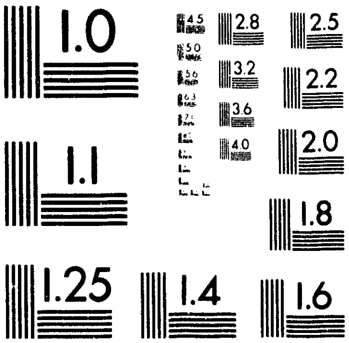
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Fabrication and characteristics of a test magnet from HTS Bi-2223 silver-clad tapes.*

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ABSTRACT

Critical currents of powder-in-tube processed silver-clad Bi-2223 short tape samples and coils have been measured at liquid nitrogen (77 K), liquid neon (27 K) and liquid helium (4.2 K) temperatures. The short samples have been characterized in fields up to 20 T and indicate a large anisotropy at 27 K with resistive behavior above 15 T in the worst field direction. A test magnet consisting of pancake coils generated magnetic fields greater than 1.0 , 0.7 and 0.11 T at 4.2 K, 27 K and 77 K respectively. The ctest magnet generates significant self-fields in background fields up to 14.5 T at 4.2 K and 27 K. Optimization of thermo-mechanical process parameters have yielded J_c's in the superconducting core > 4.0 X 10^4 A/cm^2 at 77 K, zero field and > 2.0 X 10^5 A/cm^2 at 4.2 K, zero field for short tape samples. Long lengths (>30 m) of silver-clad tape superconductors have also been fabricated and tested to carry significant amounts of

current (J_c core > 10,000 A/cm^2) at 77 K. Overall J_c of short and long samples and characteristics of the test magnet are reported.

INTRODUCTION

Since the first reports of high temperature superconductors (HTS) with transition temperatures above liquid nitrogen temperature, many interesting manufacturing methods have been developed to fabricate long lengths of conductor from these brittle ceramic materials for various potential commercial applications. To date the powder-in-tube (PIT) process has proved to offer the greatest advances towards exhibiting long length wire manufacturing potential as well as increases in current carrying ability. [1-4] The $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ compound (or Bi-2223 for short) is particularly suitable for the PIT approach since it can be readily deformed, textured, and densified by a sequence of thermo-mechanical operations. Another advantage of the PIT technique is its similarity to the industrial processes used in the manufacture of low temperature superconductors such as NbTi and Nb_3Sn.

In addition to low-field applications at liquid nitrogen temperature, the high temperature superconductors provide the potential of operating electric power devices and high-field magnets at temperatures (above 4.2 K) and fields (above 20 T) beyond the current capability of low temperature superconductors. This is possible if long lengths of HTS conductor with high current densities can be fabricated on an industrial scale. In this paper we report critical current data for short samples of silver-clad tapes at liquid helium (4.2 K) and neon (27 K) temperatures measured in external fields up to 20 T. Long lengths of material have also been processed and used to make small pancake coils. The characteristics of these small coils at liquid nitrogen (77 K), liquid neon (27 K), and liquid helium (4.2 K) are also reported.

EXPERIMENTAL

Long lengths of silver-clad Bi-2223 HTS tapes were fabricated by the powder-in-tube technique as described earlier. [3-4] Pre-reacted precursor powders were initially prepared from a mixture of high purity (>99.99%) Bi,Pb,Sr,Ca and Cu oxides and carbonates. These were carefully mixed, heat treated, ground, and packed in to high-purity silver tubes. The packed billets were lightly swaged, drawn through a series of dies, and then rolled to final size. A series of intermediate heat teatments were performed between 800 to 840 °C to enable growth and alignment of the Bi-2223 phase in the tape core. Monofilament tapes greater than 30 m in length have been processed this way. Short samples were cut from the long lengths and subjected to an additional series of uniaxial pressing and heat treating operations.

The test magnet was made by stacking and connecting in series a set of three double pancake coils made by the 'react-and-wind' approach. Each pancake was comprised of three lengths of monofilament tape that were co-wound in parallel to form a larger monolith conductor with ceramic insulation seperating each turn. Two single pancake coils were wound on a single former, seperated by ceramic insulation and heat treated together to make a set of double pancakes. These were then epoxied for strength and rigidity prior to assembling the complete test magnet.

