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A STUDY OF REFRIGERATION FOR LIQUID-NITROGEN-COOLED POWER TRANSMISSION CABLES*

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INTRODUCTION

The development of ac power transmission cables, operated at cryogenic temperatures, has been pursued for both resistive and superconducting configurations because of their ability to transmit large blocks of power over a narrow right-of-way at high efficiency [1–3]. The eventual success of these new transmission concepts depends, to a large extent, upon their ability to demonstrate economic advantages over conventional cables. The cost and reliability of large helium refrigerators have been estimated for a 40-mile superconducting transmission line [4].

This paper discusses results of a study of refrigeration systems for application to a 3000-MVA, 500-kV underground resistive cryogenic power transmission cable operated at liquid nitrogen temperatures. Such cryogenic cable systems are expected to have single-circuit transmission capacities in the range 2000 to 5000 MVA, significantly enhancing the capabilities of present-day underground transmission systems.

REFRIGERATOR REQUIREMENTS

Figure 1 shows the foam and vacuum thermal insulation concepts being studied. Although use of foam insulation produces higher refrigeration loads, it promises increased reliability, lower enclosure costs, and greater ease of maintenance [5]. Figure 2 shows the refrigeration concept in which a refrigeration station is located at the midpoint and liquid nitrogen circulated in both directions by pumps. Module

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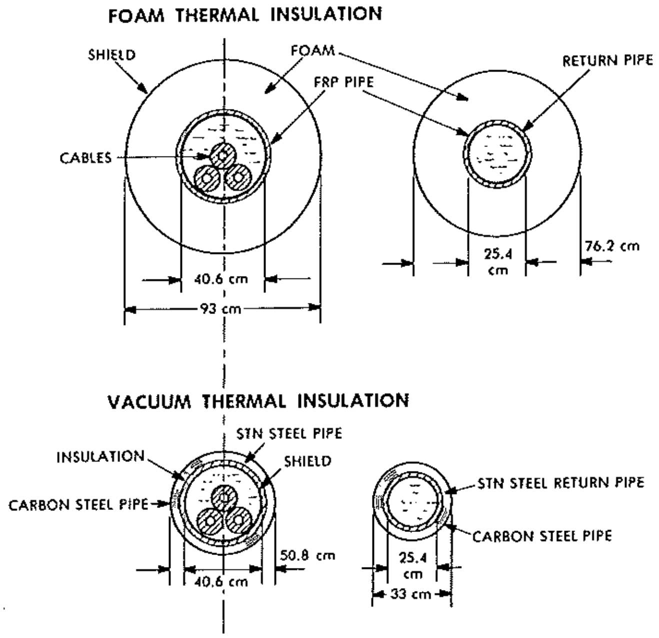

Fig. 1. Cable envelope concepts.

length is maximized by having pumps at the far ends of the line and allowing the maximum temperature rise possible while keeping the liquid nitrogen subcooled throughout the circuit. The inlet temperature of 65 K is 2 K above the freezing point of nitrogen while 97 K at 12 atm and 105 K at 14 atm represent 10 K of subcooling.

Table I presents refrigerator load estimates in kilowatts per mile for the foam and vacuum insulation concepts. Analysis of the refrigeration load at other transmission loads and cable temperatures assumes that all losses except cable conductor losses are uniform. Conductor losses are $1.38\,I^2R$ where R is the value of the dc resistance of aluminum as reported by Meissner and Voigt [6]. Conductor losses range from 8.4 kW/mile at 65 K to 26.4 kW/mile at 95 K at 2000 MVA.

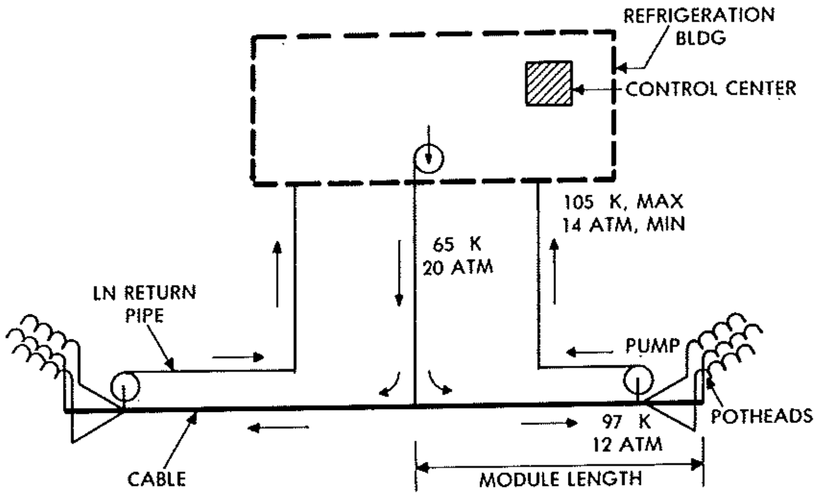

Fig. 2. Refrigeration concept, single circuit, 3000 MVA.

