

CRYOGENIC ELECTRICAL LEADS*

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INTRODUCTION

Recent developments in superconducting magnets and power transmission lines have prompted an interest in electrical leads to carry large currents into a liquid helium environment. These electrical leads allow an influx of heat to the low-temperature region both by conduction and by joule heating, causing evaporation of the cryogen. Accordingly, several attempts have been made to minimize this heat flux by adjusting the lead design and composition.¹⁻¹³ McFee¹ theoretically determined that an optimum length-to-area ratio exists for a thermally insulated lead - a short and heavy lead will conduct excessive heat, but a long and thin one will produce excessive joule heating. Mallon² presented design data for aluminum and sodium leads to supplement the data for copper given by McFee. Then Mercoureff³ discussed the expected efficiency of leads made of materials which deviated from the Wiedemann-Franz law relating thermal and electrical conductivities.[†]

The first experimental data on cryogenic electrical leads were published by Sobol and McNichol⁴ for small copper wires. They found that heat conduction from the copper wires to the surrounding helium gas greatly reduced the heat leak into the liquid helium. These results inspired Williams,⁵ Fournet and Mailfert,^{6,7} and Pippard⁸ to make further studies on the effects of heat exchange between the conductor and evaporated gas. The first large electrical leads (150 A) were constructed by Deiness,⁹ who further emphasized the importance of a large heat-exchange area between the conductor and effluent gas. Mathews et al.¹⁰ pointed out the advantage of attaching the superconductor to the submerged portions of the electrical lead, thereby eliminating a source of joule heating. Extending this idea, Keilin and Klimenko,¹¹ and Henning¹² experimentally demonstrated the advantage of soldering superconductor along the lower portion of the electrical leads. The current could then transfer to the superconductor below the critical temperature, further reducing joule heating. Finally, Efferson¹³ has presented design data on a very efficient lead which carried an optimum current of 1300 A.

The present trend clearly points to the development of larger electrical leads with increased efficiency. Full utilization of the refrigeration available in the effluent helium gas, a proper choice of conductor materials, and the attachment of superconductors to the lower portion of the leads should produce the greatest efficiency.

GAS-COOLED LEADS

Many, and sometimes conflicting, analyses have been made to determine the optimum dimensions and performance of gas-cooled leads. Often the solution was unduly complicated, and without exception the observed heat leak was many times higher than that predicted. Now sufficient experimental data are available (Table I) to substantiate

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†Thermal conductivity times electrical resistivity equals 2.45×10^{-8} times the absolute temperature ($W\Omega/^\circ K^2$).

clearly several conclusions. For each pair of leads, the helium loss from a Dewar was measured as a function of current. As shown in Fig. 1, the line drawn tangent to the data line C locates the point at which the least liquid helium is lost per ampere. Note that the optimum is very broad and that a current twice the optimum would not increase the loss unreasonably. Curves A and B in Fig. 1 demonstrate the advantage of increased gas flow. Both curves reflect the disadvantage of not having a superconductor attached to the lower portion. Whenever possible, all the effluent gas should be used to refrigerate the leads, and superconductors should be used when current is transported below the liquid level.

In Table I the liquid helium loss per kiloampere of optimum current was listed for two conditions: (1) with no current; and (2) with the optimum current in the leads. Note that the ratio of these two helium loss rates is near 0.6 on the average; Deiness⁹ analytically predicted a ratio of 0.5, which is quite close to the observed value. Also note that the helium loss rate is independent of the warm-end temperature, as predicted by Keilin and Klimenko.¹¹ Cooling the upper end of the leads with liquid nitrogen enables the leads to be shortened, but does not affect the resulting helium loss.

Very seldom is the helium loss rate of the least efficient gas-cooled lead more than twice that of the most efficient. However, in all cases the observed helium loss was several times that predicted by analysis. When the average surface heat flux given in Table I is plotted against the helium loss rate a definite trend is evident; the helium loss rate decreases with decreasing surface heat flux. Those leads which have the greatest surface area in contact with the effluent gas introduced the least heat into the liquid helium. The conclusion is that present leads are not sufficiently good heat exchangers. Further evidence was supplied by a quick experiment with aluminum foil. Five 18 in. wide, 48 in. long sheets of 0.001 in. thick aluminum foil were rolled up and pushed into a 1 in. stainless-steel tube. The cross-sectional area was 0.58 cm² which was enough to carry 1000 A. (Normally 0.4 cm² of copper will carry 1000 A, but aluminum has a slightly higher room-temperature resistivity.) The helium loss measured for the aluminum foil was 0.49 liter/hr·kA at zero current. By multiplying by two (for a pair of leads) and dividing by 0.6 (ratio of m₀/m), the predicted result in Fig. 2 was obtained, which is consistent with the general trend of decreasing helium loss with increasing conductor surface area.