Short sample transport properties were measured using the four probe technique. The measurements were done at 77 K, 27 K, and 4.2 K. At the low temperatures they were performed in background magnetic fields up to 20 T at the Francis Bitter National Magnet Laboratory. Magnetic field was applied parallel or perpendicular to the tapes broad surface, defined as H // a-b and H // c-axis of the superconducting grains respectively. Longer than 30 m of tape were also characterized by the four probe technique by spirally winding them on large ceramic mandrels and immersing them in liquid nitrogen.

The test magnet, placed in a cryostat, was positioned in the bore of a water-cooled magnet at the Francis Bitter National Magnet Laboratory. The central axial field generated by each magnet pointed in the same direction. Critical currents of the test magnet were measured at 4.2 K (liquid helium in the crysostat) at 27 K (liquid neon in the crostat) for background fields up to 14.5 T. Voltage taps were placed at the ends of each pancake coil to determine their performance individually.

The criterion for critical current was 1 μV/cm and critical current densities (J_c's) were determined for the superconducting and overall cross-sectional areas. Note that the high aspect ratio of the tape combined with the irregularities of the superconducting core make it extremely difficult to obtain an accurate value for the core cross-sections. [5] For example, techniques such as weighing the sample before and after etching the core, weighing of cut micrographs, measuring of enlarged optical micrographs, and measurements from an image analyser provide a wide range of values ranging from 8 X 10^{-4} cm^2 to 1.7 X 10^{-3} cm^2. Thus there can be a large range of the core J_c, depending on the measurement technique used. Although it is useful to determine the value of core J_c, it is more useful to know overall or engineering J_c, because it provides a design base-line for magnets and devices. In this paper we also reprt overall J_c's of the composite to elucidate the problems associated with core Jc reports.

RESULTS AND DISCUSSION

Short tape samples (3.5 to 4.0 cm in length) that had been subjected to several cycles of uniaxial pressing and heat treatment always carried the highest currents. Values above 40 A were typically attained at liquid nitrogen temperature, with the highest being 50 A. Data for a short sample is presented in Table 1 and compared with those of a long length (34 m). The long monofilament tape was processed by a two-cycle cold-rolling and heat treatment operation. Overall, or engineering J_c, determined from the cross-sectional area given by thickness times width (not considering taper of the tape edges), is also indicated in Table 1 for both samples.

Table 1. Critical current densities of short and long tapes at 77 K.

	I_c (A)	Core J_c (A/cm^2)	Overall J_c (A/cm^2)
Short Sample	50	~40,000	10,200
Long length (34 meters)	16	~12,000	3,050

Figure 1 represents superconducting core J_c's vs. applied magnetic field plots for short tape samples measured at liquid helium (4.2 K) and liquid neon (27 K) temperatures. Both principal field orientations, H ⊥ and H // to the tapes broad surface are shown in the figure. As seen from the 4.2 K plots the samples continue to carry large currents in fields up to 20 T with nearly field independent behavior for both field orientations. This behavior is consistent with previous reports. [6] However, at liquid neon (27 K) temperature a large anisotropy is observed in applied fields above 15 T. This is attributable to the large difference in irreversibility fields for the two field directions at higher temperatures and suggests limited use at these field and temperature ranges.

Figure 2 shows a photograph of the test magnet, assembled by stacking six individual pancake coils. The dimensions and pertinent parameters of the magnet and the magnet's critical current data are presented in Table 2. At 77 K, a Hall probe, was placed in the bore of the magnet, to obtain a rating of 0.0063 T / A for the assembly, which corresponds to a maximum value of field generated to be 0.11 T when using the critical current of the best performing single pancake. With the complete magnet in the superconducting state the minimum field generated was measured to be 0.08 T.