Table I. Estimated Refrigeration Loads for Alternate Cable Enclosures

	Enclosure	
Pipe	GRE*	Metallic†
Thermal insulation	Closed-cell urethane foam ($2.5\ \mathrm{lb/ft^3}$)	Evacuated multilayer
	Refrigeration load, kW/mile	
Cable		
Conductor losses‡	18.5	18.5
Dielectric**	12.5	12.5
Enclosure		
Cable shielding	0††	1.1
Cable pipe	41.9	4.0
Return pipe	32.7	2.6
Total	105.6 kW/mile	38.7 kW/mile

* Filament wound glass reinforced epoxy.

† Stainless steel inner pipe, carbon steel outer pipe.

‡ Based on average conductor losses at 80 K, 2000 MVA.

** Assumed 300 μrad dissipation factor.

†† Shield assumed to be placed over the foam insulation with losses dissipated to the surrounding soil.

Figure 3 shows the change in compressor power as a function of cable temperature assuming a Carnot cycle efficiency of 30% and 300 K ambient temperature.

$$W = \frac{Q}{0.30}\left(\frac{T_h - T_c}{T_c}\right) \tag{1}$$

The foam-insulated enclosure with a high static loss shows an increase in compressor power from 750 kW/mile at 95 K to 1050 kW/mile at 65 K with an average of 880 kW/mile for a line operating between 65 and 95 K as shown by the center dashed line. If the line is operated at 65/80 K inlet/outlet temperatures, it is seen that the foam-insulated enclosure would require more power. If the line is operated at 80/95 K, the power requirement is reduced compared with the 65/95-K operation: the vacuum-insulated line has a significantly lower compressor power requirement independent of operating temperature.

The module length is the maximum distance the liquid nitrogen can flow along the cable pipe before it must be returned to the refrigerator. This distance is limited by the allowable pressure drop of liquid nitrogen and the allowable temperature rise of liquid nitrogen. The two equations that must be satisfied are

$$\Delta P = \left(\frac{\dot{m}}{A_c}\right)^2 \frac{1}{2g}\frac{f}{\rho}\frac{L}{D} \tag{2}$$

$$\Delta T = \frac{qL}{\dot{m}C_p} \tag{3}$$

The maximum temperature is limited by dielectric voltage stresses at the surface of the cable conductor and the temperature gradient across the dielectric.