In nearly every case, the Reynolds number for the effluent gas in a lead indicates laminar flow. As such, the Nusselt number for constant-wall heat flux does not vary with flow rate, and the mode of heat transfer from the conductor is pure conduction to the gas. Large surface areas in contact with the gas will improve the heat transfer process and the lead efficiency. Of course, mechanical mixing of the effluent gas by extended surfaces on the conductor will improve the heat transfer rate, as well.

Rather simple design equations can be obtained by interpreting the mathematical formulation of a gas-cooled electrical lead together with the experimental data in Table I. First, consider the mathematical formulation. As heat is conducted toward the liquid helium region, cold effluent gas abstracts some heat, depending upon the surface area, the local temperature difference, and the heat-transfer coefficient. It would be desirable to include the local heat-transfer rate in any analysis, but this would greatly complicate the solution. Keilin and Klimenko¹¹ included a parameter, β , in their analysis to crudely account for incomplete heat exchange. However, they then concluded that β was of minor importance.

For a lead of constant area A, the governing differential equation is written

$$\frac{d}{dx} \left(k \frac{dT}{dx} \right) - \frac{mc}{2A} \frac{dT}{dx} + \frac{I^2 \rho}{A} = 0$$

$$T = T_1 \text{ at } x = 0$$

$$T = T_h \text{ at } x = L \quad , \quad (1)$$

where T_h and T_l are the high and low temperatures; x is distance; I is electrical current; k , ρ , A , and L are the thermal conductivity, electrical resistivity, cross-sectional area, and total length of the lead, respectively; and c and m are the heat capacity and total mass flow rate of the effluent gas. As a first approximation, we can integrate each term in Eq. (1) between the high and low temperatures. However, the integral of the first term, representing conducted heat, is relatively small. Very little heat is conducted into the liquid helium at one end, and it has been shown¹² that for an optimum lead the temperature gradient is zero at the upper end, corresponding to zero heat conduction. Then the remaining terms (joule heating and heat carried away by the gas) are nearly equal over the integrated length of the lead. This conclusion is experimentally substantiated by comparing the values in Table I of the joule heating and available refrigeration:

$$I^2 L/A = \frac{m}{2} \int_{T_l}^{T_h} \frac{c}{\rho} dT \quad (2)$$

The above equation can be simplified by substituting an average resistivity $\bar{\rho}$, and taking the specific heat of helium gas c to be constant; also, the helium loss rate m varies directly with the current, so that the right side of the following equation should be constant for a given lead material and temperature difference:

$$I L/A = \frac{(m/I)}{2\bar{\rho}} c (T_h - T_l) \quad (3)$$

In view of the noncritical nature of the optimum current and the unpredictable efficiency of a new lead design, the above equation is adequate for calculating lead dimensions. The helium loss rate for the leads can be estimated from Table I, although the efficiency will increase somewhat when the effluent gas caused by other system losses is significant.

A typical design procedure would be to estimate the helium loss due to the leads by checking Table I. Add to this helium loss the other losses in the system to determine a total mass flow rate to be used in Eq. (3) along with the average resistivity of the lead material. Alternately, the ratios of the second-to-last column in Table I can be used to calculate the length-to-area ratio for the optimum current. This is possible only if the average resistivity is the same and the helium loss is largely due to the leads. Generally, an area of 0.4 cm²/kA of copper has been found to be adequate for leads around 3 to 4 ft long. The area needed for other materials may be adjusted according to their room-temperature resistivity.

Another interesting relationship can be derived from Eq. (3) for the voltage drop across a lead, which should be nearly constant for a given lead efficiency and temperature difference:

$$E = I \bar{\rho} \frac{L}{A} = \left(\frac{m}{2I} \right) c (T_h - T_l) \quad (4)$$

This constant voltage drop is closely approximated in Table I.

FUTURE DEVELOPMENTS

From the preceding discussion it is evident that the lead dimensions are easily calculated and are not particularly critical. Even a simple copper or nickel tube approaches the minimum helium loss rate of the most sophisticated lead. For a small experiment the most simple configuration may be best, but for large leads careful design is mandatory. Superconducting magnets are using leads of 6000 A capacity at present.¹⁴ In the future, superconducting power transmission lines may require even larger leads.¹⁵

Certainly these two applications alone are sufficient to inspire new efforts.

Possible areas for future exploration include the use of new materials of high electrical and low thermal conductivity. Also, increasing the conductor surface area exchanging heat with the effluent gas should be attempted; the aluminum foil leads discussed earlier may represent such an improvement. Keilin and Klimenko¹¹ predict a 50% reduction in the helium loss rate by attaching superconductor along the lower portion of the leads. This improvement was not fully realized experimentally,^{11,12} possibly because of the inefficiency of the leads. More efficient leads with greater heat-exchange area may use superconductors to greater advantage.

