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U.S. Department of Energy
Superconductivity Program for Electric Power Systems

HTS WIRE DEVELOPMENT WORKSHOP

Proceedings

February 16-17, 1994
St. Petersburg Hilton and Towers
St. Petersburg, Florida

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MASTER

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FOREWORD

The 1994 High-Temperature Superconducting Wire Development Workshop was held on February 16-17 at the St. Petersburg Hilton and Towers in St. Petersburg, Florida. The meeting was hosted by Florida Power Corporation and sponsored by the U.S. Department of Energy's Superconductivity Program for Electric Power Systems.

The meeting focused on recent high-temperature superconducting wire development activities in the Department of Energy's Superconductivity Systems program. The meeting opened with a general discussion on the needs and benefits of superconductivity from a utility perspective, the U.S. global competitiveness position, and an outlook on the overall prospects of wire development. The meeting then focused on four important technology areas:

- Wire Characterization: Issues and Needs
- Technology for Overcoming Barriers: Weak Links and Flux Pinning
- Manufacturing Issues for Long Wire Lengths
- Physical Properties of HTS Coils

Following in-depth presentations, working groups were formed in each technology area to discuss the most important current research and development issues. The working groups identified research areas that have the potential for greatly enhancing the wire development effort. These areas are discussed in the summary reports from each of the working groups.

This document is a compilation of the workshop proceedings including all general session presentations and summary reports from the working groups.

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SECTION I

AGENDA

U.S. Department of Energy
Superconductivity Program for Electric Power Systems:

HTS Wire Development Workshop

February 16-17, 1994
St. Petersburg Hilton and Towers
St. Petersburg, Florida

Hosted by: Florida Power Corporation

Wednesday, February 16, 1994

7:30 a.m. **Registration Check-in**

7:30 a.m. **Continental Breakfast**
Hosted by Florida Power Corporation

8:15 a.m. **Welcome and Introductory Remarks**
Tony Padilla - Florida Power Corporation
James Daley - U.S. Department of Energy
Robert Hawsey - Oak Ridge National Laboratory

8:30 a.m. **Workshop Overview and State of Technology**
Chairperson, *Robert McConnell - National Renewable Energy Laboratory*

The Utility Perspective: Needs and Benefits of Superconductivity for Electric Transmission and Distribution
John Hancock, Senior Vice President, Energy Supply - Florida Power Corporation

The Limits to Loss-Free Current Flow in HTS Wires: An Update
David Christen - Oak Ridge National Laboratory

U.S. Technological Competitive Position
Richard Blaugher - National Renewable Energy Laboratory

9:45 a.m. **Break**

10:00 a.m. **Wire Characterization: Issues and Needs**
Chairperson, *Martin Maley - Los Alamos National Laboratory*

Microstructural examination of materials, *Victor Maroni - Argonne National Laboratory*
Texture measurements on HTS materials, *Rudy Wenk - University of California at Berkeley*
In-situ critical current measurements under strain, *Mas Suenaga - Brookhaven National Laboratory*
Measurement issues for critical current density, *Jeff Willis - Los Alamos National Laboratory*
Measurement of intrinsic mechanical properties of high- T_c superconductors using a mechanical properties microprobe, *Amit Goyal - Oak Ridge National Laboratory*

11:15 a.m. **Technology for Overcoming Barriers: Weak Links and Flux Pinning**
Chairperson, *Ken Gray -Argonne National Laboratory*

Current-limiting mechanism and the role of microcracks in BSCCO, *David Larbalestier - University of Wisconsin*
Influence of microstructural development on critical currents in powder-in-tube wires, *Dean Miller, Argonne National Laboratory*

High current density T1-1223 conductor, *Eric Tkaczyk - General Electric*
Current flow anisotropy in BSCCO tapes and high J_c biaxially textured YBCO films, *Martin Maley - Los Alamos National Laboratory*
Biaxial texture in YBCO-124 multifilamentary composite conductors, *Lawrence Masur - American Superconductor Corporation*

12:30 p.m. **Luncheon**

1:30 p.m. **Manufacturing Issues for Long Wire Lengths**
Chairperson, *Don Kroeger - Oak Ridge National Laboratory*

Improved performance of BSCCO round multifilamentary wire, *Leszek Motowidlo - Intermagnetics General Corporation*
Process control issues for fabrication of long BCCCO-2212 conductor, *Ken Marken, Oxford Superconductor*
Long-length production of HTS composite conductors made by a metallic precursor process, *Lawrence Masur - American Superconductor Corporation*
Multifactor experimental design addressing thermomechanical processing of wire, *John Bingert - Los Alamos National Laboratory*
Scale-up issues on bulk powder processing, *Balu Balachandran - Argonne National Laboratory*
Improvement of grain connectivity in thallium-based long superconducting tapes, *Jui Wang - SUNY/Buffalo*
General Electric's silver addition tape process for thallium-1223: Scale-up issues, *John DeLuca - General Electric*

3:00 p.m. **Break**

3:15 p.m. **Physical Properties of HTS Coils**
Chairperson, *Mas Suenaga - Brookhaven National Laboratory*

Bi(2223) coil performance measurement, *Pradeep Haldar - Intermagnetics General Corporation*
HTS coil requirements for motor applicaitons, *Rich Schiferl - Reliance Electric Company*
Normal zone propagation in HTS coils, *Yuki Iwasa - Massachusetts Institute of Technology*
Engineering aspects of coil design, *Mark Daugherty - Los Alamos National Laboratory*

4:00 p.m. **Technology Development and Transfer Opportunities from the Program--Industry and Lab Presentations**
Chairperson, *Thomas Bickel - Sandia National Laboratory*

Roger Poeppel - Argonne National Laboratory
Robert McConnell - National Renewable Energy Laboratory
Jeff Willis - Los Alamos National Laboratory
Tom Bickel - Sandia National Laboratory
Mas Suenaga - Brookhaven National Laboratory
Robort Hawsey - Oak Ridge National Laboratory
Don Gubser - Naval Research Laboratories
Mike Tomsic - Plastronic, Inc.
Robert Sokolowski - Intermagnetics General Corporation
Lawrence Masur - American Superconductor Corporation
John Barber - IAP Research Inc.
Industrialization of Novel Superconducting Magnet Manufacturing Methods Developed by the SSC Laboratory, *John Skaritka*
James Gaines - Superconductive Components, Inc
Justin Schwartz - National High Magnetic Field Laboratory

5:30-6:30 p.m. **Reception (Cash Bar)**

Thursday, February 17, 1994

7:45 a.m.	**Continental Breakfast** *Hosted by Florida Power Corporation*
8:15 a.m.	**Road to Commercialization** Expected Outcomes from Working Group Discussions *Robert Hawsey - Oak Ridge National Laboratory*
8:30 a.m.	**Concurrent Working Groups** *Wire Characterization: Issues and Needs* *Technology for Overcoming Barriers: Weak Links and Flux Pinning* *Manufacturing Issues for Long Wire Lengths* *Physical Properties of HTS Coils*
10:30 a.m.	**Break**
10:45 a.m.	**Summary Session—Reports from Working Group Chairpersons** Discussions
11:45 a.m.	**Closing Remarks - Workshop Evaluation**
12:00 noon	**Luncheon**
1:00 p.m.	**Tour of Bartow Power Plant**

About the tour........