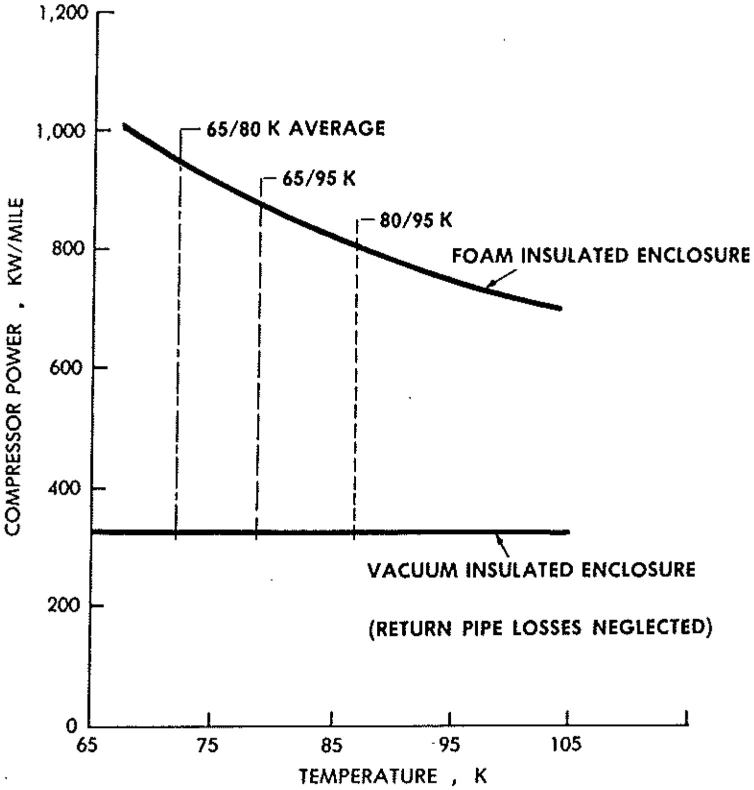

Fig. 3. Compressor power vs. temperature, 2000 MVA.

The compressor power input in Fig. 3 is based on the heat load at 2000 MVA for a single circuit cable having 3000 MVA capacity. This represents a typical average transmission load (load factor of 0.67). Maximum module length, however, is set by the maximum transmission load of 3000 MVA. Table II lists the heat load per mile at 3000 MVA for both enclosures at three assumed operating temperatures and the corresponding maximum module length. Equations (2) and (3) were used to solve for L and $\dot{m}$ based on a pressure difference of 8 atm, ΔT as noted, average fluid properties, and a friction factor of 0.06. (The relatively high friction factor is due primarily to the spacing tape that is wrapped around each cable.) Return losses are not included; thus, 95 K was assumed as a maximum outlet temperature from the cable to allow for additional temperature rise in the return line. The product of the heat load per mile and maximum length is given in Table II to give an idea of the maximum amount of refrigeration per module that will be required.

From Table II, it is observed that, (1) maximum module lengths are obtained with operation at 65/95 K, (2) longer module lengths are obtained at 65/80 K than at 80/95 K, and (3) there is a real advantage in terms of maximizing the module length in minimizing the enclosure heat leak.

Refrigerator station design and cost are based on two refrigerators each having a capacity of 925 kW and refrigerant temperatures of 64/80 K. This will permit a vacuum-insulated 30-mile line to be operated at 3000 MVA with liquid nitrogen temperatures of 65/95 K or at 1800 MVA with liquid nitrogen temperatures of 65/82 K, which can be supplied by one refrigerator. Since the 15-mile module length

Table II. Heat Load, Maximum Module Length, and Total Refrigeration per Module at 3000 MVA

Parameter	Inlet/outlet, K	Cable enclosure	
		Foam	Vacuum
Heat load, kW/mile	80/95	129	69
	65/80	108	48
	65/95	118	58
Maximum length, miles	80/95	9.6	13.7
	65/80	10.0	17.2
	65/95	15.5	24.8
Refrigeration per module, kW	80/95	1238	945
	65/80	1080	826
	65/95	1830	1438

is less than the 24.8-mile maximum possible length, the liquid nitrogen pumps at the far ends are not needed.

REFRIGERATION PROCESS

The requirement of cooling the liquid nitrogen to 65 K rules out using nitrogen as a practical refrigerant because its vapor pressure at 65 K is about 2.5 psia. Helium, hydrogen, and neon are potential refrigerants. Neon has the distinct advantage of requiring fewer stages of compression because its molecular weight is 20.18 vs. 4.00 for helium and 2.0 for hydrogen. The value of neon in the system was estimated to be less than $100,000 and the fluid is readily available. The compressor cost premium for helium and hydrogen is many times the cost of the neon; thus, neon was selected.

To provide refrigeration at 64/80 K, with an 80% efficient expander, the pressure ratio across the expander must be approximately 2.1 : 1. This low pressure ratio necessitates operating two or three expanders in series in order to minimize heat exchanger losses.

The process that was selected to be used as the basis for the cost estimate is shown in Fig. 4. It is assumed that the refrigeration rate can be reduced to 60% of maximum; thus, the expander efficiency is taken as being 80% at midload conditions and 78% at maximum and minimum load. At maximum load, the main compressor requires 9700 kW power input. Over 750 kW is recovered from the expander/booster compressors.

