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# GAS-COOLED COMPOUND POROUS CURRENT LEADS FOR CRYOGENIC CABLES

L. L. Vasil'ev, G. I. Bobrova,
L. A. Dragun, V. K. Sheleg,
and S. M. Azarov

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Studies have been made on porous current leads having a superconductor at the cold end. Estimates are made of the heat leak along the current lead in relation to the gas flow rate and current load.

Current leads are major components in cryogenic machines and cryogenic electrical transmission lines. There are many different designs for current leads for cryogenic machines, solenoids, and transmission lines handling currents from tens of amperes up to some kiloamperes. The leads in such a device work under conditions where one end (the warm one) is at room temperature and the other (the cold one) is at helium temperature, i.e., there is a temperature difference of about 300°K along the lead.

In designing such a lead one naturally has to provide not only the appropriate current carrying capacity but also the minimum heat leak to the cryogenic liquid in order to reduce the losses.

A current lead is a thermal bridge joining the warm zone to the cold one, and it also has a finite electrical resistance, which produces heat when current flows. To reduce the heat leak along the lead considered as a bridge transmitting heat by conduction, it must be made of material with the minimum thermal conductivity and be thin and long. On the other hand, to reduce the heat leak for a lead considered as a current carrier that produces heat when a current flows, it must be made of a material with a minimum electrical resistance, i.e., of a mterial having a fairly high thermal conductivity and fairly large cross section.

Therefore, the lead is subject to conflicting requirements in meeting the same purpose of providing the minimum heat leak to the helium zone. Therefore, there exists an optimum design providing the minimum leak on the basis of the heat production in the lead when a current flows and the heat leak along the material due to thermal conduction.

It has been pointed out in [1] that the minimum heat leak is also an important condition for reliable operation of cryogenic equipment. To ensure stable operation, one sometimes deliberately increases the helium flow rate above the calculated value.

It is desirable to cool the current leads to minimize the heat leak, and to make this cooling as effective as possible the heat transfer must be organized in such a way as to approximate to ideal, i.e., the temperatures of the cooling gas and lead should be equal in a given section. We therefore have to consider how to provide such conditions. It has been suggested that the surface area flushed by the gas should be increased by forming ribs on the lead and using porous metals, or else perforated metal sheets, metal grids, or sets of metal sheaths, or else to design compound leads, in which a superconductor is used to eliminate the heat production when the current flows at the cold end [2-9].

In most optimized leads, the minimum heat leak into the cold zone is 1 mW/A [10]. The calculation showed that use of a superconductor in a lead should roughly halve the leak into the cold zone, but the experimental results in the literature are very conflicting.

We have attempted to minimize both components of the heat leak along the lead. The first is due to thermal conduction and is reduced by using a material with a low thermal conductivity, while the second, which is due to the current, is reduced by using a superconductor, and that without a copper matrix. Calculations show that the leak along the lead can

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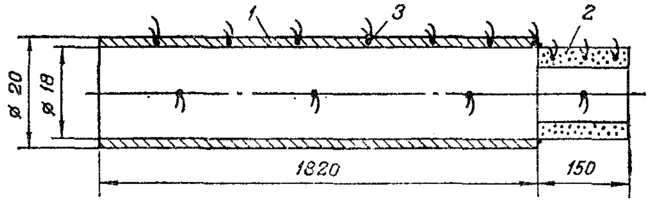

Fig. 1. Scheme for lead: 1) brass tube; 2) porous bronze insert; 3) thermocouples.

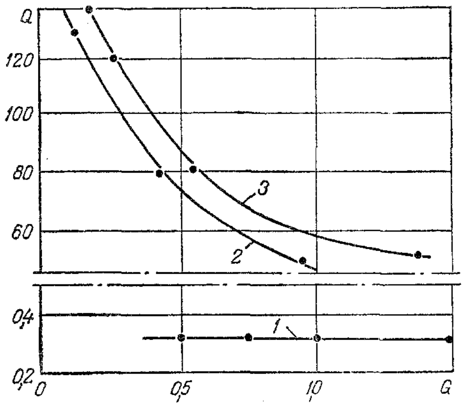

Fig. 2. Dependence of the heat leak on the coolant flow rate for three forms of lead: 1) made of a brass tube having a porous bronze insert; 2) copper tube containing a porous copper ring at the end; 3) copper tube; Q in mW and G in g/sec.

be minimized if one provides the maximum possible heat-transfer coefficient in the cold part of the lead. This conclusion was incorporated into the design.

One way of increasing the heat-transfer coefficient is to use a porous material, which increases the coefficient, as is evident from previous studies [11, 12]. The following arguments were used in designing a lead with minimum leak.

Current passing through the lead produces heat

$$\Delta Q = \rho i^2 \Delta l / s,$$

where $\rho = \rho(T)$, and in addition there is a heat leak along the lead due to thermal conduction

$$\Delta Q = \lambda \Delta T s / \Delta l,$$

where $\lambda = \lambda(T)$.