In the development and introduction of new products, designers must be cognizant of a variety of different factors including the operating environment in which the equipment will be used, the organizational culture and operating practices of potential users, and the presently accepted products that the new offering will displace. Since many of the major utility applications of superconductivity are targeted at power plants, this tour provides an opportunity to see an operating plant environment and learn what is important to the plant's operating personnel. Bartow Power Station has three oil-fired units (two 120-MW units and one 230-MW unit). The tour will be specifically directed at potential applications of superconductivity, such as generators, large motors, station step-up transformers, transmission lines (short, long), fault current limiters, shunt and series reactors, transformers, and related cooling systems. Station personnel will be available to discuss and answer questions from an operations and maintenance perspective.

SECTION II

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St. Petersburg, Florida
February 16-17, 1994

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SECTION III

WELCOME AND INTRODUCTORY REMARKS

MISSION

Assist U.S. industry in developing the technology needed to proceed to commercial development of high-temperature superconducting electric power applications

VISION

By 2010, the U.S. electric power systems equipment industry will regain a major share of the global market by offering superconducting products that out perform the competition. In the U.S., the power grid will gain increased efficiency and flexibility

PARALLEL ACTIVITIES:

- Wire Development
- Electric Power Applications Development
- Superconductivity Partnership Initiative

BACKGROUND

- DOE manages the national effort to help enable commercial applications of high temperature superconductivity for electric power

- DOE program organized around three activities:
  - wire development
  - electric power applications development, including major wire development groups
  - superconductivity partnership initiative

- Workshop focus is on wire development - reflects a major program emphasis

- Program is transitioning to more application-specific technology development

GOALS

- Review methods to achieve practical HTS wire forms
- Discuss expected progress against the critical issues that must be resolved if practical HTS wires are to be commercially successful
- Review critical technology needs in each wire development area
- Outline areas for research emphasis in the program that have the potential for greatly enhancing the wire development effort
- Learn of new technology transfer, development, and product sales opportunities

NEAR-TERM GOALS:

- Establish technology for commercially useful HTS wire and prototype magnets
- Incorporate HTS components in electric power applications

ISSUES

- Need to reduce the cost of wire production.

- Efforts underway to reduce:
  - processing time
  - reduce number of processing steps
  - develop alternatives to silver sheathing
  - develop new low-cost approaches to wire fabrication

- Need to be able to measure the performance characteristics of wire and relate these characteristics to physical properties such as texture

ISSUES (cont.)

- Need to improve the current density of even the best wires by at least a factor of two to enable practical "engineering" critical current densities for applications
- Need to continue aggressive development of high performance coils with specific application targets
- Other needs

AGENDA

Day 1:

- Workshop Overview and State of Technology
- Wire Characterization: Issues and Needs
- Technology for Overcoming Barriers: Weak Links and Flux Pinning
- Manufacturing Issues for Long Wire Lengths
- Physical Properties of HTS Coils
- Technology Development and Transfer Opportunities from the Program
- Reception

AGENDA

Day 2:

- Road to Commercialization
- Concurrent Working Groups:
  1) Wire Characterization: Issues and Needs
  2) Technology for Overcoming Barriers: Weak Links and Flux Pinning
  3) Manufacturing Issues for Long Wire Lengths
  4) Physical Properties of HTS Coils
- Summary Session: Reports from Working Group Chairpersons
- Workshop Evaluation
- Luncheon
- Tour of Bartow Power Plant

WORKSHOP OBJECTIVES

- delineate and clarify the **key technical issues** associated with HTS wire development
- share **recent progress** that may help resolve these issues
- define **problem areas** that may require special attention within the DOE program
- provide an **opportunity for dialogue** with colleagues

WORKSHOP OBJECTIVES (cont.)

- obtain **information on technology available** from the laboratories and private companies
- identify special **facility** and **resource needs**
- suggest **potential new/different approaches** and partnerships to improve HTS wire performance

EXPECTED OUTCOMES

- identify critical development issues and needs to enable practical commercial HTS wire for electric power applications
- hear and record participant's views on areas for research and development emphasis which will strengthen the program
- make available research results from the program laboratories and private sector participants
- hear about new opportunities for partnership and commercialization

SECTION IV

WORKSHOP OVERVIEW AND STATE OF TECHNOLOGY

THE ELECTRIC UTILITY PERSPECTIVE:

NEEDS AND BENEFITS OF SUPERCONDUCTIVITY

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WHY SUPERCONDUCTIVITY?

PROMISE OF ELECTRIC ENERGY THAT IS:

- CHEAPER
- MORE EFFICIENT
- LESS POLLUTING

FLORIDA POWER CORPORATION

WHO ARE WE:

- 2nd Largest Investor Owned Utility
- A Subsidiary of Florida Progress
- 1,242,529 Customers
- 5,416 Employees
- Covering an area of 20,000 sq. miles
- 7,500 MW of Generating Capacity
- 4,454 Miles of Transmission Lines
- 22,390 Miles of Distribution Lines

FLORIDA POWER CORPORATION AND SUPERCONDUCTIVITY

PAST

- Headed effort to bring Engineering Test Model (10 MWH) to Florida in 1987.
- Active Participation in Super Conducting Magnetic Energy Storage through EPRI.

FLORIDA POWER CORPORATION AND SUPERCONDUCTIVITY

PRESENT

- Conducting study of Superconducting Magnetic Energy Storage Applications in Florida (with DOE/City of Tallahassee and the High Magnetics Lab).

FLORIDA POWER CORPORATION AND SUPERCONDUCTIVITY

OUR FUTURE ROLE

- Participate in Applied R&D Efforts via EPRI.
- User of Products of Superconductivity Research.

ELECTRIC UTILITY AND SUPERCONDUCTIVITY

"What We Expect From Superconductivity"

- Cost Competitive - Capital and O&M
- Contributes to customer (commercial and industrial) ability to compete in world market
- Reliability - Equivalent to alternatives
- Durability
- Safety
- Public Acceptance

Where would we use Superconductivity?

- Transmission and Distribution Lines
- Transmission and Distribution Equipment
  - Transformers
  - Protective Devices
- Generators
- Motors
  - Power Plants
  - Customers
    - Commercial and Industrial
- Energy Storage
  - Macro - Mini - Micro

TIME GOAL

- Superconductivity Research and Industry need to develop a realistic time schedule, linked to the cost goal. Without this information, planning is not possible.

LOGISTICS

- The total $ needed to achieve the cost and time goals have to be clearly stated and the goals adjusted based on "actual" support.

We recognize that R&D results are not always predictable. However, it is vital that we apply our best thinking to set realistic targets. It helps in the

CHALLENGES

REAL APPLICATIONS

- **Superconductivity Research and Industry efforts must have a clear vision of the future based on:**

COST GOAL

- **Superconductivity Research and Industry need to identify a clear cost goal, backed by real and verifiable assumptions.**

ARE WE ON THE RIGHT TRACK?

Every single Superconducting R&D project we have evaluated is on the "High Potential Value" category.