The ratio of work, W, to refrigeration, Q, for a Carnot cycle providing cooling over a distributed temperature is given by

$$\frac{W}{Q_{\text{Carnot}}} = \left[\left(\frac{T_h}{T_1 - T_2}\right) \ln\left(\frac{T_1}{T_2}\right)\right] - 1 \tag{4}$$

For the refrigerator conditions shown in Fig. 4, the temperatures are $T_h = 308\ K$, $T_1 = 80.0$ K, and $T_2 = 63.7$ K. This results in an ideal ratio for W/Q_{Carnot} of 3.31. The actual refrigerator efficiency is 31.5% of Carnot since the actual ratio of W/Q is 9700/925. Units of this size according to Strobridge [7] typically have an efficiency of 30% to 35%. Further refinements of the cycle might result in improving a few points.

The refrigeration rate can be reduced either by reducing the throughput of the compressor and expanders, or by removing some neon from the system to reduce the

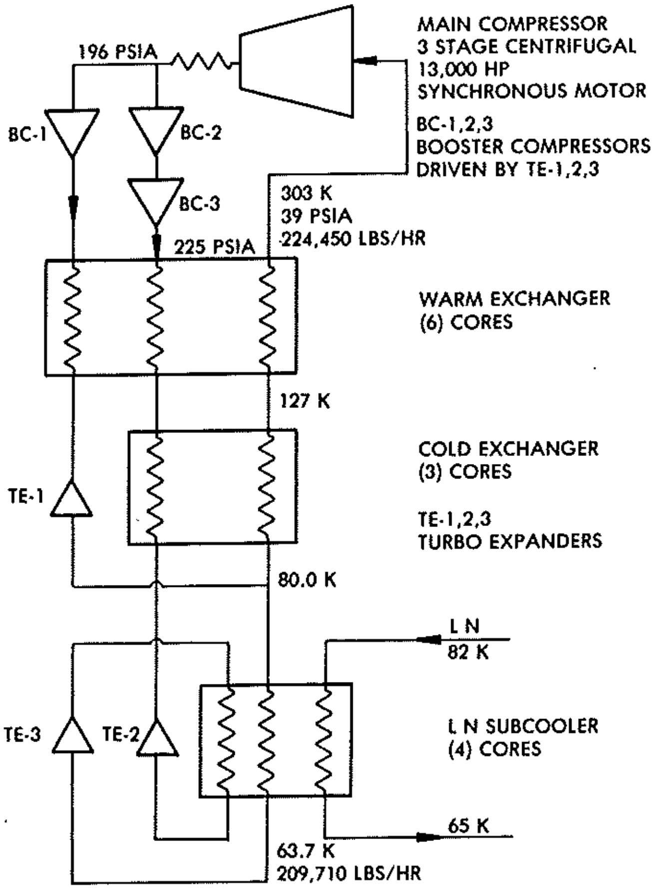

Fig. 4. Neon refrigerator cycle for 925 kW of refrigeration.

operating pressure. A neon storage compressor and tank are included to permit storage of the neon during maintenance, and these can be used to adjust the operating pressure level. For either control method, the compressor and expanders operate at essentially fixed pressure and temperature ratios.

RELIABILITY

The liquefier section of the APCI air separation liquefaction plant at Wharton, New Jersey is very similar in terms of process, equipment, and size to the neon refrigerator. The plant has been in operation since late 1968.

Nitrogen is fed from the air separation unit at ambient temperature and 1 psig. A 1700 hp nitrogen makeup compressor boosts the pressure to 65 psig where it joins with the return recycle flow to be compressed to about 450 psig in the 17,000 hp main nitrogen compressor. The flow from the main nitrogen compressor is split to feed two cold boxes each of which can produce 250 to 300 tons/day of liquid nitrogen. Within each cold box, there is a group of core-type heat exchangers that form the warm exchanger and a second group that forms the cold exchanger. Foam insulated lines connect each cold box to "companders" which consist of two turbo expanders connected by a gear box to a booster compressor which raises the inlet pressure to the cold box to 650 psig.

Table III. Reliability Data from APCI Wharton Plant

Item	Number	MTBF, hr	MTTR, hr	Outages exceeding 6 hr	Outages exceeding 24 hr
Power failures	13	5,800	2.6	0	0
Main air compressor (5000 hp)	2	37,700	5.8	1	0
N_2 Make-up compressor (1700 hp)	4	18,800	4.1	1	0
Main N_2 compressor (17,000 hp)	17	4,700	24.7	15	7
Companders (2 sets)	16	9,400 each	16.1	10	3
N_2 cold boxes (2)	1	150,000	5.8	0	0
Electrical equipment	4	18,800	12.5	4	0
Major scheduled maintenance	5	15,100	185.7	5	5
Minor scheduled maintenance	14	5,400	46.5	14	10
Storage tanks (two, 2000 tons)	0	—	—	0	0

Notes

1. Total on stream time is 75,350 hrs.
2. Maintenance done while plant is shut down because of power interruption or full storage is not included; however, maintenance extending beyond normal restart time is included.
3. Compressor failures include controls, instrumentation, and coolers. Main nitrogen compressor includes 1 cooling tower failure and 11 cooler failures.
4. Outage time includes time to cooldown, typically 2 hr from a warm condition.

