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LIQUID HELIUM BOIL-OFF MEASUREMENTS OF HEAT LEAKAGE FROM SINTER-FORGED BSCCO CURRENT LEADS UNDER DC AND AC CONDITIONS

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DISCLAIMER

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ABSTRACT

Liquid helium boil-off experiments are conducted to determine the heat leakage rate of a pair of BSCCO 2223 high-temperature superconductor current leads made by sinter forging. The experiments are carried out in both DC and AC conditions and with and without an intermediate heat intercept. The current ranges are from 0-500 A for DC tests and 0-1,000 A_{rms} for AC tests. The leads are self-cooled. The results show that magnetic hysteresis (AC) losses for both the BSCCO leads and the low-temperature superconductor current jumper are small for the current range covered in the present experiments. It is demonstrated that significant reduction in heat leakage rate (liquid helium boil-off rate) is realized by using the BSCCO superconductor leads. At 100 A, the heat leakage rate of the BSCCO/copper binary lead is approximately 29% of that of the conventional copper lead. Further reduction in liquid helium boil-off rate can be achieved by using

an intermediate heat intercept. For example, At 500 A, the heat leakage rate of the BSCCO/copper binary lead is only 7% of that of the conventional copper lead when an intermediate heat intercept is employed.

INTRODUCTION

Recent experiments have demonstrated that high-temperature superconductor current leads significantly reduces liquid helium boil-off rate compared to conventional copper leads.[1-3] The reduction in liquid helium boil-off rate is the results of both the relatively low thermal conductivity and the extremely low resistive heating of the ceramic superconductors at currents below the critical current. Further reduction in liquid helium boil-off rate can be achieved by employing intermediate heat intercept at the junction of the upper stage conventional copper lead and the lower stage high-temperature superconductor lead at temperatures below the critical temperature. High-temperature superconductor current leads can be used both in DC (superconducting magnets) and in AC (fault-current limiter) applications. Under AC condition, additional dissipation due to magnetic hysteresis is also present.

In this paper, we describe the results of two separate experiments on liquid helium boil-off rate under DC and AC conditions for BSCCO 2223 current leads fabricated by sinter forging. The test sample were a pair of BSCCO 2223 bars. Detailed description of powder synthesis and the processes for forming the superconductor bars can be found in reference 4. Recent experiments show that the DC critical current densities of these leads are between 950-1300 A/cm^2 at 77 K and >5000 A/cm^2 at 4 K.[4] The experiments reported here are carried out at two different facilities at Argonne National Laboratory (ANL) and Tokyo Electric Power Company (TEPCO). Table 1 shows the parameters and the conditions under which these two experiments are conducted. The experiments at ANL are at relatively low currents (≤260 A) and that at TEPCO are at higher currents (up to 1,000 A). The major difference between the tests conducted at these two facilities is that an intermediate heat intercept is used at the TEPCO facility while intermediate heat intercept is not employed in the ANL tests even though such capability is available.

EXPERIMENTAL APPARATUS

Figure 1 shows a schematic of the liquid helium dewar at ANL. The dewar consists of an inner liquid-helium reservoir within an outer liquid-helium reservoir that is thermally shielded from the room-temperature environment by multiple insulation layers in a vacuum environment and a liquid nitrogen reservoir. A cryocooler is also shown in Fig. 1 for intercepting the heat conducting down the copper leads. However, it is not used in the present experiments. Detailed description of the characteristics of this dewar and its performance can be found elsewhere.[2,5] The instrumentation system includes temperature, pressure, voltage drop, vapor mass flow, and liquid level measurements. Three silicon diodes are employed to measure temperature distribution along one of the high-temperature superconductor leads as shown in Fig. 1. Two relatively large copper plates were employed as thermal shorts between the cold end of the high-temperature superconductor leads and the low-temperature superconductor jumper. The thermal shorts provide large heat transfer area and serve to reduce the contact resistances and to maintain the temperature at the cold end of the high-temperature superconductor leads at approximately 4.2 K. Two voltages were soldered to the copper thermal shorts as shown in Fig. 1. All the data are fed to a computer for online monitoring and for recording.

Figure 2 shows a schematic of the liquid helium dewar at TEPCO. It also consists of two liquid helium reservoirs within a liquid nitrogen reservoir. In addition, the facility at TEPCO has an external liquid helium dewar which provides helium vapor to cool the upper stage copper leads and serves as heat intercepts at the junctions of the copper leads and the high-temperature superconductor leads. The temperatures at the junctions can be controlled by adjusting the vapor mass flow from the external liquid helium dewar. The mass flow from helium boil-off in the test dewar and that from the external dewar are measured separately as shown in Fig. 2. Locations of temperature sensors and voltage taps are also shown in Fig. 2. There were four BSCCO bars per lead employed for the TEPCO experiments.