Including the work on:

- **Motors**
- **Generators**
- **SMES**
- **Wires**
- **Magnets/Coils**
- **Fly Wheels**

BOTTOM LINE:

Superconductivity is vital to our long term future as a company and as a nation. It deserves the joint effort to which we all aspire.

Limits to Loss-Free Current Flow in HTS Conductors: An Update

D. K. Christen

Solid State Division
Oak Ridge National Laboratory

SPP HTS Wire Development Workshop
Feb 16-17, 1994
St. Petersburg, FL

Factors that Limit Loss-Free Conduction in HTS

- ***Inter-Grain Connectivity***
  - Grain Alignment (Strongly Anisotropic Sc Properties)
  - Grain Boundary Coupling (Overcoming "Weak Links")

- ***Intra-grain Flux Pinning***
  - Optimization of defects
  - Intrinsic Material Limits (Strong Anisotropy, Large kT)

Inter-Grain Connectivity

- ***Present HTS Conductors have both Strong- and Weak-Link Components***

- ***The Well-Connected Component Represents a Small Volume Fraction***

Evidence (in Tl1223 thick films)

$H || c$

— Scaling of properties for different films, etc.

— $J_c(B)$ much less than, but otherwise similar to "strong" materials (e.g. epitaxial thin films)

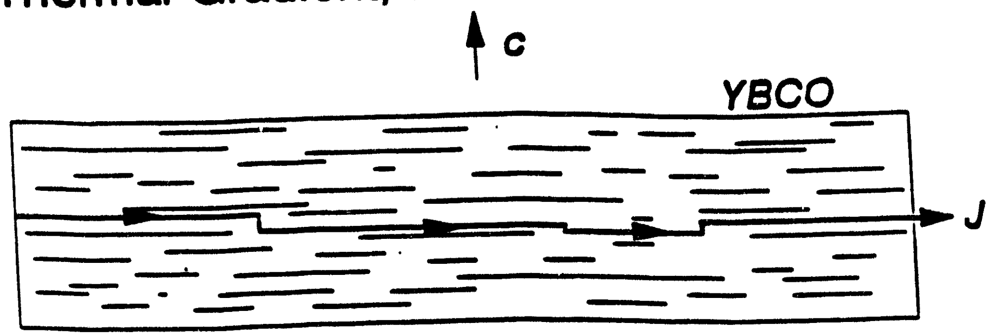
— Artificial flux pinning defects enhance the properties at high fields

- ***Transport Properties can be Greatly Enhanced by Improvements in Processing***