Power for the plant is supplied on an interruptible basis, which gives the power company the option of requesting the nitrogen recycle compressors be turned off during periods of peak demand. The air separation unit is turned down and kept cold during a power interrupt period so that the plant can typically be producing high-purity product within 2 to 3 hr after the nitrogen recycle system is restarted.

Advantage is taken of these outages to do minor scheduled maintenance. Scheduled maintenance is classified as minor when the relatively few operating personnel on the site perform this work.

Table III tabulates the number of outages for the Wharton plant due to failures and maintenance, the mean time between failures (MTBF), mean time to repair (MTTR), and the number of outages exceeding 24 hr. Previous studies [4] have shown that rotating machinery, expanders and compressors, typically have MTBF's that are in the range of 20,000 to 30,000 hr when controls are included. It is seen that the main air compressor, on the other hand, has an abnormally low MTBF. The large number of failures of the coolers suggests a design or operating problem.

Table IV extracts from the Wharton plant experience the data that is relevant to the neon refrigerator. The two most important parameters are the number of failures per year, λ, ($\lambda = \text{MTBF}^{-1}$) and the maintenance time, ξ, hours per year, ($\xi = \lambda \times \text{MTTR}$). Scheduled shutdowns are not failures, thus λ is the mean time between outages for unscheduled maintenance.

The groupings in Table IV assume the following:

1. Scheduled maintenance is similar to the Wharton plant excluding power interruptions and full storage outage periods. This is conservative in that it includes

Table IV. Reliability Parameter Values Used to Analyze Neon Refrigerator System Based on Wharton Plant Data

	MTBF, hr	λ Fail/yr	MTTR, hr	ξ, Maintenance, hr/yr
Scheduled maintenance				
Major	15,100	0.58	185.7	107.7
Minor	5,400	1.62	46.5	75.4
Subtotal		2.20		183.1
Compressor system				
Electrical equipment	18,800	0.47	12.5	5.9
Main compressor	4,700	1.86	24.7	45.9
Subtotal		2.33		51.8
Cold box system				
Cold box	150,000	0.06	5.8	0.4
Companders*	7,000	1.25	16.1	20.1
Subtotal		1.31		20.5

* Compander MTBF is reduced from Wharton data to account for additional wheels.

work on the air separation unit, but is optimistic in that some maintenance work is actually performed during those outages.

2. The compressor system is the same as the main nitrogen compressor plus cooling tower and electrical equipment.
3. The cold box systems and neon companders have a total of six wheels (vs. 3 for the nitrogen cold box) but the same lube oil system; thus, MTBF is reduced 25%.

Table V lists possible operating conditions of the refrigerators and defines the refrigeration system to have failed when both refrigerators are off. This is conservative in that there is most probably a period of 10 to 20 hr that power can be carried after the refrigerators are off. Table III shows that of the 57 failures listed, only 31 exceeded 6 hr and 15 exceeded 24 hr. During most of the time only one refrigerator is needed. The thermal inertia of the line permits the utility to keep the second refrigerator in a nonoperating standby mode and cool it down in less than 2 hr when needed.

If it is assumed that the refrigeration station consists of two 925-kW refrigerators which are independent, then using the reliability parameters of Table IV, the station has a calculated MTBF of 9.5 yr. By manifolding the compressors so that either one can supply either cold box, the MTBF is increased to 14.2 years. The addition of a spare compressor to the manifold increases the MTBF to 45 years. This spare unit could probably not be justified during the initial years of installation when the cable is likely to be operated below full capacity.