EXPERIMENTAL RESULTS AT ANL

Figure 3 shows the variation of the total heat leakage rate with current (DC and AC). At low currents (<50 A), the total heat leakage rate is about the same (within experimental error) between DC and AC tests. This is because the hysteresis (AC) losses in the superconductors are small at these low currents. At 100 A or A_{rms}, the difference in boil-off rate between DC and AC tests is small but measurable as shown in Fig. 3. The difference in total heat leakage rate between AC and DC tests at a current of 100 A or A_{rms} is approximately 10 mW. The total heat leakage rate increases with AC current, however, the relationship is not linear as shown in Fig. 3. The total heat leakage rate includes all the heat that crosses the liquid helium boundary in the inner helium reservoir plus any heat sources which are submerged in the liquid helium. The former includes conductive (through current leads and vessel walls), convective (between vapor space above the liquid and the liquid helium), and radiative heat transfer between the liquid helium and the surrounding environment. The latter includes dissipation caused by any contact resistances (soldered joints) between a short copper transition piece and the low-temperature superconductor current jumper, Joule heating in the copper piece, and AC (magnetic hysteresis) loss in the low-temperature superconductor current jumper. In the present experiments, two relatively short copper plates with fairly large surface area were used as transition between the high-temperature superconductor current leads and the low-temperature superconductor current jumper. Because of the large surface area of the copper plates and the relatively low current, dissipations due to contact resistance and Joule heating, are probably negligible compared to other forms of heat leakage into the liquid helium. The losses due to magnetic hysteresis of the low-temperature superconductor current jumper are also small at these low currents. For example, the voltage drop across the thermal shorts is approximately 30 μV at a current of 100 A_{rms}. At this current, the combined heating rate due to contact resistances, Joule heating, and magnetic hysteresis of the low-temperature superconductor is less than 3 mW. In any case, at these low currents the total heat leakage is small (the total heat leakage is less than 0.20 W at a current of 260 A_{rms}). Experiments were conducted to determine the heat leakage rate without the presence of the current leads. The heat leakage rate obtained in this manner is referred to as the background heat leakage rate. Subtracting the background heat leakage rate from the total heat leakage rate gives the heat leakage rate through the high-temperature superconductor current leads only and the results are shown in Fig. 4. At low currents, the background heat leakage rate is a significant portion of the total heat leakage rate. As the current increases, the heat conducted down the leads increases correspondingly and the background heat leakage rate becomes only a small fraction of the total heat leakage rate. The temperature distribution along one of the superconductor lead is shown in Fig. 5.

The heat leakage rate shown in Figs. 3 and 4 is calculated from the measured vapor mass flow rate by using the following equation

$$Q = h_{fg}(dm/dt) / (1 - \rho_g/\rho_f) \qquad (1)$$

where Q is the heat leakage rate, h_{fg} is the latent of vaporization, dm/dt is the measured vapor mass flow rate, and ρ_g and ρ_f are the vapor and liquid density of helium; respectively. Derivation of equation (1) and discussions of its significance for liquid helium boil-off experiments are given in references 5 and 6.

