 (Continued)

REFRIGERATION SYSTEM USER	ADDRESS	TYPE OF EQUIPMENT	DATE OF VISIT OR CONTACT
International Research and Development Co., LTD.	Newcastle- Upon-Tyne, England	Fawley station homopolar motor refrigeration system - BOC turbo-expanders. Oil Lube screw compressor devel- opment for British Defense Ministry.	August
Rutherford Laboratory	Oxford, England	BOC turbo-refrigerator on bubble chamber.	August
Culham Laboratory	Abingdon, England	Supercritical helium refrigerator with BOC turbines on super- conducting Levatron.	August
CERN	Geneva, Switzerland	Superctitical helium system on Omega magnet - Sulzer expanders and compressors.	August
Center for Nuclear Studies (CENG)	Grenoble, France	- L'Air Liquide system on cold neutron-moderator experiment. - Small L'Air Liquide turbine system (150W)	August
BOC	London, England	Discuss state-of-the-art on helium refrigerators.	August
Sulzer Brothers	Winterthur, Switzerland	Discuss state-of-the-art on helium refrigerators.	August

FIGURE 1
PROGRAM SCHEDULE BY TASK

SHADING SHOWS PERCENT OF WORK COMPLETED

UNION CARBIDE-LINDE DIVISION
REFRIGERATOR FLOW SCHEMATIC
FOR 8 KM SECTION OF TRANSMISSION LINE
(8 KM BETWEEN REFRIGERATION STATIONS)

η = ISENTROPIC
EFFICIENCY

SUMMARY

@ 75% COMPRESSOR EFFICIENCY,
TOTAL POWER REQUIRED
IS 1390 KW

FIGURE 2

BASED ON ENCLOSURE DIAMETER = 50 CM

BROOKHAVEN NATIONAL LABORATORY
REFRIGERATOR FLOW SCHEMATIC - PLAN 3A
FOR 12 KM SECTION OF TRANSMISSION LINE
(12 KM BETWEEN REFRIGERATION STATIONS)

COMPRESSOR 2

η_{IS} - ISENTROPIC
EFFICIENCY

FIGURE 3

FLOW SCHEMATIC
BASED UPON NO GAS BLEEDS FOR LEAD COOLING

LOS ALAMOS SCIENTIFIC LABORATORY
REFRIGERATOR FLOW SCHEMATIC
FOR 5 KM SECTION OF TRANSMISSION LINE
(10 KM BETWEEN REFRIGERATION STATIONS)

FIGURE 4

FLOW SCHEMATIC BASED UPON BI-POLAR SUPERCONDUCTOR
CONFIGURATION AND A HEAT LOAD OF 0.25 WATTS/METER

FULL OR HALF SIZE REFRIGERATOR OPTIONS

OPTION 1

L = DISTANCE BETWEEN REFRIGERATION STATIONS

OPTION 2

FIGURE 5

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