PRACTICAL SUPERCONDUCTOR DEVELOPMENT
FOR ELECTRICAL POWER APPLICATIONS

ARGONNE NATIONAL LABORATORY

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JUL 31 1997

QUARTERLY REPORT FOR THE PERIOD ENDING JUNE 30, 1997

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This is a multiyear experimental research program focused on improving relevant material properties of high- T_c superconductors and on development of fabrication methods that can be transferred to industry for production of commercial conductors. The development of teaming relationships through agreements with industrial partners is a key element of this program.

Technical Highlights

Recent work on Bi-2223 is discussed. Topics include Ag-clad conductor development and microstructural effects on properties.

Effect of Pb Content on Microstructure and J_c of Bi-2223 Tapes

The J_c of Bi-2223 tapes depends strongly on their Pb content, as shown in Fig. 1 for Bi-2223 monofilaments processed at 820°C in 8% O_2 [1]. The sharp maximum in J_c vs. Pb content was interpreted in the following way: When Pb content is less than optimal ($\approx Pb_{0.30}$), the 2223-formation kinetics are too slow for complete formation of the 2223 phase. As a result, connectivity of the 2223 phase is poor and J_c is low. When the Pb content is greater than optimal, J_c is limited because connectivity is disrupted by Pb-rich phases that coat the Bi-2223 grain boundaries. When the Pb content is optimal, the formation of 2223 is complete and the formation of Pb-rich phases is limited, so 2223 connectivity is good and J_c reaches a maximum. This interpretation suggests that the performance of samples with low Pb contents may be improved by increasing the kinetics of 2223 formation. Below is a report on efforts to improve the performance of samples with low Pb content ($\leq Pb_{0.25}$) by heat treating them at higher temperatures.

To determine temperatures at which 2223 formation proceeds to completion in low-Pb samples, tapes with $Pb_{0.20}$ and $Pb_{0.25}$ were equilibrated for 50 h (in 8% O_2) at a series of temperatures. After equilibration at the selected temperature, the tapes were furnace-cooled and then peeled, and X-ray patterns were collected to determine the extent of 2223 formation. $Pb_{0.25}$ samples contained $\approx 50\%$ 2223 after 50 h at 832°C, while $Pb_{0.20}$ samples were $\approx 50\%$ converted to 2223 after 50 h at 840°C. Because these rates of 2223 formation are similar to those for $Pb_{0.30}$ tapes processed at 820°C, complete thermomechanical sequences were performed on $Pb_{0.20}$ and $Pb_{0.25}$ monofilament tapes at 840 and 832°C, respectively. That is, $Pb_{0.20}$ and $Pb_{0.25}$ tapes

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Fig. 1.
Critical current (I_c) versus Pb content for monofilament tapes heat-treated at 820°C in 8% O_2 for a total heat treatment time of 250 h with intermediate pressing after 50 and 150 h.

were heated for 50 h in 8% O_2 at 840 and 832°C, respectively, then uniaxially cold pressed at ≈ 2 GPa, processed for another 100 h at their respective temperatures, pressed a second time, then heated for a final 100 h at the same temperatures. Processing the tapes at the higher temperatures increased the critical current, I_c , for $Pb_{0.20}$ from ≈ 2 A at 820°C to ≈ 31 A at 840°C; I_c for $Pb_{0.25}$ increased from ≈ 11 A at 820°C to ≈ 28 A at 832°C. X-ray diffraction patterns collected from the fully processed tapes confirmed that 2223 formation was essentially complete ($>98\%$ 2223) after processing at the higher temperatures.

The I_c and X-ray results for low-Pb samples are consistent with a model of 2223 formation in which a transient Pb-rich liquid is crucial to the formation of 2223. In this model, the Pb-rich liquid forms when the solubility limit for Pb in 2212 is exceeded. (The powder used in this study initially consists of Pb -2212, Ca_2CuO_3 , and CuO .) Because the solubility limit for Pb in 2212 and 2223 displays a maximum versus temperature [2], the solubility limit for Pb in 2212 may be exceeded in low-Pb samples by heating to sufficiently high temperatures, i.e., above the temperature for maximum Pb solubility. When the solubility limit is exceeded, the Pb-rich liquid forms and the conversion to 2223 is enhanced. As a result, 2223 connectivity is improved and J_c increases.