EXPERIMENTAL RESULTS AT TEPCO

Figure 6 shows the variation of total heat leakage (calculated from the measured helium boil-off rate) with current for DC and AC tests. The total heat leakage data is also shown in Tables 2 and 3, together with the heating rate generated by contact resistances (soldered joints) calculated from the measured voltage drop between the lower ends of the two BSCCO leads (the locations of the voltage taps are shown in Fig. 2). The total heat leakage rate consists mainly the heat conducted down the leads and the heat generated by the heat sources in the liquid helium. Table 3 indicates that at a current of 978 A_{rms}, the heating rate calculated from the measured voltage drop is equal or greater than the total heat leakage rate, which means that the entire boil-off comes from the heat sources in the liquid helium. In other words, very little heat is conducted down the current leads. This observation is consistent with the temperature distribution along one of the BSCCO lead shown in Fig. 7. At a current of 978 A_{rms}, Fig. 7 shows that the temperature gradient at the lower end of the BSCCO bar is very small, indicating very little heat reaches the liquid helium by conduction (estimated to be less than 10 mW based on the measured temperature gradient at the lower end of the BSCCO bar). Figure 7 also shows that at the same vertical location, the temperature is lower when the current is higher. This can only occur if there are more vapor cooling at higher current. The additional vapor flow obviously comes from the heat sources in the liquid helium. The heat sources in the liquid helium include the contact losses and the AC losses of the low-temperature superconductors. The AC losses of the low-temperature superconductors are relatively small at these currents. For example, at a current of 1000 A_{rms}, the AC losses are estimated to be approximately 20 mW, which is only a small fraction of the total heat leakage rate of 517 mW. The DC critical currents (determined from separate measurements of individual short samples) of the low-temperature superconductors and the BSCCO bars are not exceeded in the present tests. Therefore, a majority of the heat must come from the contact resistances of the soldered joints. If both the low-temperature superconductors and the BSCCO bars are in their superconducting states over their entire length, the contact resistances of the soldered joints should not change with current. This is clearly shown in Table 2, where the contact resistance is approximately constant (0.09 $\mu\Omega$) for all the DC tests. Also, the contact resistances should be the same for the DC and AC tests, provided that the superconductors are in their superconducting states. Based on the contact resistance measured from the DC tests, we can calculate the heating rate generated by the contact resistance for the AC tests and the results are shown in the last column of Table 3. Comparing the values in the last two columns of Table 3 shows that there is a large difference between the heating rate due to contact resistance determined directly from the measured voltage drop and that inferred from the DC contact resistance. This large difference indicates that the contact resistance of the AC tests has drastically changed from its DC value. The reason for this change is not clearly understood at present. One possibility is that, even though the bulk of the BSCCO bars and the low-temperature superconductors are in their superconducting states, critical currents near the soldered joints between the BSCCO bars and the low-temperature superconductors might have been exceeded as a result of current redistribution locally. A closer examination of the test setup indicates that there is a transition between the lower ends of the BSCCO leads and the low-temperature superconductor current jumper. The transition is made of small diameter (0.5 mm) low-temperature superconductor wires. There are a total of 32 transition wires (four for each BSCCO bar). There are two types of soldered joints. One type of the soldered joints is at the junction of a BSCCO bar and the low-temperature superconductor wires. The other type of soldered joints is at the junction between the low-temperature superconductor transition wires and the low-temperature superconductor current jumper. At the junction of the BSCCO bar and the transition wires, there are four small diameter (0.5 mm) low-temperature superconductor wires attached to one BSCCO bar. The cross-sectional area of a BSCCO bar is approximately 5.0 mm^2 while that of the four wires is only 1.6 mm^2. Since there is about a factor of 3 reduction in cross-sectional area, there must be current redistribution in the BSCCO bar before it is transferred to the low-temperature superconductor wires. This current redistribution could cause the current density to increase by a factor of 3 locally and hence exceeded the DC critical current density of the BSCCO bar. The result would be a large increase in contact resistance. At the junction between the transition wires and the low-temperature superconductor current jumper, there are eight groups of wires (each group has four transition wires) soldered to the low-temperature superconductor current jumper. The current distribution in the low-temperature superconductor current jumper immediately adjacent to the soldered joint might not be uniform and local current density could exceed the DC critical current density of the superconductor. For example, the DC critical current of the low-temperature superconductor current jumper is 1600 A which is equivalent to 1131 A_{rms}. For the AC test with a current of 978 Arms, a 20 % increase in local current could cause the superconductor to become dissipative. This conjectured increase in contact resistance can be avoided by redesigning the soldered joints.

Figure 8 shows the comparison of the total heat leakage rate between the tests conducted at ANL and TEPCO. Even though the two experiments were carried out at different current ranges, it clearly demonstrate the advantage of using a intermediate heat intercept because the slope for the ANL data is steeper than that of the TEPCO data, which means that boil-off is less if a heat intercept is employed. The previous comparison may not be fair because either an additional liquid helium (or nitrogen) source or a cryocooler is required in order to intercept the heat conducted down the upper stage copper leads. However, in most applications, liquid helium or nitrogen are readily available. In certain applications, a cold shield maintained by a cryocooler or cryo-refrigerator is present in the device (such as a micro-SMES with a 60 K cold boundary). Under these circumstances, it is worthwhile to tap into the existing heat sink and provide a heat intercept at the copper/superconductor junctions.

Finally, we can compare the total heat leakage rate obtained in the present experiments with that of conventional copper lead. Only comparison under DC condition will be made here. The data in Fig. 3 (for two leads) shows that at a current of 100 A, the total heat leakage rate for the BSCCO lead is 29 mW per lead. The heat leakage rate for copper lead at 100 A is approximately 100 mW. Thus, without using a intermediate heat intercept, the heat leakage rate of the BSCCO lead is 29% of that of the conventional copper lead. The data in Fig. 6 (for two leads) shows that at a current of 500 A, the total heat leakage rate for the BSCCO lead is 34 mW per lead. The corresponding heat leakage rate for a copper lead is 500 mW. Thus, by using an intermediate heat intercept, the heat leakage rate for BSCCO lead is only about 7% of that of the copper lead.