Table V. Failure Criteria

Test number	Cable condition	Refrigerator condition	Liquid nitrogen temp., K	Power MVA
1	Failed	Failed	>100	0
2	Critical	Failed	<100	1800
3	Normal	1 ON	80/65	1800
4	Full load	2 ON	95/65	3000

ECONOMIC EVALUATION

In order for a refrigerated underground power transmission line to be as reliable as present overhead lines, it is assumed that the MTBF of the refrigerator has to exceed 20 yr. The refrigeration station components as shown in Fig. 5, which are used as the basis of a cost estimate include a spare compressor.

All of the costs are based on past experience with similar equipment. The cost of designing the first unit is not included, but engineering costs that are typical of adapting an existing design to new installations are included. First unit design costs would be less than $1,000,000. The first unit costs in addition would include about $200,000 of spare parts that would go into a central depot to be available for a group of future plants. The costs that are listed are manufacturing costs. Markups vary for different components, but for a turnkey project, they average 20% of the manufacturing cost.

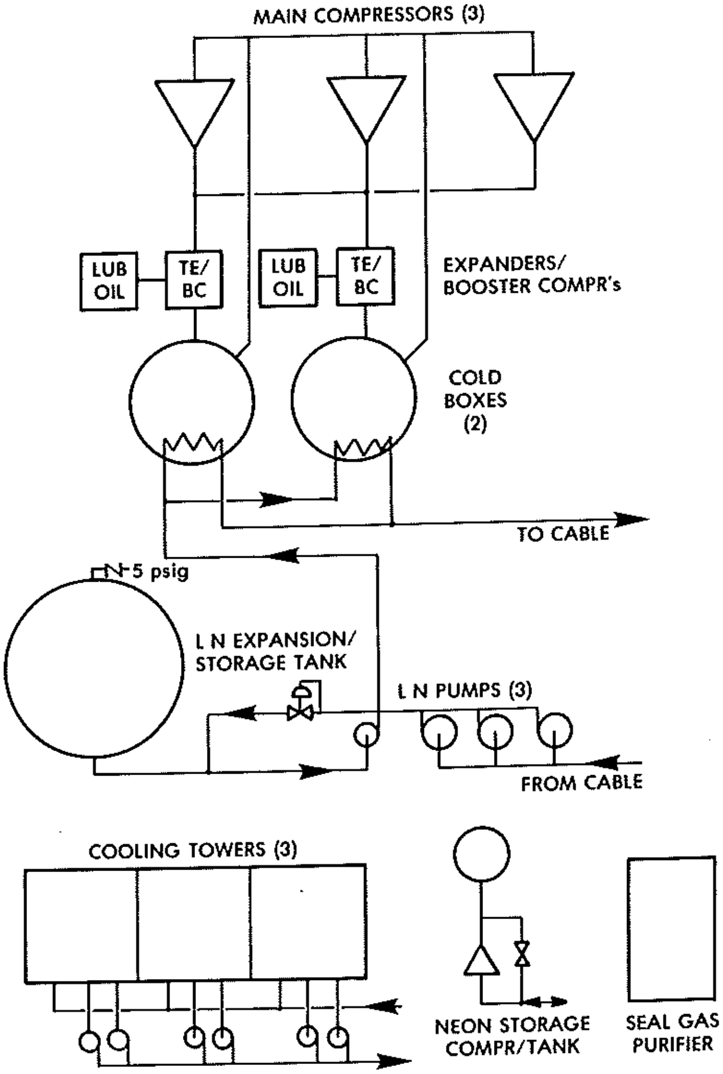

Fig. 5. Refrigeration station for liquid-nitrogen-cooled power line.

Table VI presents the results of the cost study with items grouped by major subsystems. Total cost of \$20,206,000 includes \$10,533,000 for the basic equipment, \$4,774,000 for facilities (about 45% of the basic equipment cost), \$1,531,000 for reserve (10%) and \$3,368,000 for markup.

The addition of the spare compressor adds \$4,261,000 (29%) to the cost of the basic refrigerator and the liquid nitrogen pump/storage system adds \$1,190,000. The cost estimate includes \$45,000 for neon, but does not include the cost of liquid nitrogen required to cool down and fill the line (about \$60/ton).