Considering the large activation energies (≈ 1 -2 MJ/mol) associated with the formation of Bi-2223 [3], the heat treatment temperature for $Pb_{0.20}$ tapes (840°C in 8% O_2) was significantly higher than that typically used to process Bi-2223 tapes ($\approx 825^\circ\text{C}$). The results also suggest that the Bi-2223 phase field may extend to higher temperatures than previously believed. Majewski et al. [4] showed that Bi-2223 is stable up to $\approx 850^\circ\text{C}$ for $Pb_{0.30}$ and $\approx 875^\circ\text{C}$ for $Pb_{0.20}$, but their results were obtained in air and their tapes contained no silver, which is known to affect the stability of Bi-2223 [5]. To determine the high-temperature boundary of the 2223 phase field in 8% O_2 , fully converted Bi-2223 tapes (i.e., tapes that contained $>98\%$ 2223 by X-ray) were equilibrated in 8% O_2 for 1000 min at a series of temperatures, then quenched in oil.

X-ray patterns of the peeled tapes were examined to indicate whether the 2223 had decomposed, i.e., whether the phase boundary had been crossed during equilibration. As a separate method for determining the high-temperature 2223 phase boundary, the melting points of fully converted Bi-2223 tapes were determined by acoustic velocity measurements [6].

Figure 2a shows that Bi-2223 ($\text{Pb}_{0.20}$) is fully converted (i.e., $\approx 100\%$ 2223) after heating for 250 h at 840°C in $8\% \text{O}_2$. When such a fully converted tape is held for 1000 min at 850°C in $8\% \text{O}_2$ and then quenched, lines for the Bi-2201 phase appear (Fig. 2b), indicating that the Bi-2223 phase decomposed partially. Similarly, Fig. 3 compares fully converted $\text{Pb}_{0.25}$ samples before and after being held for 1000 min at 844°C in $8\% \text{O}_2$. Figure 3a shows that the sample is nearly 100% 2223 after heating for 250 h at 832°C in $8\% \text{O}_2$, while Fig. 3b shows that the sample does not decompose during equilibration at 844°C . Acoustic velocity measurements show an onset of melting for $\text{Pb}_{0.20}$ and $\text{Pb}_{0.25}$ samples at $850\text{--}858^\circ\text{C}$. The X-ray and acoustic velocity data suggest that the high-temperature phase boundary for the Bi-2223 single-phase field lies between 844 and 850°C for Pb contents between $\text{Pb}_{0.20}$ and $\text{Pb}_{0.25}$ and that it may not depend as strongly on Pb content, as indicated by Majewski et al. [4]. In principle, acoustic velocity and X-ray measurements should yield the same temperature for the phase boundary; however, acoustic velocity measurements are dynamic (made at a ramp rate of $3^\circ\text{C}/\text{min}$), which may cause an apparent shift in the phase boundary to higher temperature. Despite the slight discrepancy in the exact temperature of the phase boundary, X-ray and acoustic velocity measurements both indicate that the Bi-2223 phase field extends $\approx 15\text{--}20^\circ\text{C}$ higher than typical processing temperatures for Bi-2223 tapes ($\approx 825\text{--}830^\circ\text{C}$ in $8\% \text{O}_2$).