SUMMARY AND CONCLUSIONS

Liquid helium boil-off experiments were conducted to determine the heat leakage rate of BSCCO 2223 high-temperature superconductor current leads made by sinter forging. The experiments were carried out under both DC (0-500 A) and AC (0-1,000 A_{rms}) conditions and at two different experimental facilities, one at ANL and the other at TEPCO. The main features of the ANL and the TEPCO tests and their differences are summarized in Table 1. The results show that at low currents (<100 A), the differences in heat leakage rate between DC and AC tests are small. The difference increases as the current is increased well above 100 A. The experimental results demonstrate that significant reduction in heat leakage rate (liquid helium boil-off rate) can be achieved by using an intermediate heat intercept at the junctions between the upper stage copper leads and the lower stage superconductor leads. Without the intermediate heat intercept, the heat leakage rate of the BSCCO/copper binary current lead is approximately 29% of that of the conventional copper lead. With the intermediate heat intercept, the heat leakage rate of the BSCCO/copper binary lead is only about 7% of that of the conventional copper lead. In the TEPCO experiments, it was determined that most of the helium boil-off is due to the heat generated by the contact resistance at the soldered joints between the BSCCO bars and the low-temperature superconductors (used as current jumper in the experiments) for the AC tests, although it is not clear what causes the contact resistance to increase. The magnetic hysteresis (AC) losses of both the BSCCO leads and the low-temperature superconductor current jumper are small compared to the heat generated by contact resistance in the AC tests of TEPCO experiments.

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Table 1. Parameters and conditions for the liquid helium boiloff experiments conducted at ANL and TEPCO.

	ANL	TEPCO
DC test	0-100 A	0-500 A
AC test	0-260 A_{rms} f = 60 Hz	0-978 A_{rms} f = 50 Hz
Cooling	Self-cooled	Self-cooled
Heat intercept	No	Yes
No. of BSCCO bars per lead	1	4
Sinter-forged BSCCO bars		
Cross-sectional area	0.48 cm^2	0.50 cm^2
Length	18 cm	25 cm

Table 2. Measured total heat leakage rate and heating rate due to contact resistance for DC tests.

Current (A)	Total heat leakage rate (mW)	Heating rate due to contact resistance* (mW)
0	52	0
350	62	11
499	68	22

*The contact resistance determined from voltage drop measurements is approximately 0.09 μΩ.

Table 3. Measured total heat leakage rate and heating rate due to contact resistance for the AC tests.

Current (A)	Total heat leakage rate (mW)	Heating rate due to contact resistance (mW)	Heating rate due to contact resistance* (mW)
0	52	0	0
507	181	146	23
978	517	616	86

Figure Captions

Figure 1. A schematic of the liquid helium boil-off experimental apparatus at ANL.

Figure 2. A schematic of the liquid helium boil-off experimental apparatus at TEPCO.

Figure 3. Variation of total heat leakage rate with current for tests conducted at ANL.

Figure 4. Variation of heat leakage rate through the BSCCO superconductor leads with current for tests conducted at ANL.

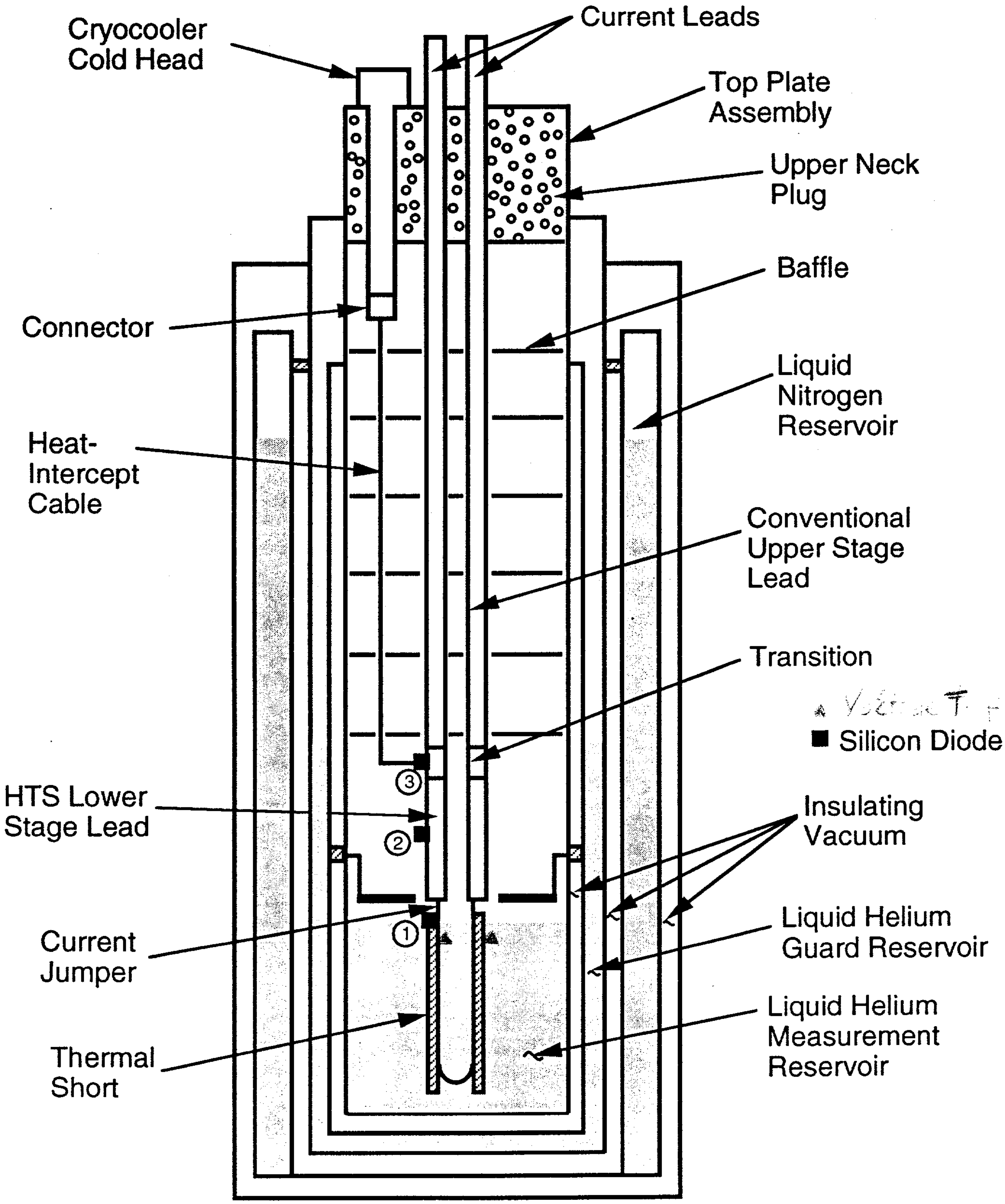
Figure 5. Variation of temperature along the BSCCO superconductor lead (measured by silicon diodes) with current (AC) for tests conducted at ANL.

