DESIGN AND PRODUCTION OF EFFICIENT CURRENT LEADS FOR 1500-A, 50-Hz SERVICE IN A 77-4 K TEMPERATURE GRADIENT*

U. Balachandran, C. A. Youngdahl, M. T. Lanagan, S. E. Dorris, J. J. Picciolo,
J. Cluff, T. Brent, M. Marinelli, B. Fisher, P. Winandy, J. Wenzlaff,
T. Askew, R. Niemann, and R. B. Poeppel
Energy Technology Division
Argonne National Laboratory
Argonne, IL 60439 USA

M. Nakade and T. Hara
Tokyo Electric Power Company
Tokyo 182, Japan

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Design and Production of Efficient Current Leads for 1500-A, 50–Hz Service in a 77-4 K Temperature Gradient

U. BALACHANDRAN,[1] C. A. YOUNGDAHL,[1] M. T. LANAGAN,[1] S. E. DORRIS,[1] J. J. PICCIOLO,[1] J. CLUFF,[1] T. BRENT,[1] M. MARINELLI,[1] B. FISHER,[1] P. WINANDY,[1] J. WENZLAFF,[1] T. ASKEW,[1] R. NIEMANN,[1] R. B. POEPPEL,[1] M. NAKADE,[2] and T. HARA[2]

[1]Energy Technology Division, Argonne National Laboratory, Argonne, IL 60439, USA
[2]Tokyo Electric Power Company, Tokyo 182, Japan

ABSTRACT

Two arrays of BSCCO 2223 bars were designed and produced for use in current leads for a power utility fault-current limiter operating at 4 K. Each conduction-cooled array, consisting of four parallel bars arranged within a 100-mm-diameter boundary, delivered 1500 A peak, 50–Hz AC through a 77-4 K temperature gradient while dissipating <0.2 W. The sinter-forged bars displayed DC critical current densities of 950-1300 A/cm^2 at 77 K and >5000 A/cm^2 at 4 K. Magnetic field sensitivity was relatively low. Thermal conductivity tests showed values higher than literature values for polycrystalline BSCCO 2223 made by other processes.

KEYWORDS: Superconductor, bismuth, current lead, downlink, alternating current

INTRODUCTION

Electrical downlinks (current leads designed for operation in a cryogenic temperature gradient) that incorporate high temperature superconductors (HTS) are being designed and constructed to serve fault-current limiter (FCL) and magnetic energy storage devices that operate in liquid helium. The HTS thermal conductivity is comparatively low, and Joule heating by 50-60 Hz alternating current (AC) at an intensity below the direct current (DC) critical range is low relative to that of alternative metallic conductors [1,2]. The goal of the work described here was to develop and produce two conduction-cooled HTS bar arrays each 100 mm in diameter and capable of transporting 1500-A peak AC at 50 Hz through a 77-4 K temperature gradient with <0.2 W power dissipation.

DEVELOPMENT OF HTS RODS AND BARS

The material selected for fabrication of the AC downlinks was bismuth-lead-strontium-calcium-copper oxide (BSCCO). Polycrystalline BSCCO 2212 bars made by melt casting showed promise [3], and bulk BSCCO 2223 fabricated by sinter forging displayed the best electrical properties in 77 K tests [4].

Powder synthesis of $Bi_{1.8}Pb_{0.4}Sr_{2.0}Ca_{2.0}Cu_{3.0}O_{10}$ (2223) used the two-powder process [5] with spray pyrolyzed powders obtained from Seattle Specialty Ceramics Co. The powders were calcined first at reduced total pressure (6 h/750°C/ 3 torr of O_2) to remove residual carbonates, then at ambient pressure in CO_2-free air (24 h/840°C for 2212, and 48 h/900°C for $CaCuO_2$) to produce nearly single-phase materials as determined by x-ray diffraction analyses. The powders were then mixed in proportions to give the 2223 stoichiometry and calcined to yield the powder desired. Alternatively, the reaction was done during heat treatment after the mixture was pressed into rods or bars.

Several processes for forming the superconductor rods or bars were tested: uniaxial cold pressing or cold isostatic pressing (CIP), followed by sintering in air at 855-865°C; multiple CIP with intermediate and final sintering; and cold pressing followed by sinter forging. In sinter forging, the sample is compressed at a controlled rate during heat treatment. Melt casting of 2212 was also studied in a parallel effort [3], and commercially available melt-cast BSCCO was obtained and evaluated. Results of electrical tests of products of the various processes, summarized in Table 1, showed that sinter-forged 2223 was superior at 77 K. Mechanical tests also showed that this material was a superior form of BSCCO [6]. An apparatus was constructed to fabricate sinter-forged bars in sizes suitable for downlink applications.

ELECTRICAL AND THERMAL PERFORMANCE OF DOWNLINK BARS

Individual sinter-forged bars with 0.5-0.6 cm^2 cross-sectional area, 25 cm length, and 77 K critical currents up to 710 A were DC–pulse–tested through and beyond their critical values. An example of the results is given in Fig. 1. Applied magnetic fields typical of current–lead applications (50-100 G) had little effect on critical current, as shown. Material from a longitudinally sectioned, sinter-forged bar was pulse-tested at a series of temperatures below 77 K and in applied magnetic fields up to 1 T. Results are given in Fig 2. All of these results illustrate the dramatically improved performance of bulk HTS materials recently developed.