Knowing that Bi-2223 is stable up to $844\text{--}850^\circ\text{C}$ in $8\% \text{O}_2$, we processed rod-in-tube (RIT) samples with $\text{Pb}_{0.20}$, $\text{Pb}_{0.25}$, $\text{Pb}_{0.30}$, and $\text{Pb}_{0.35}$ at temperatures in $825\text{--}850^\circ\text{C}$ in $8\% \text{O}_2$. The samples were fabricated by inserting a solid silver rod (3 mm O.D.) into the center of a silver tube (6.35 mm O.D. $\times$ 4.35 mm I.D.), then packing Bi-2223 precursor powder around the rod and processing by conventional powder-in-tube methods [7, 8]. The tape had an overall thickness of $\approx 250 \mu\text{m}$ after rolling and the superconductor layer between silver rod and sheath had a thickness of $\approx 10 \mu\text{m}$. Sections of tape (≈ 30 mm long) were processed in $8\% \text{O}_2$ for 50 h at the selected temperature, then uniaxially cold pressed at ≈ 2 GPa, processed for another 100 h at the same temperature, pressed a second time, then heated for a final 100 h at the chosen temperature. I_c was measured by the four-probe technique with a $1 \mu\text{V}/\text{cm}$ criterion.

Figure 4 shows J_c versus Pb content for RIT samples heat treated in $8\% \text{O}_2$ at temperatures of $825\text{--}850^\circ\text{C}$. Each point represents the average of I_c measured for three separate samples. The data for 825°C show the same sharp maximum at $\text{Pb}_{0.30}$

Fig. 2. X-ray patterns from Bi-2223 ($\text{Pb}_{0.20}$) monofilaments after (a) heating for 250 h at 840°C in 8% O_2 , (b) heating for 250 h at 840°C in 8% O_2 , then holding for 1000 min at 850°C in 8% O_2 and quenching into oil. Peaks at $\approx 22^\circ$, 29.5° , and 37° 2θ are due to Bi-2201.

Fig. 3. X-ray patterns from Bi-2223 ($\text{Pb}_{0.25}$) monofilaments after (a) heating for 250 h at 832°C in 8% O_2 , (b) heating for 250 h at 832°C in 8% O_2 , then holding for 1000 min at 844°C in 8% O_2 and quenching in oil.

Fig. 4.

Critical current density versus Pb content for rod-in-tube samples heat-treated in 8% O₂ at temperatures 825-850°C.

that was seen in Fig. 1 for samples sintered at 820°C. As the heat treatment temperature increases from 825-845°C, J_c increases significantly for samples with low Pb content (Pb_{0.20} and Pb_{0.25}) and the sample with a high Pb content (Pb_{0.35}). The increase in J_c for low-Pb samples is thought to result from enhanced kinetics of Bi-2223 formation, as described above. X-ray analysis of peeled tapes confirms that Bi-2223 content increases in low-Pb samples as heat treatment temperature increases and is nearly complete (>98% Bi-2223) after 250 h at 837°C. Majewski et al. [4] suggest that J_c may increase for the Pb_{0.35} sample because the higher temperature lies within the 2223 single-phase field, whereas the lower processing temperatures lie in a multiphase field. As the heat treatment temperature increases from 845 to 850°C, J_c decreases for all Pb contents. The X-ray data from samples quenched from this temperature range suggest that J_c decreases for these samples because they lie outside the 2223 single-phase field at 850°C.

Figure 5 shows photomicrographs of Pb_{0.25} RIT samples processed for 250 h in 8% O₂ at 825°C (Fig. 5a) and 845°C (Fig. 5b); Fig. 6 shows photomicrographs of Pb_{0.30} RIT samples processed under the same conditions. The density of the Pb_{0.25} sample increases noticeably and J_c increases from ≈ 7.2 to ≈ 17.3 kA/cm², as the processing temperature increases from 825 to 845°C. While there is no obvious increase in the density of the Pb_{0.30} sample as the processing temperature increases from 825°C (Fig. 6a) to 845°C (Fig. 6b), the dense regions appear larger and better connected to one another in the sample processed at higher temperature. These observations of the Pb_{0.25} and Pb_{0.30} samples suggest that processing at the higher temperatures may improve connectivity in Bi-2223 tapes; however, while the higher processing temperatures increased J_c significantly in low-Pb samples, they increased J_c only $\approx 5\%$ for Pb_{0.30}. Possible explanations for the small increase in J_c for Pb_{0.30} are the nonuniformity in superconductor thickness, or "sausaging," that was particularly evident at higher processing temperatures, and the effect of second phases, primarily CuO and the (Sr,Ca)₂CuO₃. While the second phases were not noticeably larger after

Fig. 5. Secondary electron photomicrographs (longitudinal view) of Pb_{0.25} rod-in-tube samples processed for 250 h in 8% O₂ at (a) 825°C, and (b) 845°C.