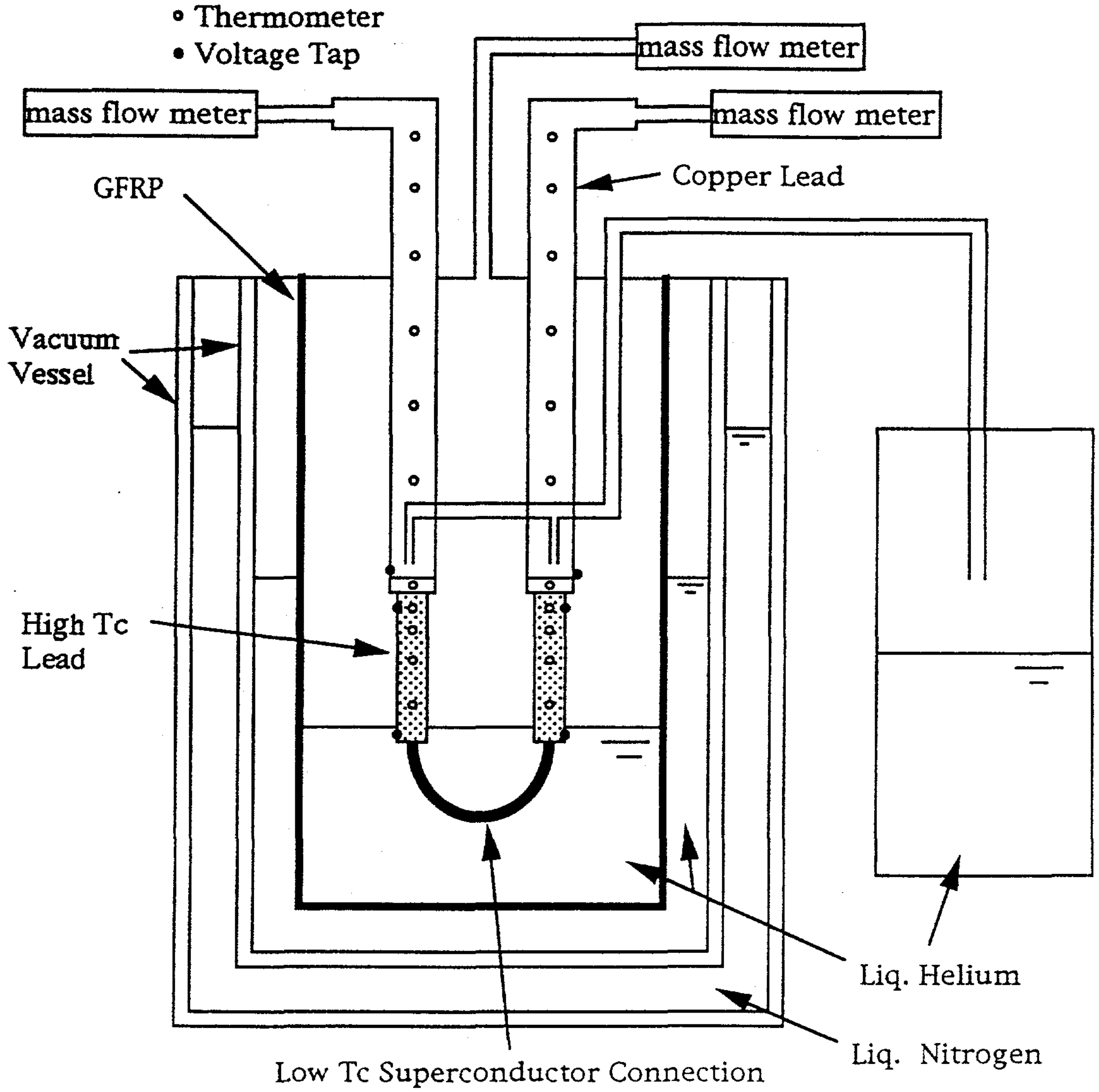
Figure 6. Variation of total heat leakage rate with current for tests conducted at TEPCO.