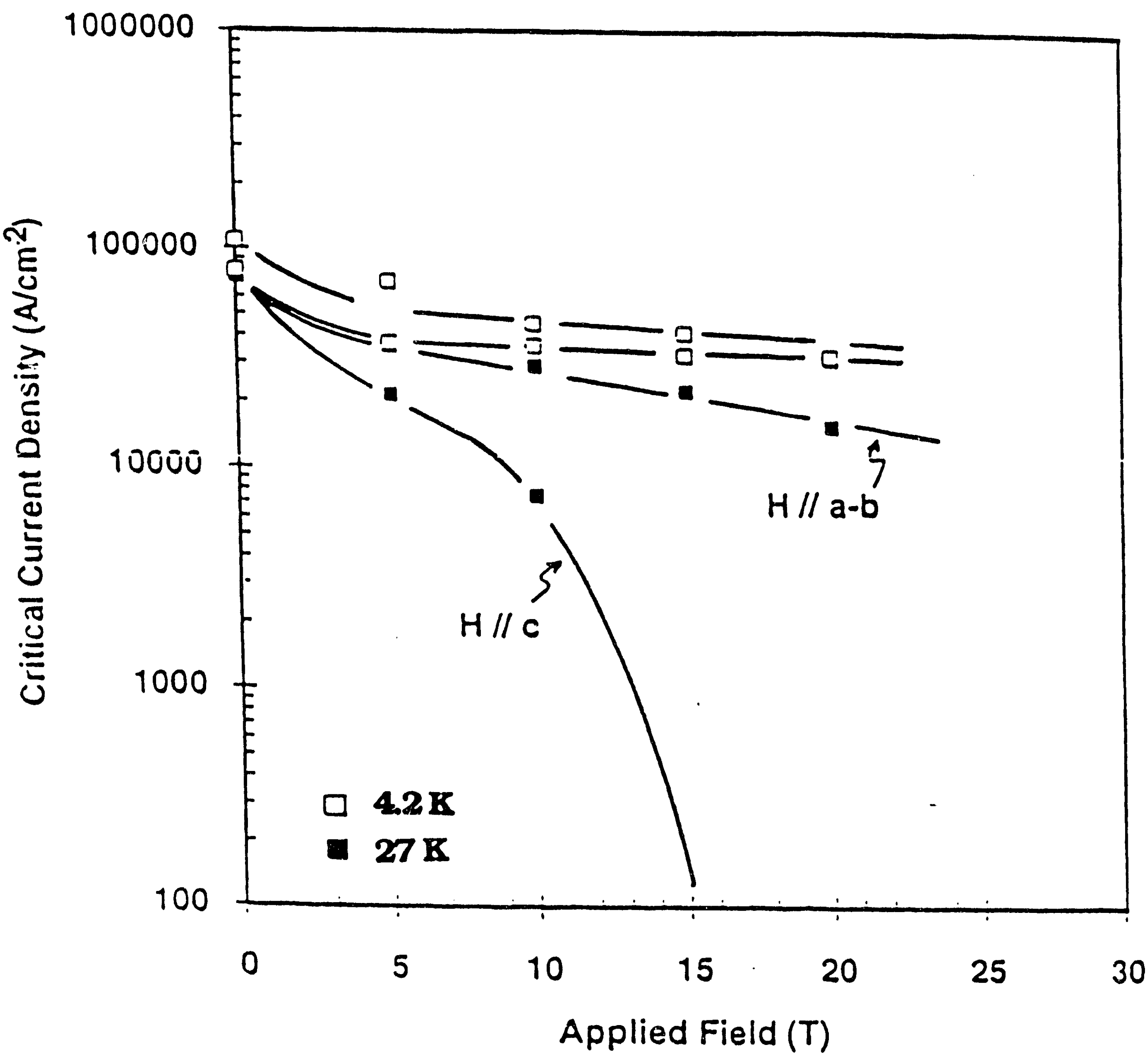

Figure 1. Core J_c versus background magnetic field for short tape samples at 4.2 K and 27 K.

Table 2. Parameters and critical current results of a test magnet.

Winding Inner diameter (cm)	2.50
Winding Outer diameter (cm)	7.50
Coil Height (cm)	5.33
No. of co-wound tapes per pancake	3
Total length of tape (m)	153
Total no. of turns	330
Overall winding cross-section (cm^2)	0.348
No. of pancake coils	6

	Ic (A)								
	4.2K				27 K				77 K
Pancake No. / Field (T)	0	5	10	14.5	0	5	10	14.5	0
1	135	113	107	87	92	77	70	61	14
2	150	97	92	70	102	65	58	50	16
3	170	138	112	74	116	70	63	53	16
4	170	106	95	100	125	95	80	69	19
5		93	78	67	93	63	54	48	14
6	118	82	71	60	78	58	49	42	13