Fig. 6. Secondary electron photomicrographs (longitudinal view) of $\text{Pb}_{0.30}$ rod-in-tube samples processed for 250 h in 8% O_2 at (a) 825°C, and (b) 845°C.

processing at the higher temperatures, they appeared to spread more along the 2223 grain boundaries rather than remain as isolated blocky particles, as they do after processing at lower temperatures. Figure 7 shows a striking example of how second phases coat 2223 grain boundaries across nearly the entire superconductor layer; Figs. 5 and 6 show how the second-phase morphology changes as processing temperature increases. If second phases truly coat the 2223 grain boundaries more effectively at higher temperatures, control of second-phase content (through adjustments in composition) may be crucial to realizing the benefits of higher processing temperatures.

Formation, Stability, and Reactivity of Pb-Rich Phases in Ag/Bi-2223 Conductors

Our investigations of the behavior of Pb-rich phases in Ag/Bi-2223 composites (carried out in collaboration with American Superconductor Corporation [ASC] and other member institutions of the ASC-led Wire Development Group) have continued. Recent work has focused on aspects of Pb-rich phase formation mechanisms, stability, and reactivity with other secondary phases. In a previous progress report, we presented results that illustrated the recurring strong tendency of alkaline earth plumbates and copper oxide to coexist in close proximity in both

Fig. 7. Secondary electron photomicrograph (longitudinal view) of Pb_{0.25} rod-in-tube sample. Dark gray second phase coats the 2223 grain boundaries and extends across most of the superconductor thickness.

partially and fully processed Ag/Bi-2223 composite conductors. Second-phase aggregates consisting of CuO surrounded by Ca_2PbO_4 have been found in the ceramic core regions of both mono- and multifilamentary composites. This observation provided evidence that Ca_2PbO_4 and CuO do not react with one another under typical Ag/Bi-2223 heat treatment conditions; such reactions could cause barriers to their dissipation should they become aggregated during precursor powder processing. In a prior related study, Sung and Hellstrom [3] saw no indications of an interfacial chemical interaction during $\text{Ca}_2\text{PbO}_4/\text{CuO}$ reaction-couple tests at temperatures up to 825°C . To follow up on this finding, ASC prepared two pellets containing a blended mix of Ca_2PbO_4 and CuO (mole ratio = 1:2.75, i.e., typical for Bi-2223 precursor powders) and heated them for 48 h in 0.075 atm of O_2 , one at 835°C and the other at 845°C . X-ray diffraction analysis (at ASC) and Raman microscopy (at ANL) showed no evidence of phases other than Ca_2PbO_4 and CuO in either pellet. This finding, taken together with our prior Raman imaging results and the work of Sung and Hellstrom [3], clearly shows that alkaline earth plumbates and copper oxide are inert to one another during Ag/Bi-2223 heat treatment and must, therefore, be dissipated via reaction with other phases. Accordingly, steps should be taken during Ag/Bi-2223 precursor powder processing to minimize the possibility of agglomeration of these two phases.