Figure 7. Variation of temperature along the length of the BSCCO superconductor lead for tests conducted at TEPCO.

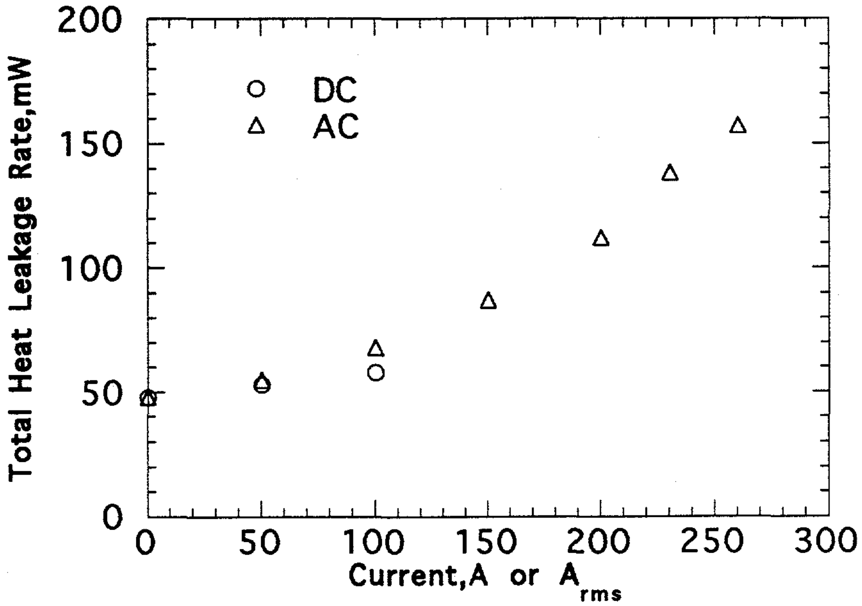
Figure 8. Comparison of total heat leakage rate at different currents between tests conducted at ANL and TEPCO. (a) DC tests; (b) AC tests.

Measurement Dewar Schematic

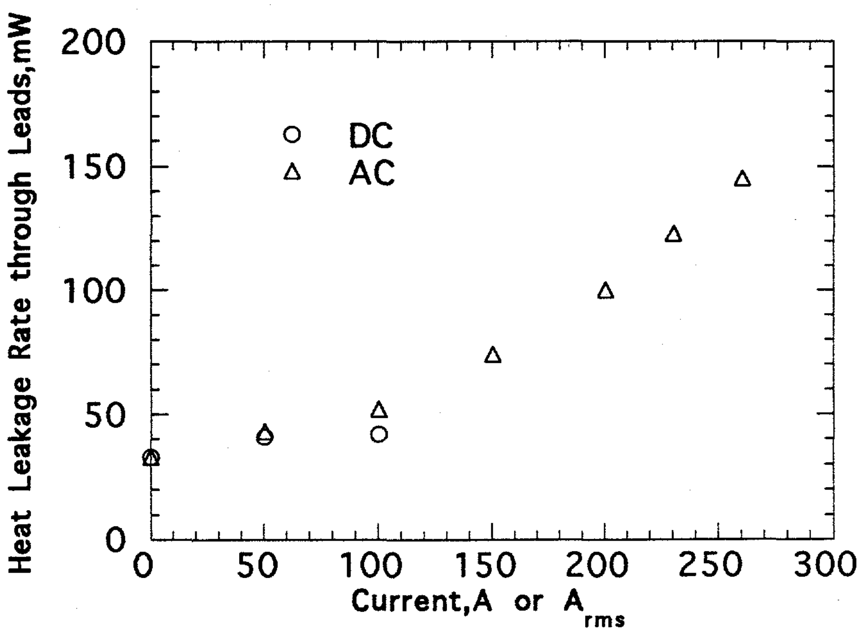




Testing Apparatus for Heat Leakage of Hifh Tc Leads



Total Heat Leakage Rate,mW
200
150
100
50
0
DC
AC
0
50
100
150
200
250
300
Current,A or A
rms