Another area to explore is off-optimum design. Systems with short duty cycles use less liquid helium if the leads are operated at more than the optimum current. When the operation time is quite short, transient effects may prove to be useful. Experimentally we observe that a pair of leads will require 5 to 30 min to reach equilibrium. It is possible to overload greatly a lead for a short time without damage or excessive helium loss, and that may be useful for special systems.

The advent of the gas-cooled electrical lead has reduced the liquid helium loss by a factor of thirty when transporting electrical current into a low-temperature environment. Future improvements should further reduce the helium loss, but probably not to the same degree.

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TABLE I. PERFORMANCE OF ELECTRICAL LEAD PAIRS

Optimum Current	Lead Description	Helium Loss No. Current m_0	(1 liters/hr-kA)*		Voltage Drop Pair (mV)	Joule Heating (watts)	Refrigeration Available*** $mc(T_h - T_1)$ (watts)	Avg. Surface Heat Flux (watts/cm ²)	I L/A (kA/cm)	Reference
			Optimum Current m	Ratio m_0/m						
1	#34 AWG copper wire, 25 cm long; LN precooling	1.9	3.3	0.58	-----	----	0.2	----	125 LN precooled	4
10	Helical Cu strip, 0.79 cm wide, 0.018 cm thick, lead length 23 cm	2.04	4.75	0.43	-----	----	2.9	----	----	5
150	High-purity Ni tubes, 22 cm long; 0.42 cm i.d., 0.56 cm o.d.	1.46	2.86	0.51	50	7.5	26	0.06	33 Ni tube	9
100	10 - #22 AWG Cu wires; length unknown	3.15	4.5	0.70	-----	----	27	----	----	11
200	1/4-in. o.d. phos-deox Cu tube, 0.030-in. wall, 55-in. long; superconductor attached and only half boil-off through leads	2.88	5.76	0.50	-----	----	70	0.19	210	12
200	Cu screen of 0.01-in. wire; 200 wires vertical and horizontal; 32-in. long; superconductor attached	2.3	3.25	0.70	195	39	40	0.05	162	Present
2000	Folded Cu sheet in sq. stn. steel tube; 0.01-in. thick, 12-in. wide, 48-in. long. Superconductor attached.	3.1	4.7	0.66	210	420	550	0.056	315	Present
500	1920 Cu wires, #38 gage and 60 cm long; superconductor attached	1.74	2.72	0.64	225	113	110	0.012	200	13
1300	5120 Cu wires, #38 gage and 60 cm long; superconductor attached	1.62	2.71	0.60	225	293	286	0.012	195	13

*The helium loss for insulated copper leads is 84 liters/hr-kA (McFee¹).

***The upper temperature T_h was greater than room temperature in several cases because the power cable heated the top of the lead.