Our exploration of the $(\text{Bi,Pb})_3\text{Sr}_2\text{Ca}_2\text{Cu}_1\text{O}_z$ (3221) phase has also continued in recent months. Again in collaboration with ASC, we have investigated a plausible 3221 formation mechanism involving an equimolar reaction of the $\text{Bi}_2\text{Sr}_2\text{Cu}_1\text{O}_x$ (2201) phase (a common Bi-2223 precursor phase and decomposition product) and Ca_2PbO_4 . Two pellets were prepared from a blended mix of 3221 and Ca_2PbO_4 powders (mole ratio = 1:1) and heat treated for 48 hours in 0.075 atm O_2 , one pellet at 835°C and the other at 845°C . The pellet heat treated at 835°C showed visual evidence of partial reaction, and Raman microscopy revealed the presence of the 3221 phase. The pellet heat treated at 845°C melted nearly completely and spread over the bottom of its container. X-ray diffraction and Raman microscopy both revealed the presence of 3221 in the residue that coated the container. This result is consistent with previous thermal analysis measurements at ASC, which showed that the melting point of the 3221 phase (composition dependent) is $\approx 840 \pm 5^\circ\text{C}$. We are now exploring the extent to which 3221 is connected with liquid-phase formation during heat treatment of Ag/Bi-2223 composites.

Members of the Wire Development Group from the University of Wisconsin (UW) and ASC recently showed that reductions in the cooling rate following the final heat treatment of an 85-filament Ag/Bi-2223 composite conductor produced an increase in both J_c and the irreversibility field [9]. There was evidence that the slower-cooled specimens contained greater amounts of Pb-rich phases (particularly 3221) than the faster cooled specimens. We received three samples from the series studied by the UW/ASC team for Raman microscopy examination. The results

(listed in Table 1) show that the second-phase content of the fastest cooled sample (5°C/min) is dominated by $(\text{Ca,Sr})_2\text{CuO}_3$ (2/1) and $(\text{Ca,Sr})_{14}\text{Cu}_{24}\text{O}_{41}$ (14/24) and that these alkaline-earth cuprate phases are located mainly in the mid-core region of each filament. At the intermediate cooling rate (0.16°C/min), the 2/1 content diminishes, increasingly more CuO forms (mainly at the Ag/BSCCO interface), and the alkaline earth plumbate phase begins to appear. At the slowest cooling rate (0.005°C/min), CuO is the dominant second phase and maintains its persistence at the Ag/BSCCO interface. Also, at the slowest cooling rate we begin to detect the 3221 phase, whose presence was also reported by the UW/ASC team [9]. Again in this study, we see the recurring theme of CuO coexisting with the Pb-rich but copper-deficient plumbate and 3221 phases. The connection of the second phase buildup and accompanying Bi-2223 decomposition with the increases in J_c and H^* observed by the UW/ASC team [9] remains to be elucidated, but these results offer hope that intrinsically occurring second phases in Ag/Bi-2223 composites can be molded into flux pinning networks.

Table 1. Results of Raman microscopy analysis of specimens from UW/ASC cooling rate study [9]

Cooling Rate ^a (°C/min)	J_c^b (kA/cm ²)	H^{*c} (T)	Raman Microscopy Analysis Results	
			Second Phases	Pb-Rich Phases
5	~8	~0.13	2/1 ^d $\approx$ 14/24 ^d $\gg$ CuO	none ^f
0.16	~12	~0.13	14/24 ^d $>$ CuO ^e $>$ 2/1 ^d	$(\text{Ca,Sr})_2\text{PbO}_4$
0.005	~24	~0.20	CuO ^e $\gg$ 14/24 ^d $\approx$ 2/1	3221 ^g

^aCooling rate from 825°C to 730°C [9].

^b J_c at 77 K and self field (1 $\mu\text{V}/\text{cm}$) [9].

^c H^* measured with $H \parallel c$ [9].

^dLocated mainly in mid-core region.

^eLocated mainly at Ag/BSCCO interface.

^fXRD at UW showed no 3221 [9].

^gXRD at UW showed 3221 [9].

Effects of Oxygen Partial Pressure during Processing of Ag/Bi-2223 Conductors

In another collaborative effort forged through the ASC-led Wire Development Group, we are assisting Los Alamos National Laboratory (LANL) in the characterization of Ag/Bi-2223 composites that LANL (T. G. Holesinger) had subjected to variable oxygen pressures during composite processing. Raman microscopy was used to examine specimens of composite monofilament tape

subjected to three different processing paths, each consisting of four 50-h cycles at 820°C with intermediate pressing. The three processing paths were:

- Series I: each full cycle (50 h) in 0.075 atm O₂;
- Series II: first half of each cycle (25 h) in 0.075 atm O₂,
followed by second half-cycle in 0.15 atm O₂;
- Series III: each full cycle (50 h) in 0.15 atm O₂.