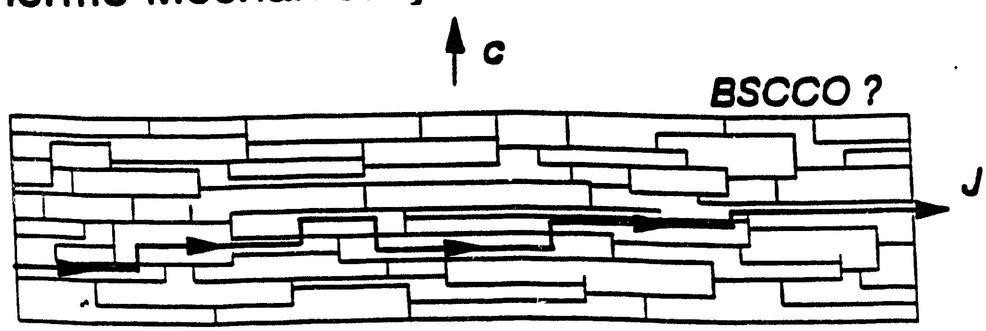
Inter-Grain Connectivity

- ***Identified (or Proposed) Mechanisms***

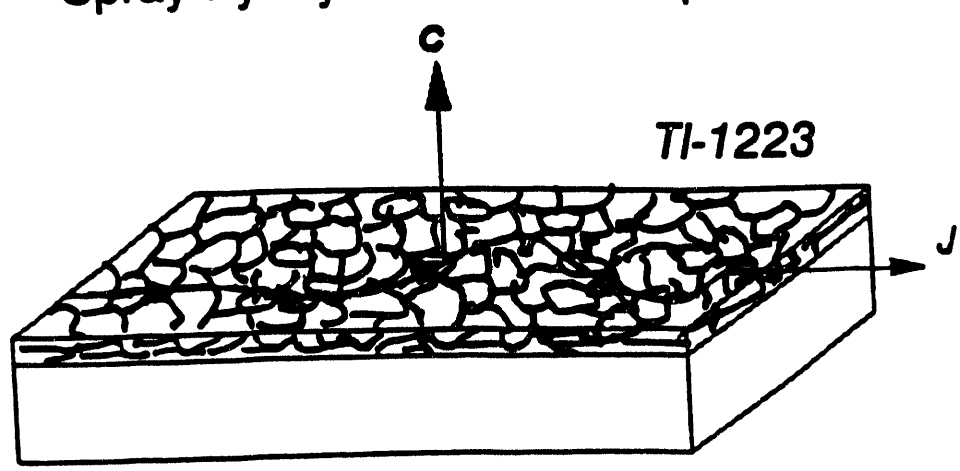
Thermal Gradient, Melt-Processed YBCO



Thermo-Mechanically Processed PIT BSCCO



Spray-Pyrolyzed Tl-1223 Deposits

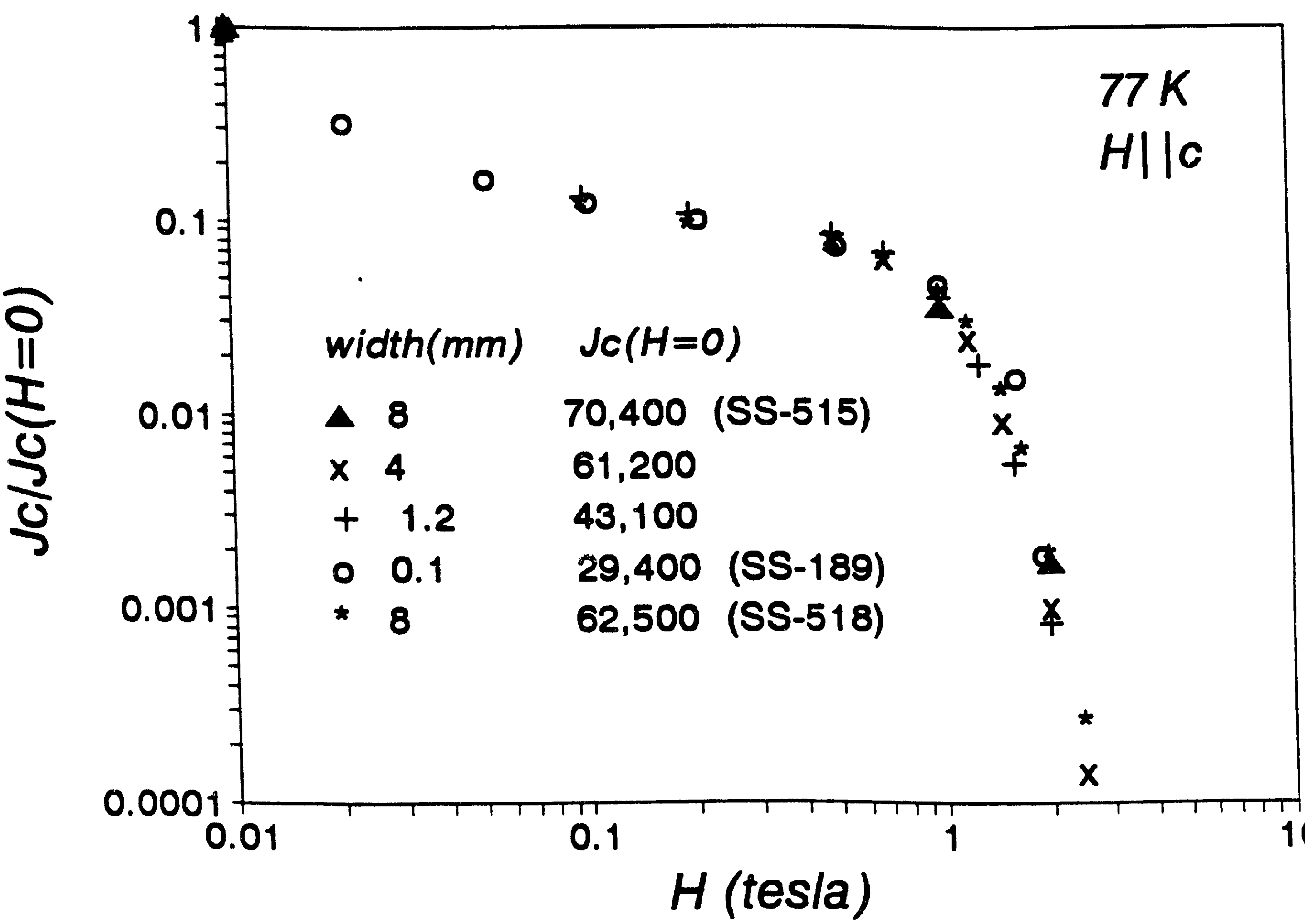


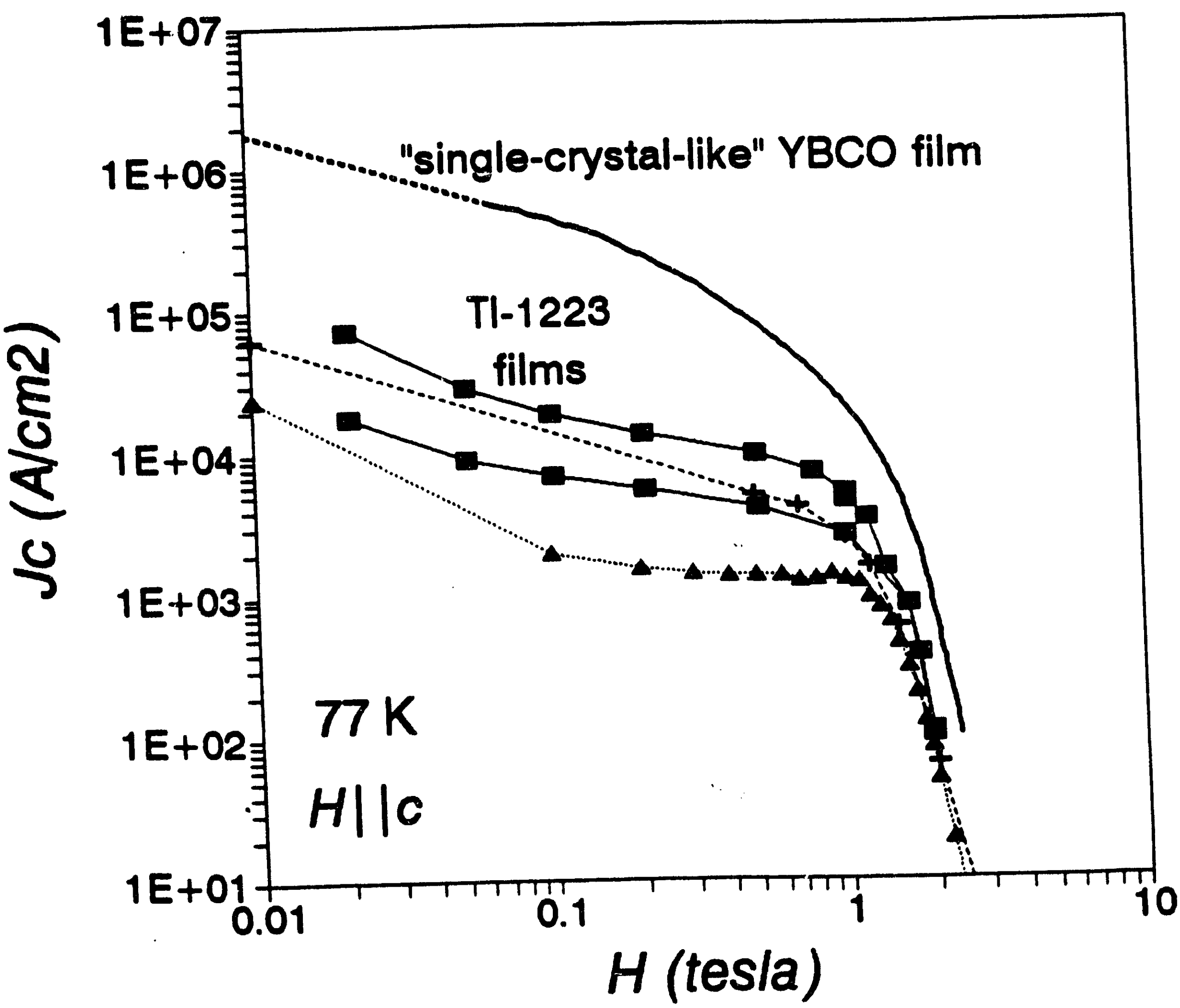
J_c of Tl-1223 Deposits on Polycrystalline YSZ

- The overall field dependence is similar for different samples, and for different widths of same sample