Tests of AC transport in individual bars revealed that power losses, associated with magnetic hysteresis, were low at utility line frequencies when current peaks were kept well below the DC critical current range. Figure 3 shows an example of power-loss test results obtained with a sinter-forged bar at 77 K. Although the critical current was low in the range considered for use in downlinks, the energy loss/cycle-cm was only 25 μJ at 375 A (265 A RMS), an acceptable value for a four-bar 1500-A downlink in 50-Hz service. Results from early tests of melt-cast rods at 77 K transporting AC at various intensities and frequencies are included in Fig. 3. The frequency independence of the energy loss per cycle is notable. AC power loss tests of samples in liquid helium showed losses of only 10 to 25% of those of samples at 77 K.

Low resistance electrical contacts to the bars were made during the sinter-forging process. A thin silver sheet is used on the HTS surfaces to mediate the forces applied by the forging platens and to chemically isolate them from the HTS. The silver becomes intimately bonded to the HTS and afterward is used in making solder connections to metallic leads. Silver strips 2 cm long were retained on both sides of both ends of bars prepared for downlink use, and the rest of the silver layers was peeled away. In lap-joint resistance tests, the half-joint contact resistivities at 77 K were 300 nW-cm^2 or less, including the HTS/silver interface, silver metal thickness, and solder thickness contributions.

Literature values of thermal conductivity at 60-80 K for polycrystalline Pb-BSCCO 2223 made by static sintering differ by a factor of 2, and reported single-crystal values are much higher than those of polycrystalline samples [7]. The dramatic improvement of J_c produced by sinter forging suggested that thermal conductivity may have been increased as well. The possibility was briefly explored. Analysis showed that the peak of the thermal conductivity-temperature function in the range of interest occurred near 67 K, as in prior work, but that the peak value may be about 29 mW/cm-K, i.e., greater by 1/3 than the highest value previously reported for polycrystalline samples. Results of helium boiloff tests of a sinter-forged bar in an 80-4 K gradient suggested that the peak value may be somewhat higher still.

DOWNLINK DESIGN AND TESTS

Certain design constraints were imposed by a desired compatibility between the assemblies and a helium boiloff test facility constructed in Japan by the Tokyo Electric Power Co. (TEPCO) to support the development of fault-current limiters that will operate in liquid helium [8]. Compatibility was achieved as shown in Fig. 4. For each downlink, the copper connector that holds the HTS bars in place was made to fit a mating part in the boiloff test system. The connector geometry provided a 100-mm-diameter area within which the bar ends could be located. Slots 2 cm deep were milled into the copper to accept the bar ends with their silver contacts. Soft solder (60/40 Sn/Pb) was used

Table 1. Electrical performance of BSCCO Rods/Bars at 77 K

Mfr. Method	I_c (A)	J_c (A/cm^2)
Multi–CIP	190–285	600–900
Melt–cast		
Source A	270	450
B	350	740
B	710	530
Sinter–forged		
Full–size bar	750–975	1000–1300
Small bar	300	8000

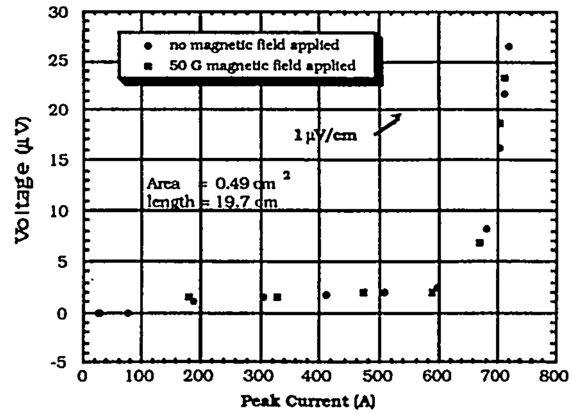

Fig. 1. Voltage versus current for sinter–forged BSCCO sample at 77 K.

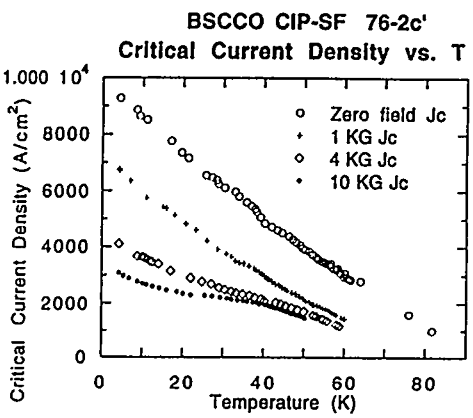

Fig. 2. Sinter–forged BSCCO critical current density versus temperature.