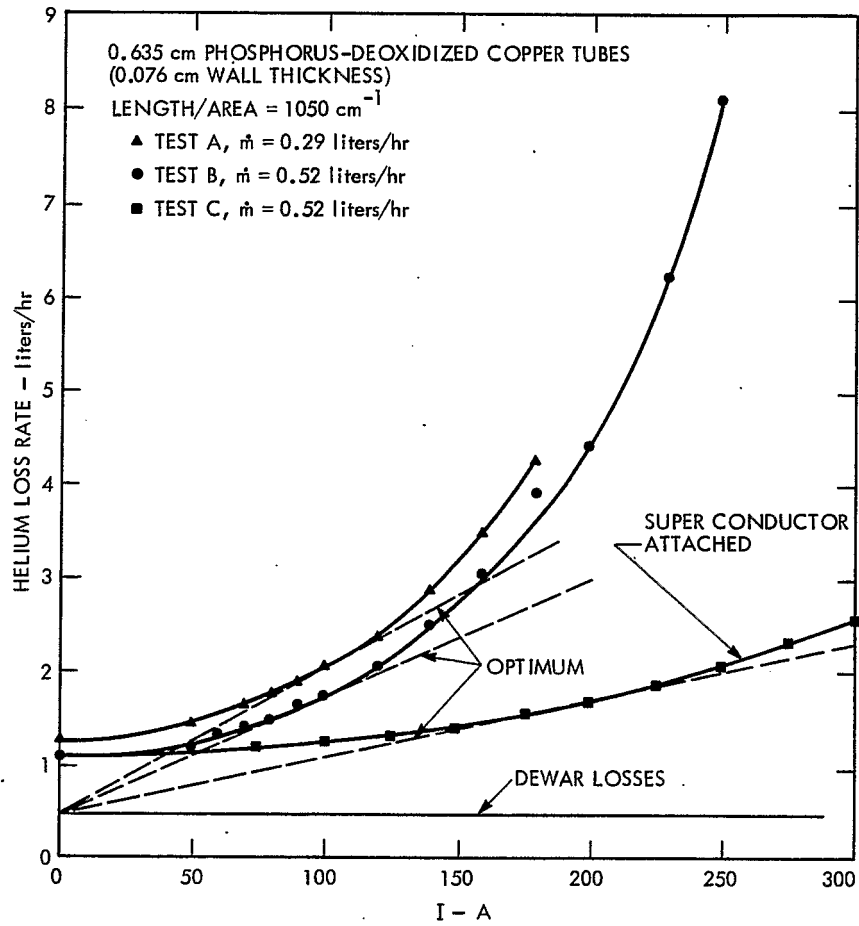


Fig. 1. Experimental determination of the optimum current for an electrical lead.

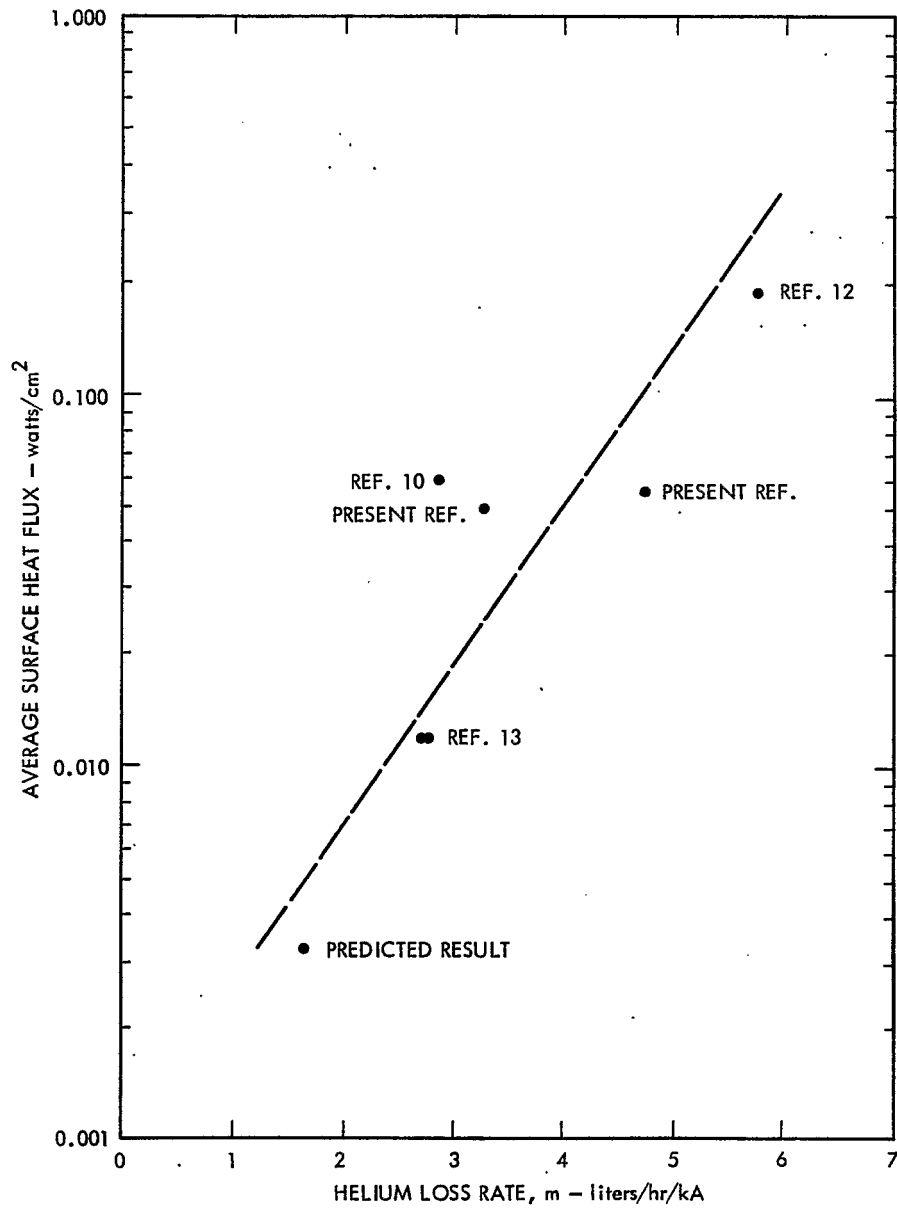


Fig. 2. Helium loss rate as a function of average surface heat flux.