Heat Leakage Rate through Leads,mW
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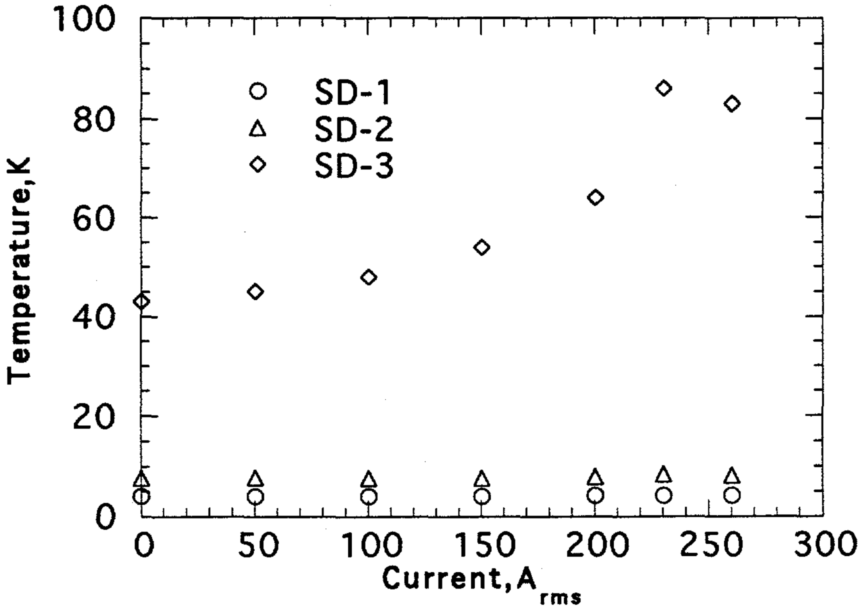
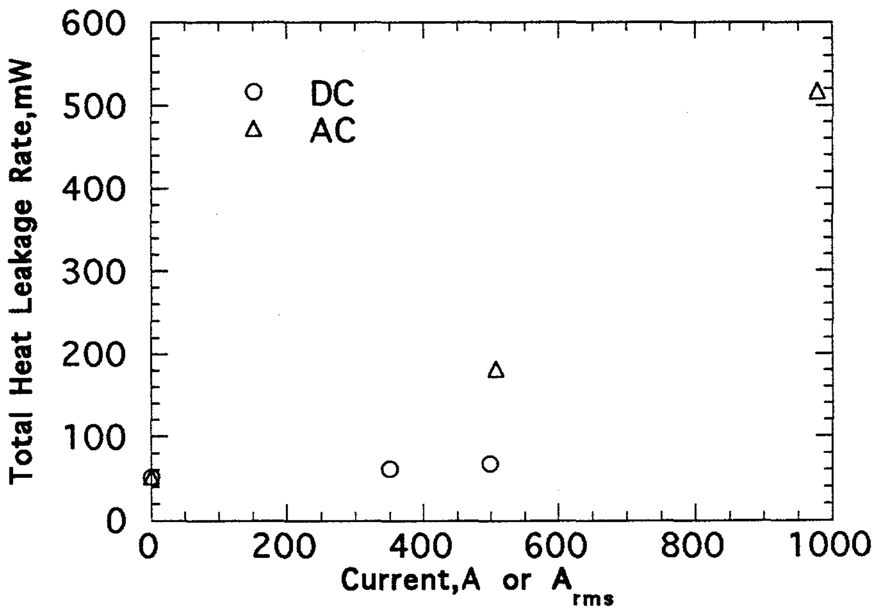
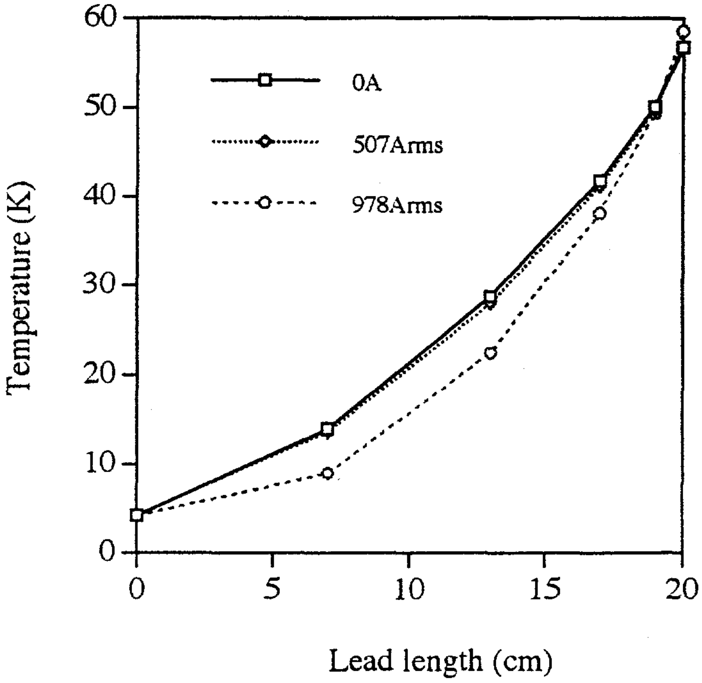
150
100
50
0
DC
AC
0
50
100
150
200
250
300
Current,A or A_{rms}