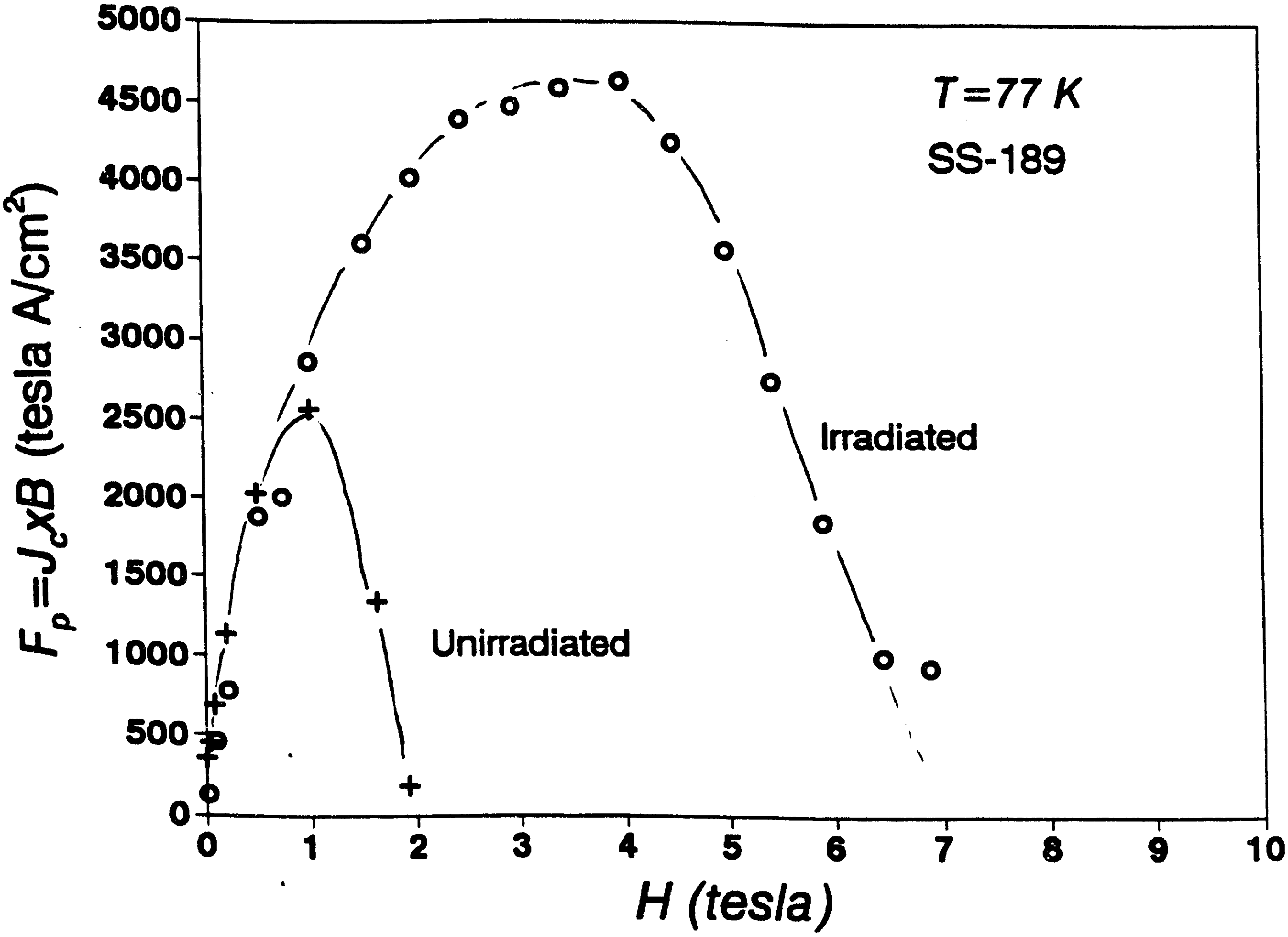
- J_c vanishes at the same irreversibility field

— The flux-pinning defect microstructure is similar
—Different samples have different fractions of well-connected material





"single-crystal-like" YBCO film
Tl-1223
films
77 K
H||c
Jc (A/cm2)
H (tesla)
1E+07
1E+06
1E+05
1E+04
1E+03
1E+02
1E+01
0.01
0.1
1
10



The Flux Pinning Force Density F_p of Heavy Ion Irradiated Tl1223

- At high field J_c and B_{irr} are enhanced
  — *the properties are limited by intra-grain flux pinning*

Intra-Grain Flux Pinning

- *Optimal Defects: Normal columns that occupy every vortex*

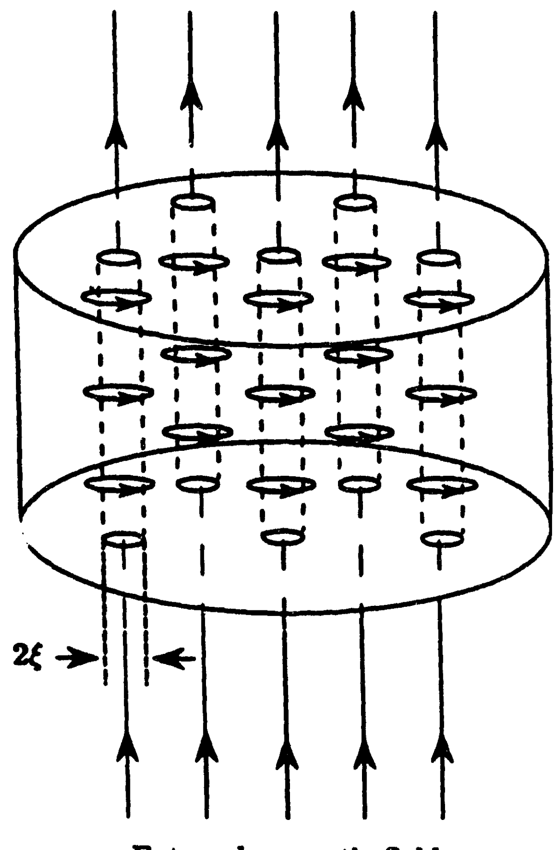
INNING ENERGY/UNIT LENGTH OF VORTEX

$$_o \simeq \frac{H_c^2}{4\pi} \pi \xi_{ab}^2 = \frac{\phi_o^2}{32\pi^2\lambda_{ab}^2}$$

MAXIMUM CRITICAL CURRENT DENSITY

$$J_{c,max} \sim J_d \simeq 0.4 \; H_c/\lambda_{ab}$$

(J_d = depairing critical current density)



Intra-Grain Flux Pinning

- *Comparison of HTS and LTS at Low Temperature*

$$J_{c,max} \approx 0.4\ H_c/\lambda_{ab}$$

Estimate $J_{c,max}$ at $T \simeq 4.2\ K$

Material	$T_c(K)$	$H_c(Tesla)$	$\lambda(nm)$	$J_{c,max}(A/cm^2)$	$J_{c,obs}(A/cm^2)$
Nb_3Sn*	17.9	0.45	100	6×10^7	$\gtrsim 1\times10^6$
V_3Si*	16.8	0.45	110	6×10^7	–
Nb47wt%Ti†	9.3	0.125	250	7×10^6	$\gtrsim 1\times10^6$
$Y_1Ba_2Cu_3O_7$	90	1.1	140	1×10^8	5×10^7
Bi-2223+	105	1.0	220	6×10^7	–
Bi-2212+	85	~1.0	300	5×10^7	6×10^6
Tl-2223#	122	~1.0	173	8×10^7	$\sim 1\times10^7$

*Orlando, *et al.*, PRB 19, 4545 (1979)