To provide the minimum heat leak into the cold zone, the material should have the minimum resistivity and minimum thermal conductivity at 10-15°K, i.e., at the working temperatures in the region of the junction between the current lead and the cable. A material of minimum resistivity is electrolytic copper, but its thermal conductivity is high at 1300 W/m·deg at 15°K [13].

Phosphor bronze has a low thermal conductivity; measurements were made on the thermal conductivities of specimens sintered from bronze powder. The value for the 100-300-μm fraction was 1.2 W/m·deg.

If it were possible to reduce the resistance of the current-carrying components made of a material based on porous bronze, then a lead containing such components would provide a low heat leak into the cold zone. The superconductor $Nb_3Sn$ was sealed into the porous specimens, this being made by diffusion of niobium and tin during sintering. The literature has several papers dealing with cermet superconductors made from fine niobium and tin powders [14, 15]. These experiments gave positive results.

The current lead was made as a brass tube of length 1820 mm, diameter 20 mm, and wall thickness 1 mm. At the cold end, the porous bronze ring insert was soldered to it, which had the superconductor sealed into the wall. The dimensions were length 150 mm, outside diameter 17 mm, and wall thickness 3.5 mm.

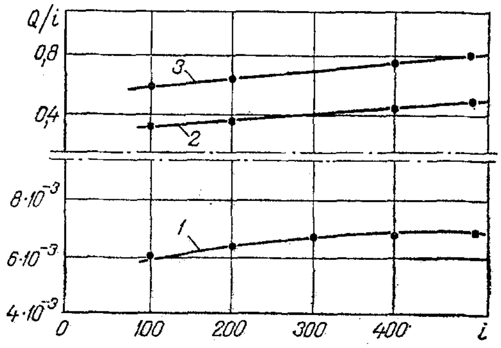

Fig. 3. Current dependence of the heat leak for the following leads: 1) brass tube containing porous bronze insert; 2) copper tube containing porous copper insert; 3) copper tube; Q/i in mW/A and i in A.

The brass tube was in direct contact with the superconductor in the bronze ring insert, so the current flowed through the tube and the superconductor. The bronze matrix had a low thermal conductivity and acted as a thermally insulating sleeve, which minimized the first component of the heat leak, while the superconductor reduced the second component. Therefore, the heat leak was small. The measurements were made on a laboratory model for the superconducting cable which was simliar to that described in [16]. Figure 1 shows the scheme for the lead.

The heat leak was determined at zero current load. For comparison, we estimated the leakage for two leads. One was made in the form of a copper tube of the same dimensions as the brass lead. The second consisted of a copper tube having a porous copper ring at the cold end sintered from copper powder and fitted onto the wall of the superconductor. The dimensions of the second were as in the above current lead. Figure 2 shows the results.

Increasing the helium flow rate had virtually no effect on the leak through the brass lead with the porous insert, whereas the effect was substantial for the copper lead. Also, the leak itself was less by two orders of magnitude than that for the copper lead. As the porous insert made it possible to produce axial and radial helium flows, one can regulate the heat leak by adjusting the cooling conditions by redistributing the flow either in the radial direction or the axial one for a given helium flow rate at the inlet to the lead [12], which is particularly important for a lead designed for a current of tens of kiloamperes.

It should be noted particularly that a condition for reliable operation of such a lead is that the porous insert should have a working temperature throughout its length less than the critical temperature of the superconductor. Therefore, during the experiments we selected a length of 150 mm as being the optimum one.

Figure 3 shows estimates of the leak in relation to the current for the brass lead with a bronze insert. The parameters were as follows: helium flow rate at the inlet in the range 0.1-1.5 g/sec, helium pressure 1.1-1.05 atm, helium temperature at the inlet 8-10°K, thermal conductivity of the sintered bronze insert 1.2 W/m·deg in the range 5-15°K, cross section of brass in lead 60 mm², and currents in the range from 0 to 650 A.

With or without a current load, the leak along the lead with the bronze insert was less by two orders of magnitude than that in the copper lead. The value was estimated as

$$\Delta Q = \lambda_{\text{ins}} \Delta T s_{\text{ins}} / \Delta l_{\text{ins}}.$$

The temperature differences along the insert were measured with copper—copper/iron thermocouples, which were inserted in the wall at intervals of 50 mm. The cross section of the insert was 70 mm² with allowance for the porosity.

It should be emphasized particularly that the use of porous copper inserts containing a superconductor did not give a useful result. Although the thermal conductivity of the sintered porous copper was much less than that of the monolithic material, it still was quite high, and the component of the heat leak through the sintered insert due to conduction was large, as is evident from Fig. 3, i.e., the only suitable material for the porous inserts that has been tested and has given low leakage is bronze powder.

The leak via porous copper containing a superconductor was virtually the same as for compound leads in which the copper tube is soldered to a superconductor in the form of a sheath, i.e., wires in a copper matrix.

## NOTATION

Q, heat flux; i, current; $l$, length; s, cross section; $\rho = \rho(T)$, resistivity; T, temperature; $\lambda$, thermal conductivity.

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