LANL observed distinct differences in the phase assemblages, compositions, and J_cs, depending on which oxygen treatment was used. Of particular importance in the correlation of transport properties and microstructure was the redistribution of Pb in both the secondary phases and the Bi-2223 matrix. The highest J_c values were associated with tapes that contained Ca₂PbO₄ as part of the phase assemblage with concomitantly lower concentrations of Pb in the superconducting phase. The highest J_c (30.4 kA/cm²) was obtained on tapes processed by the Series II route (variable pressure processing). Series I samples (0.075 atm O₂ processing) did not contain Ca₂PbO₄, had slightly higher concentrations of Pb in the superconducting phase, and had significantly lower J_c values. The performance of Series III samples (0.15 atm O₂ processing) was comparable to (but did not exceed) the performance of the Series II samples.

Raman microspectroscopy examinations of Series I, II, and III samples were made by defocusing the laser to cover a ≈30 μm region (usually a multiphase region) and recording the Raman spectrum of the entire laser-covered area. Typically, these spectra contained bands attributable to several phases. After obtaining the defocused spectrum, the laser was spot-focused (<5 μm diameter) on individual phases in the region probed with the defocused laser, and spectra of these individual phases were recorded. It was not possible to fully quantify the amount of each detected phase from sample to sample, but enough regions of each sample were probed to obtain a sense of which phases were present in the largest amount. The principal phases that were found (in varying amounts) in virtually all samples were the layered phase(s) Bi-2223/Bi-2212 (not distinguishable by Raman microscopy measurements on textured samples), the calcium-rich version of the 2/1 phase, and copper oxide. Ca₂PbO₄ was detected in some but not all samples, as described below. The 14/24 phase was detected as well, but only in a very few instances (mainly Series III).

Raman spectra that are typical of those recorded in all of the LANL samples are shown in Fig. 8. Spectrum A in Fig. 8 is from a region that appeared to be nearly pure Bi-2223; spectrum B is that of a second-phase particle known from SEM/EDX to be the Ca-rich 2/1 phase; spectrum C contains bands that originate from calcium plumbate (the bands between 500 and 600 cm⁻¹) and the Bi-2212/Bi-2223 phase.

Fig. 8.

Typical Raman microprobe spectra obtained for samples in LANL variable oxygen study. Assignments are (A) Bi-2212/Bi-2223 = BSCCO, (B) Ca-rich 2/1 phase, (C) Ca_2PbO_4 + BSCCO, (D) CuO + BSCCO, and (E) 14/24 phase + BSCCO. See text for additional details.

Spectrum D is that of CuO , with Bi-2212/Bi-2223 contributing to the band at 628 cm^{-1} . The band assignments for spectra A through D in Fig. 8 are based on our prior studies of standard materials. A key finding of this work was that the Series I samples (the ones that received the entire heat treatment in 0.075 atm O_2) showed no evidence of calcium plumbate at the end of the processing cycle. All wire specimens that were subjected to final heat treatment in 0.15 atm O_2 (i.e., Series II and III) showed unambiguous Raman evidence for calcium plumbate. Again, CuO was prominent wherever Ca_2PbO_4 was present.

Spectrum E in Fig. 8 contains a broad band that peaks near 580 cm^{-1} . This band is due to the 14/24 phase, but is seen only sporadically in the LANL samples, indicating that there is either very little 14/24 in most of these samples or it is present in the form of very small crystallites (too small to be seen by defocused Raman). The band at $\approx 205\text{ cm}^{-1}$ in spectrum E is one that was observed often in the entire series of spectra recorded for the LANL samples. It usually is accompanied by a set of weaker bands in the $410\text{ to }450\text{ cm}^{-1}$ region. We attribute these bands to

small particles of polishing grit because we have not observed them in any of our prior Raman studies of Ag/Bi-2223 composite conductors and they no longer were observed in the same samples after repolishing at ANL.