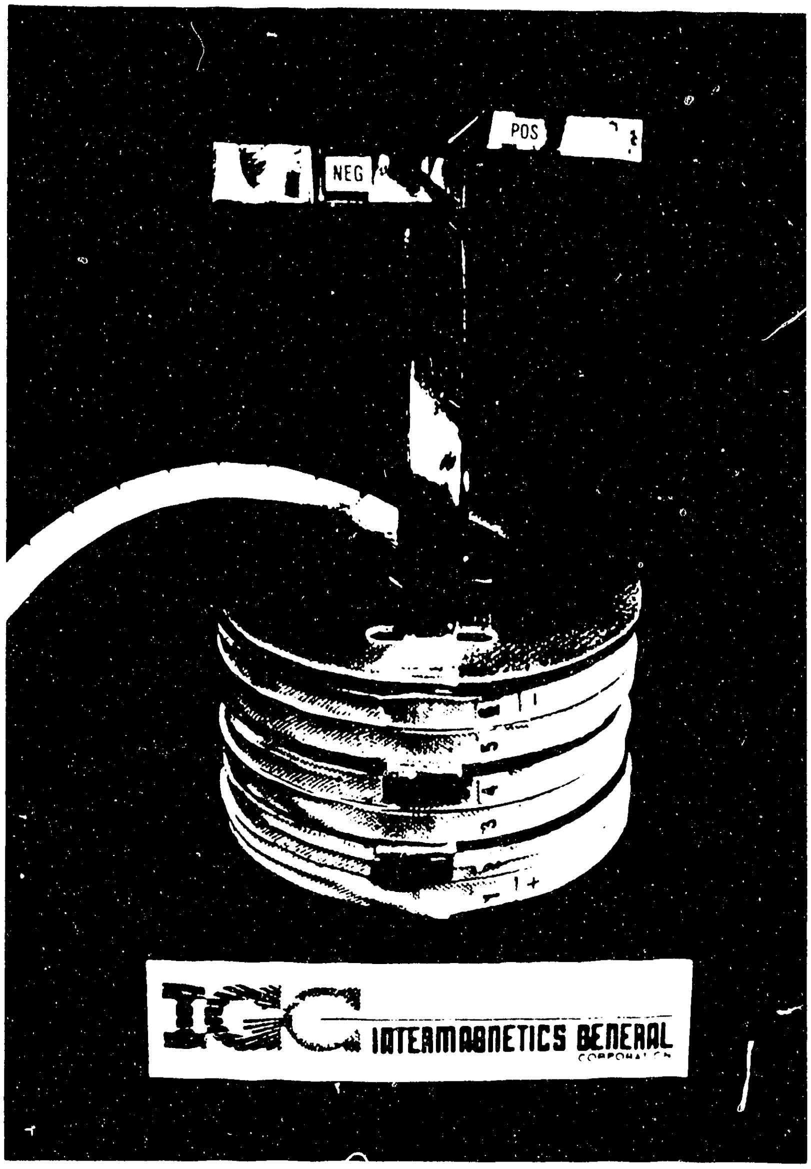

Figure 2. Photograph of the test magnet assembled with six single pancake coils.