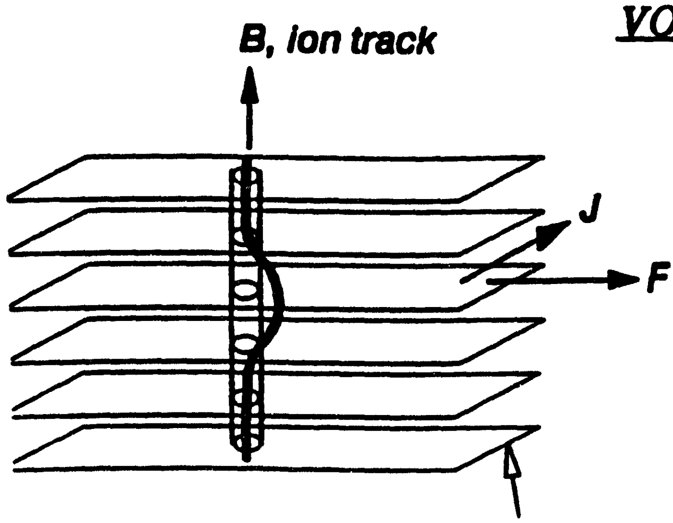
†Cooley, *et al.*, APL 58 2984 (1991)

+Thompson, *et al.*, Physica B 165, 1453 (1991)

#Thompson, *et al.*, PRB 41, 7293 (1990)

Intra-Grain Flux Pinning

- *Complicated Behavior at High Temperature*
  - — Large thermal energies kT
  - — Weak vortex stiffness (line tension)



VORTEX HALF-LOOP and KINK FORMATION

[Nelson and Vinokur, PRL **68**, 2398 (1992)]

[Brandt, PRL **69**, 1105 (1992)]

ENERGY CONSIDERATIONS

Pinning line energy: u_p

Vortex line tension: $\tilde{\varepsilon} = \epsilon/\gamma^2$

Lorentz line force: $J\phi_o/c$

ENERGY SCALE: $U_o = (u_p \tilde{\varepsilon})^{1/2}\, 2\sqrt{2}\, a$

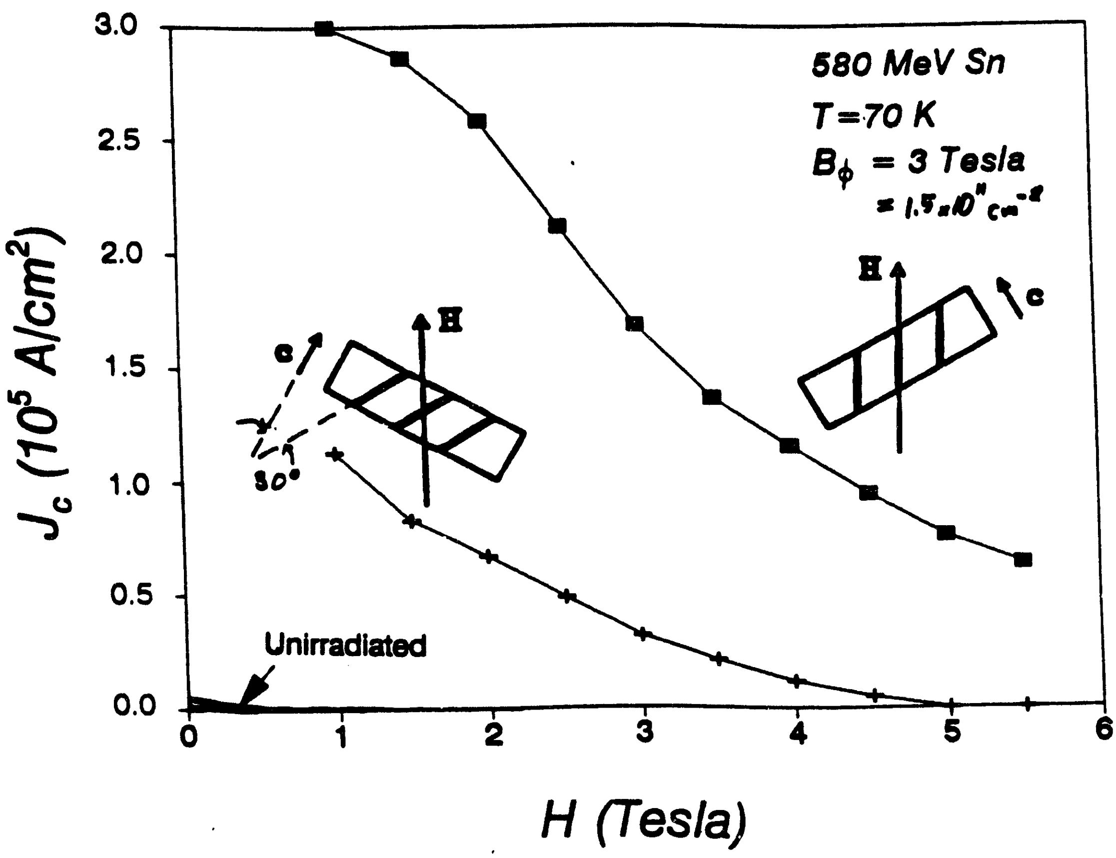
CURRENT DENSITY SCALE: $J_o = u_p\, c/\phi_o\, a$

Effective Pinning Energy: $U_{eff} \propto (m_{ab}/m_c)^{1/2} << 1$

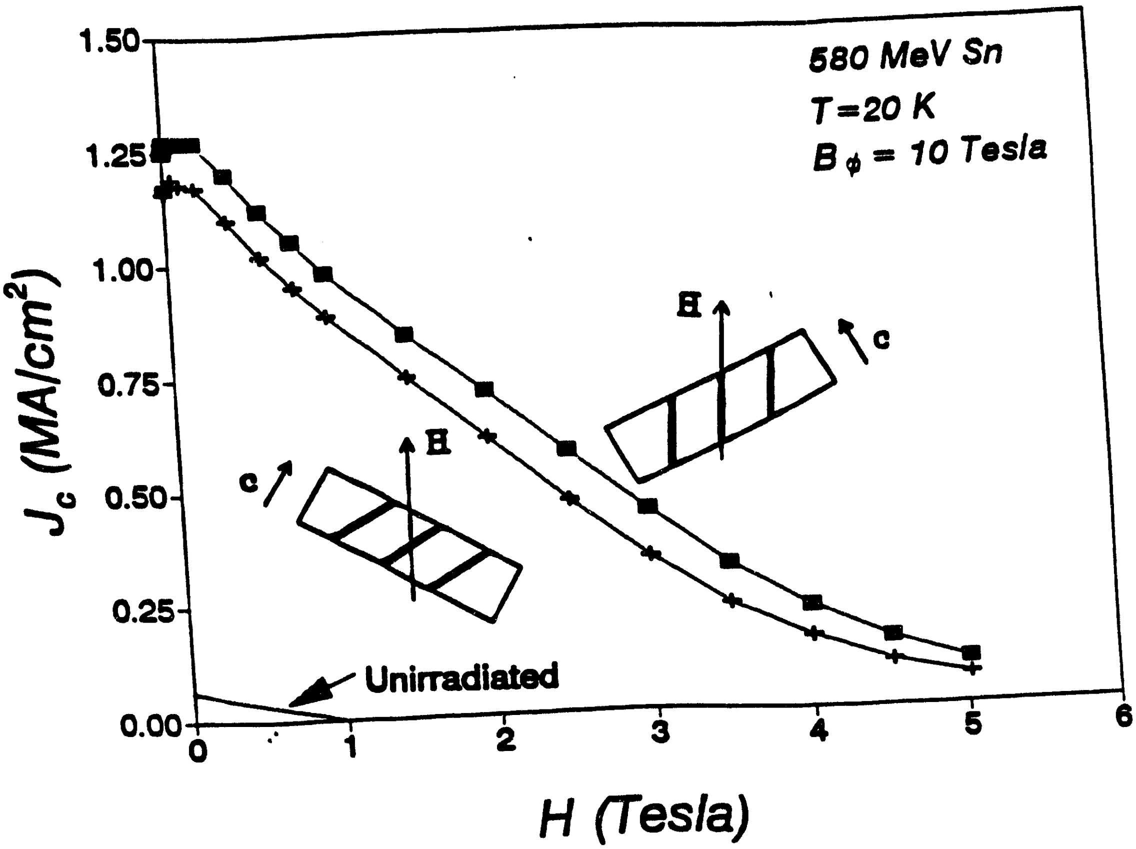
Dissipation (electric field): $E = E_o \exp(-U_{eff}/kT)$