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Interactions

Balu Balachandran and Ken Goretti presented papers at the Materials Research Society Spring Meeting in San Francisco, March 31 – April 3, 1997. Coated-conductor development and AC losses in HTSs were the main focus in the HTS Symposium.

Balu Balachandran, Roger Poeppel, and Dick Weeks attended the Industrial Overview Committee (IOC) meeting at ORNL, April 30–May 1, 1997.

Scientists and engineers from Rockwell Automation (Reliance Electric), Cleveland, OH, visited ANL and discussed HTS research activities on May 2, 1997.

Several people from the HTS group participated at the American Ceramic Society 99th Annual Meeting & Exposition, May 4–7, 1997, Cincinnati, OH. Balu Balachandran organized a symposium on High-Temperature Superconductors.

Professor Jeff Wolfenstine of the University of California at Irvine visited Argonne on May 4-7, 1997. Topics covered included mechanical-property characterization for superconductors and substrates.

Balu Balachandran visited DOE/HQ, Washington DC, for the HTS FWP review meeting on May 21, 1997.

Steve Dorris attended the open session of the Bismuth Wire Development Group meeting, May 21, 1997, Madison, WI.

List of Publications

Published:

Y. S. Cha, R. C. Niemann, J. R. Hull, C. A. Youngdahl, M. T. Lanagan, M. Nakade (Tokyo Electric Power Co.), and T. Hara (Tokyo Electric Power Co.), Liquid Helium Boil-off Measurements of Heat Leakage from Sinter-forged BSCCO Current Leads under DC and AC Conditions, Proc. 1995 Cryogenic Engr. Conf., Columbus, OH, July 17-21, 1995; in Advances in Cryogenic Engineering, Vol. 41, Part A, ed. P. Kittel, pp. 603-610 (1996).

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STATUS OF INDUSTRIAL INTERACTIONS (April-June 1997)
 Cost-Shared Arrangements
 Does Not Include Contracts Closed Prior to 12/31/96^a

Company	Technology Area	Cost Share (\$K)				ANL P.I.	Status
		DOE		Participant			
		to ANL	to Participant	to ANL	to Participant		
American Superconductor	BSCCO phase evolution	150	0	0	150	Maroni	Work in progress.
Ames Laboratory/Iowa State University	Deformation of ceramic powders		85			Balachandran	Work in progress.
BASF	Green-state superconductor texturing	150	0	0	175	Dorris	Work on hold.
Commonwealth Research Corp.	Magnetic bearings and flywheel energy storage	0	0	1350	350		Work in progress.
Florida State University – National High Field Magnet Laboratory	Hot rolling of HTSC		20			Balachandran	Work in progress.
IGC	BSCCO wire production scaleup – Phase II	1000	500	0	500	Balachandran	Work in progress.
Illinois Superconductor Corp.	Fault current limiter	200	0	0	200	Hull	Work completed.
New Mexico Tech	Explosive consolidation of HTSC		26			Balachandran	Work in progress.
New York State Institute on Superconductivity	HTSC wire development		36			Lanagan Goretta	Work completed.
Superconductive Components, Inc.	Development of levitators for bearing applications	125	0	0	125	Balachandran	Work in progress.

STATUS OF INDUSTRIAL INTERACTIONS (April-June 1997) (Contd.)
 Cost-Shared Arrangements
 Does Not Include Contracts Closed Prior to 12/31/96^a

Company	Technology Area	Cost Share (\$K)				ANL P.I.	Status
		DOE		Participant			
		to ANL	to Participant	to ANL	to Participant		
University of Houston	Melt processing of HTSC		24			Balachandran	Work in progress.
University of Pittsburgh	Freeze drying of superconductor		100			Balachandran	Work in progress.
ZerRes Corp.	Current lead characterization	100	0	0	100	Hull	Work completed.

^aThose with contracts closed prior to 3/31/93 were shown in a separate table included with the March 1993 progress report.