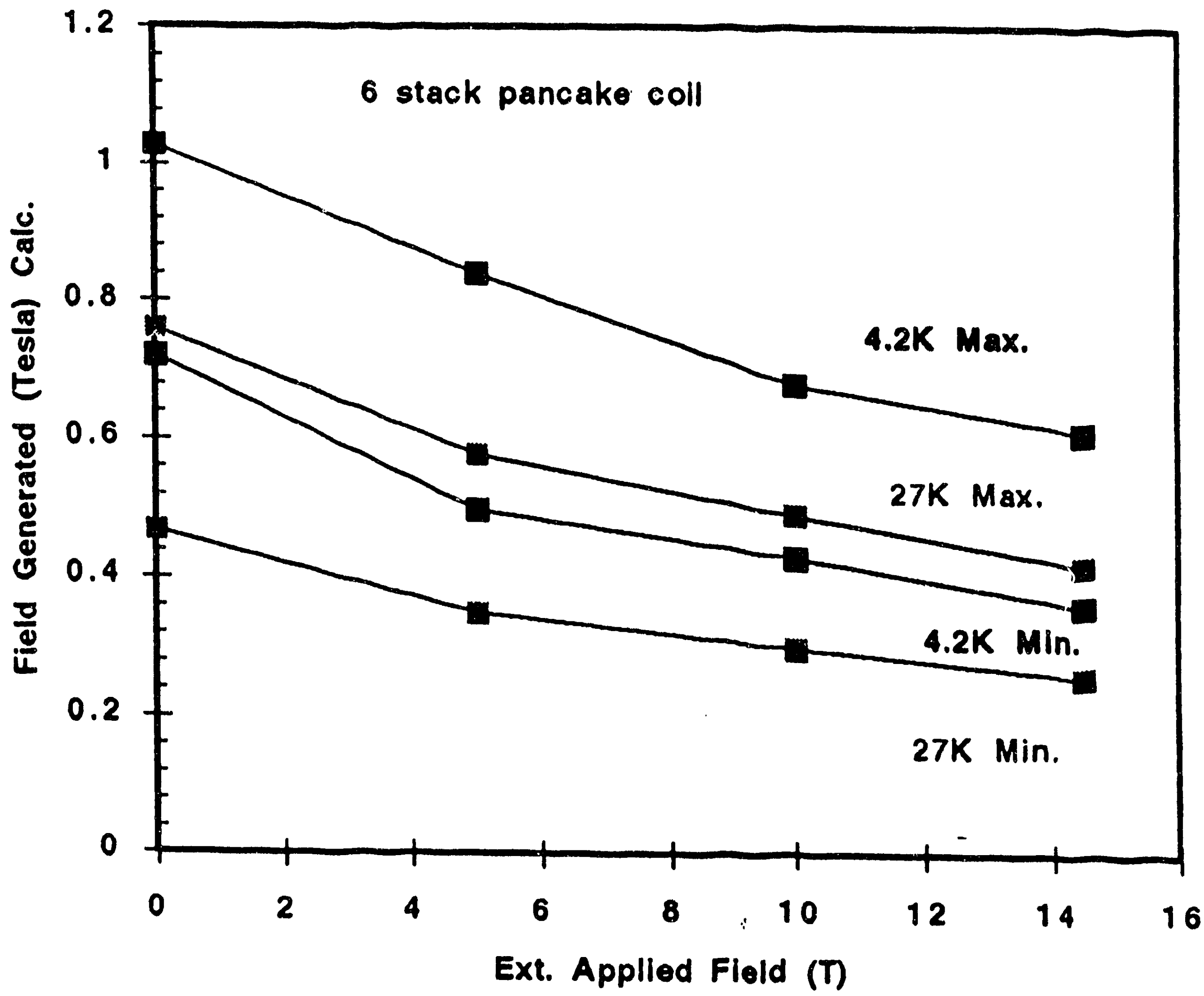

Figure 3. Maximim and Minimum values of the field generated in the test magnet at liquid helium (4.2 K) and liquid neon (27 K) temperatures.

Figure 3 presents plots of the central field generated by the test magnet versus background field at 4.2 K and 27 K. The central field generated was calculated by multiplying the current times the field constant (0.0063 T/A) of the entire assembly. Since the individual pancake coils of the magnet performed differently a range of values ranging from minimum to maximum are plotted. The maximum generated field corresponds to the highest critical current carried by the single pancake coils while the minimum field represents the coil with the least critical current. The magnet generated a maximum self-field of 1.03 T at 4.2 K without an applied field and 0.61 T in a background field of 14.5 T. At 27 K these values correspond to 0.76 and 0.42 T, respectively. The values at 27 K are consistent with the expectation that a very small component of the H ⊥ orientation is seen by the tapes, enabling the coil to maintain its superconducting behavior in the high field range.

The set of results presented here indicates that HTS materials are promising for high-field magnets and electric power devices operating at a temperature below ~ 30 K. Operation at temperatures above 4.2 K could improve refrigeration efficiency and reliability.

ACKNOWLEDGEMENTS

Work at Argonne National Laboratory and part of work at Intermagnetics General Corporation is supported by the U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy, as part of a DOE program to develop electric power technology, under Contract W-31-109-Eng-38. Part of the work at the Francis Bitter National Laboratory (FBNL) is also supported by the U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy, as part of a DOE program to develop electric power technology, The FBNL is supported by National Science Foundation.

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