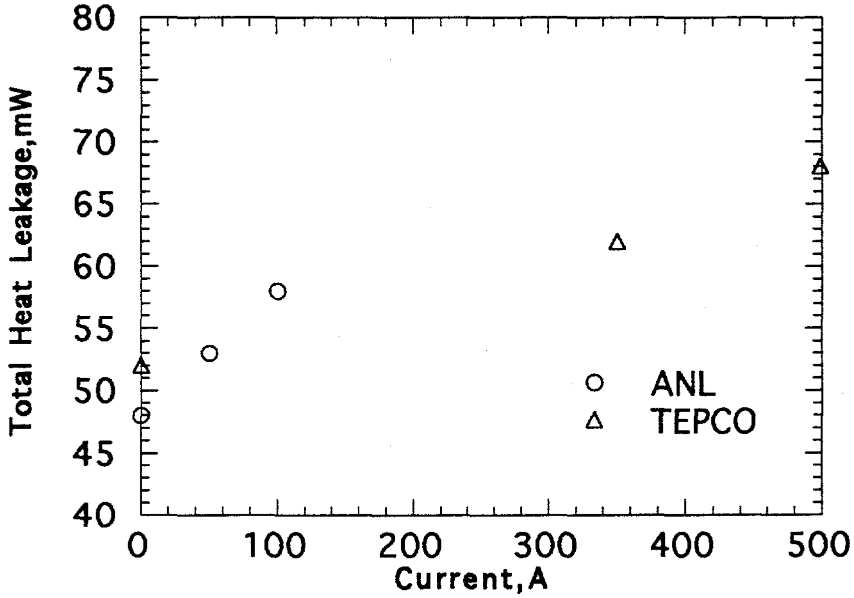


100
80
60
40
20
0
Temperature,K
SD-1
SD-2
SD-3
0
50
100
150
200
250
300
Current,A rms

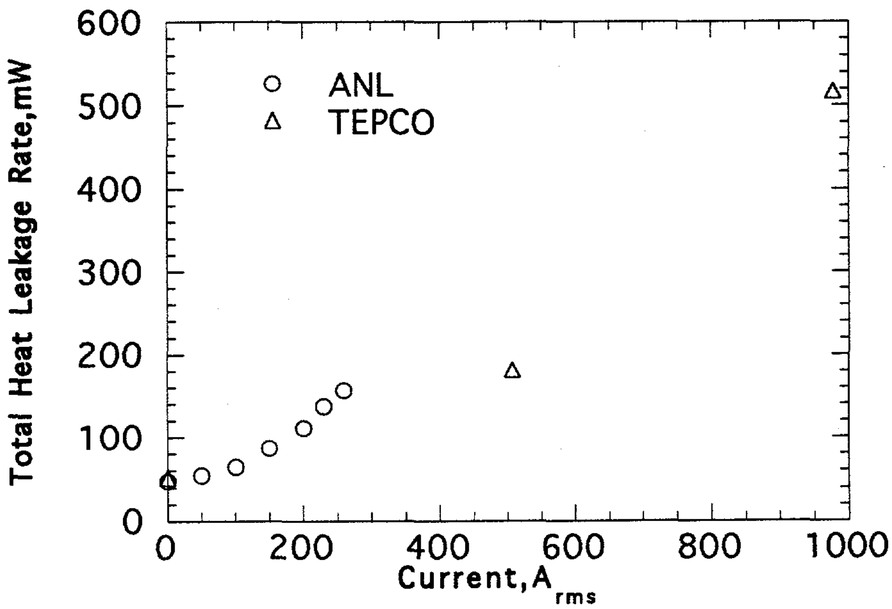

600
500
400
300
200
100
0
DC
AC
0
200
400
600
800
1000
Total Heat Leakage Rate,mW
Current,A or A rms

Temp. distribution
(A.C. 0A,507Arms,978Arms)




80
75
70
65
60
55
50
45
40
Total Heat Leakage,mW
0
100
200
300
400
500
Current,A
ANL
TEPCO

8a



600
500
400
300
200
100
0
Total Heat Leakage Rate,mW
ANL
TEPCO
0
200
400
600
800
1000
Current,A rms

8b