Table VI. Refrigerator Station Cost Estimate, 1850 kW Refrigeration at 64/80 K

	Quantity	Cost, 1000$	
Compressor system			
Main neon compressors	3	5750	
Electrical	All	650	
Cooling towers/pumps	3	280	
		6680	6,680
Cold box system			
Cold box shell and assembly	2	580	
Heat exchangers	2 sets	1308	
Companders w/lube oil	2 sets	590	
Valves	All	260	
Instruments and controls	All	260	
Vacuum pump	1	50	
		3048	3,048
Neon recovery system			
Seal gas purifier	1	40	
Neon compressors	1 set	52	
Neon storage tubes	10	115	
		207	207
Liquid nitrogen pump storage system			
Pumps	3	148	
Storage tank	1	450	
		598	598
			10,533
Facilities			
Construction		3500	
Spares		290	
Maintenance supplies		240	
Engineering		505	
Freight		50	
Miscellaneous		189	
		4774	4,774
			15,307
Reserve, 10%			1,531
			16,838
Markup, 20%			3,368
Total			20,206

Table VII. Operating Cost, for Continuous Operation at 3,000 MVA

Power	21,250 kW
Cooling water makeup	350 gpm
Chems and lubes	\$25,000/yr
Maintenance	\$295,000/yr
Staff	2 Supervisors 4 Operators 2 Mechanics

Table VII lists the utilities, services, and supplies required per year. All of the operating costs assume continuous operation at maximum load, 3000 MVA. The staff would be the same for any operating condition; however, the other operating costs are reduced as the electrical load is reduced. Maintenance cost is 1.75% of the capital cost, not including markup, and includes the cost of mechanics who are not part of the staff.

SUMMARY

The refrigeration requirements for a single-circuit resistive cryogenic cable transmitting 3000 MVA have been estimated to be 58 and 118 kW/mile for vacuum-insulated and foam-insulated cables, respectively.

A neon refrigeration process has been identified that uses turbo compressors and expanders and other equipment that is common to a standard nitrogen plant. The refrigeration station includes two refrigerators and possibly a spare compressor. One such station can serve a transmission distance of approximately 30 miles.

In the case of the vacuum insulated cable enclosure, one refrigerator of 925 kW capacity can meet the refrigeration load at 1800 MVA operation. The liquid nitrogen would enter the cable at 65 K and be discharged at 82 K.

Plant reliability estimates were made using data based upon operating experience at a 500-ton/day nitrogen plant that has been in service for 10 yr. On the basis that a failure is defined as the inability to transmit 1800 MVA, the MTBF has been estimated to be 14.2 yr with two identical refrigerators and exceeds 40 yr if a spare compressor is used.

The cost of the refrigeration station, constructed as a turnkey project, is estimated at \$15,700,000. A spare compressor will add approximately \$4,300,000.

ACKNOWLEDGMENT

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NOTATION

A_c = free cross-section area of cable
C_p = specific heat of liquid nitrogen
D = equivalent diameter of enclosure
f = friction factor
g = gravitational constant
I = electrical current
L = length
$\dot{m}$ = mass flow rate of liquid nitrogen
ΔP = pressure drop of liquid nitrogen

R = electrical resistance
ΔT = temperature rise of liquid nitrogen
T_1 = temperature of liquid nitrogen leaving cable
T_2 = temperature of liquid nitrogen entering cable
T_c = temperature of liquid nitrogen
T_h = temperature of ambient
q = heat load per mile
Q = total heat load
W = compressor power input
W/Q_{Carnot} = Carnot cycle ratio of compressor input power to refrigeration

Greek Symbols

ρ = density of liquid nitrogen
λ = failure rate
ξ = maintenance time

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DISCUSSION

Question by A. Patterson, Westinghouse Research and Development Center: If the liquid nitrogen recirculation time is two to three days, how can the stored liquid nitrogen energy be used for peak shaving purposes? The response time of the system appears to be much too slow.

Answer by author: The line can be designed and operated such that under normal conditions the refrigerator can be turned off for periods of 10 to 20 hr. The potential thus exists for turning off the refrigerator during peak load periods to save power. As the question implies, it typically takes more than a day for the liquid nitrogen to circulate through the line, thus the dynamics of using the thermal storage capacity of the line for peak shaving have to be carefully studied. This has not been done yet.

Question by R. W. Fast, Fermi National Accelerator Laboratory: What type of aluminum alloy was assumed and what was its resistivity ratio?

Answer by author: Reference [6] describes the aluminum as "an annealed polycrystalline sample with undetermined impurities." Resistivity ratio is 0.1008 at 77.7 K and 0.0075 at 20.4 K. These ratios are appreciably less than the values reported by Holborn in this reference for aluminum with 0.4% impurities.

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