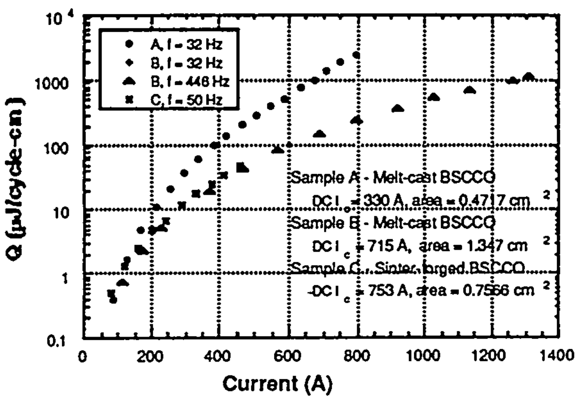

Fig. 3. BSCCO at 77 K; energy loss per cycle–cm versus AC.

to complete the joints. At the opposite ends of the bars, the silver contacts were joined to Nb-Ti low-temperature superconductor wire held in place with soft solder, for connection to components in the liquid helium.

Specification of the number of HTS bars and their cross-sectional areas and lengths depended on several considerations. For a given AC current transported in an HTS array, the power loss is less if (a) higher-J_c material is employed, (b) the total cross-sectional area is held constant while the number of conductors is increased [9], or (c) the total cross-sectional area of the HTS is increased. Both power loss and thermal conductivity are temperature–dependent. A further complication is introduced when tapered bars are considered. Decisions were made with the help of a computer spreadsheet program applied to 1-mm increments of bar length. Computation showed that four parallel bars – each 0.5-0.6 cm^2 in area and containing a temperature gradient extending 21 cm from 77.3 to 4.2 K – would satisfy the electrical and thermal requirements. The predicted thermal dissipation during operation at full power is detailed in Table 2. Less than 0.2 W total dissipation per array is expected.

To demonstrate the mechanical suitability of a downlink array (Fig. 4) when operated at full current and thus full magnetic self-field, an assembly was tested at 1075 A RMS, 60 Hz, in liquid nitrogen. No undesirable results were observed.

Helium boiloff tests of the two downlinks in the TEPCO facility are in progress with the arrangement shown in Fig. 5. Results obtained to date, shown in Fig. 6, are encouraging.

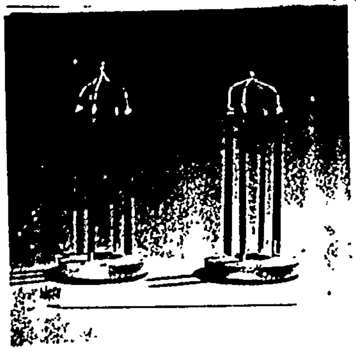

Fig. 4. Two superconductor downlinks (shown inverted).BSCCO bars extend from copper connector to flexible Nb–Ti leads.

Table 2. Heat flow to 4.2 K terminal of downlink bar*

AC power loss (50 Hz)	26.5**
Heat flow from 77.3 K	20.4
Upper contacts (interface)	0.7
Lower contacts (total)	1.0
Total	48.6 mW
Idle bar heat flow	35.5 mW

*Length = 21 cm, area = 0.578 cm^2, contact area = 4 cm^2, AC (p) 375 A.
**With loss at 4.2 K, 0.25 loss at 77.3 K.

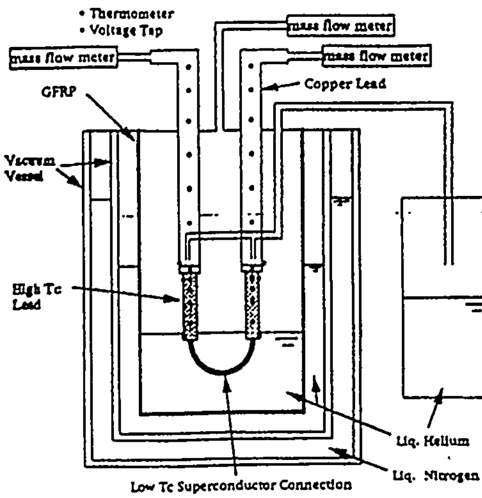

Fig. 5. Testing apparatus for heat leakage of high–T_c leads.

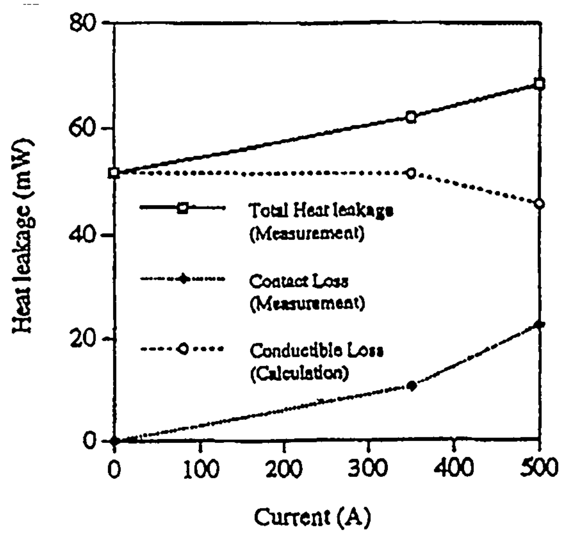

Fig. 6. Heat flow versus DC current for downlink pair.

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