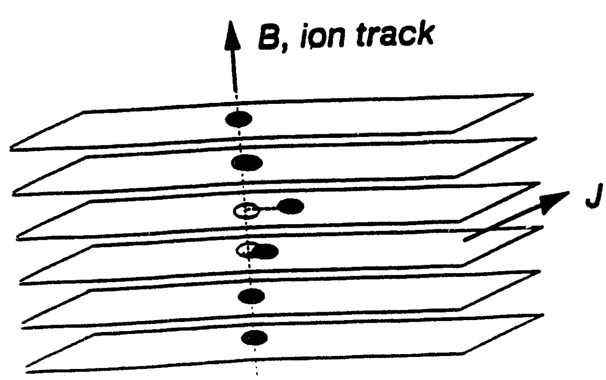
e.g., $(m_{ab}/m_c)^{1/2} \approx \begin{cases} \frac{1}{5.5} & \text{YBCO} \\ <\frac{1}{150} & \text{Bi2212} \end{cases}$

$YBa_2Cu_3O_7$ Single Crystal

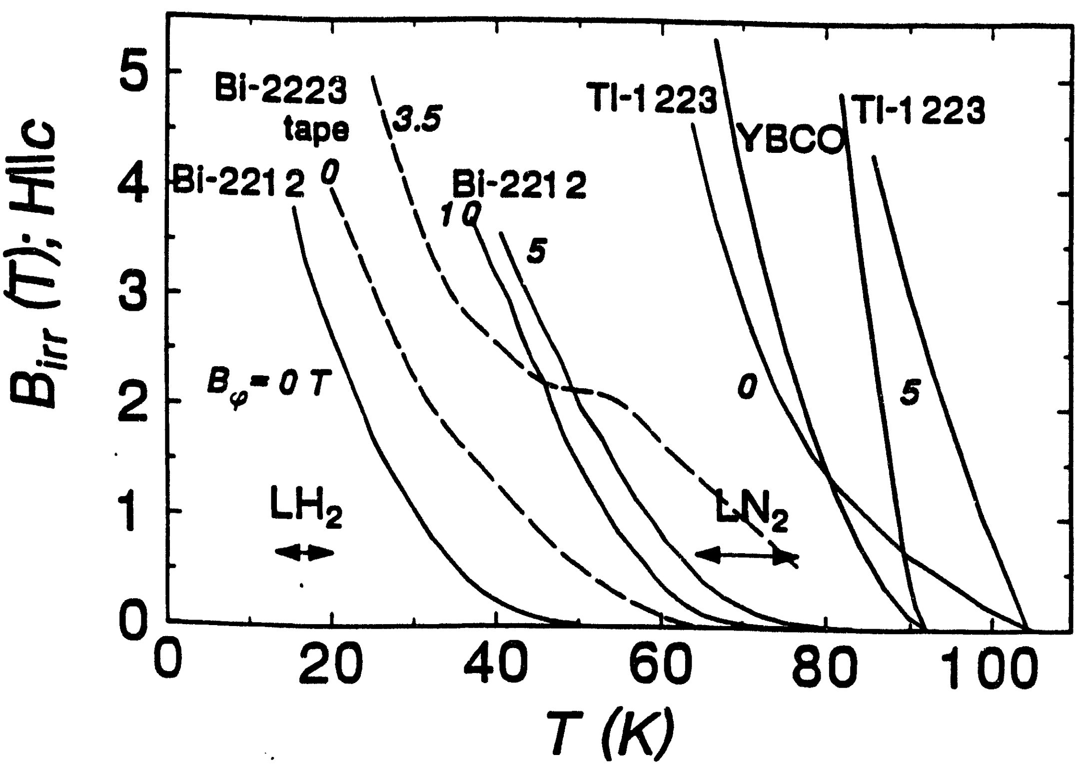


$Bi_2Sr_2Ca_1Cu_2O_8$ Single Crystal

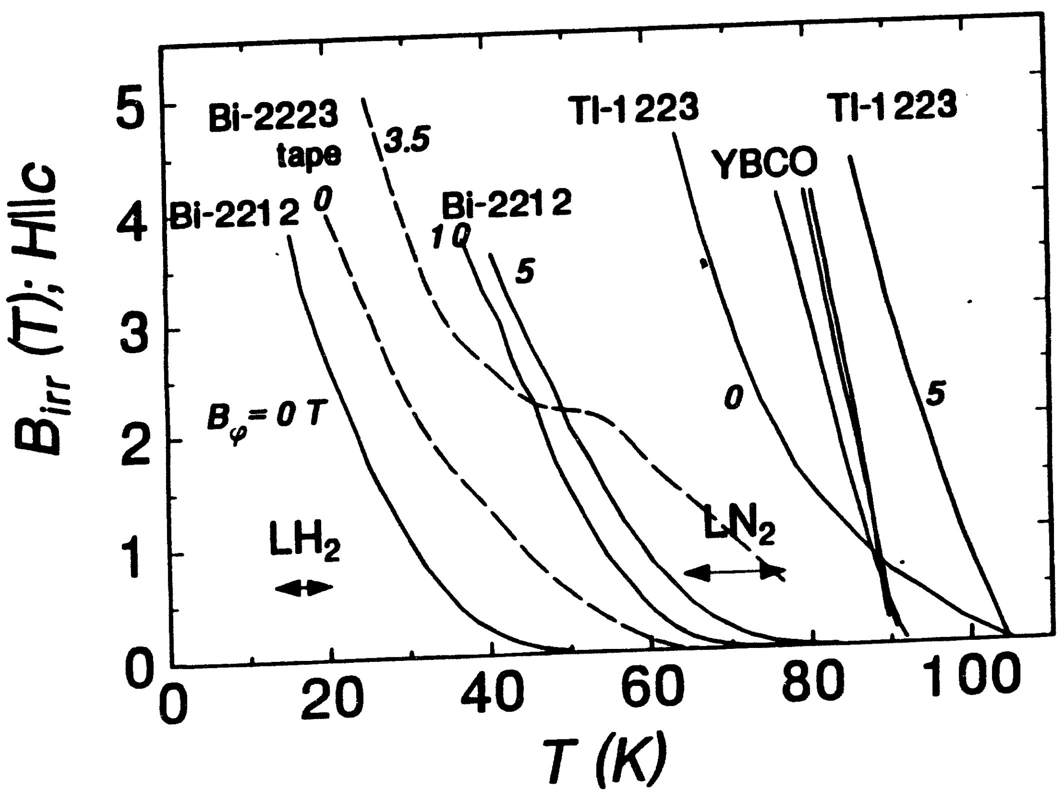




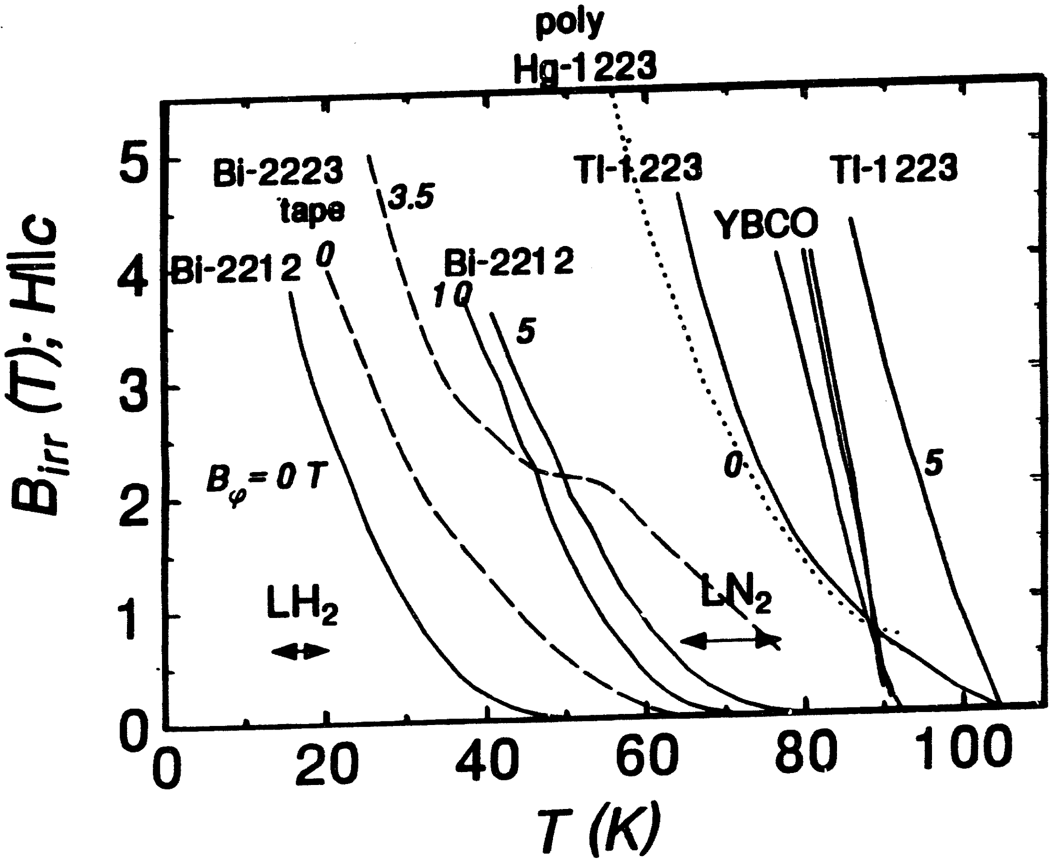
ENHANCEMENTS IN THE IRREVERSIBILITY LINE OF VARIOUS HTS MATERIALS BY HEAVY ION IRRADIATION



ENHANCEMENTS IN THE IRREVERSIBILITY LINE OF VARIOUS HTS MATERIALS BY HEAVY ION IRRADIATION



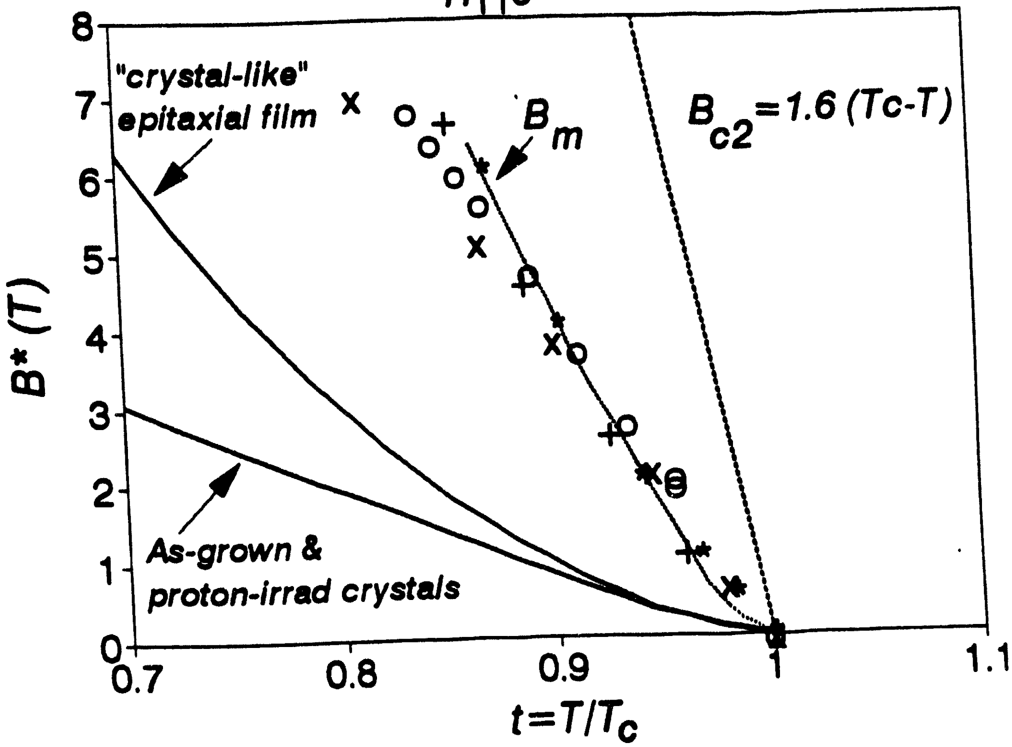
ENHANCEMENTS IN THE IRREVERSIBILITY LINE OF VARIOUS HTS MATERIALS BY HEAVY ION IRRADIATION



Vortex "Melting Line"

[Farrell, *et al.*, PRL 67, (1991)]
[Safar, *et al.*, PRL 69 (1992)]
[Worthington, *et al.*, PRB (1992)]
[Kwok, *et al.*, PRL (1993)]

YBCO
H||c



o *Heavy Ion Irrad Crystal* $B_\phi = 4\ T$

x *Heavy Ion Irrad Film* $B_\phi = 3.5\ T$

+ * *Hi-Jc epitaxial films*

ORNL PHOTO 10617-93

SUMMARY

- *Present HTS conductors have both weak- and strong-link components.*
  - The strong-linked component is a small volume fraction (1 — 10%)

- *The mechanism for the strong-linked component is partially recognized*
  - Improvements in processing should provide large enhancements

- *The strong-linked component is limited by flux pinning*
  - Improvements in flux pinning defect structures can provide large enhancements

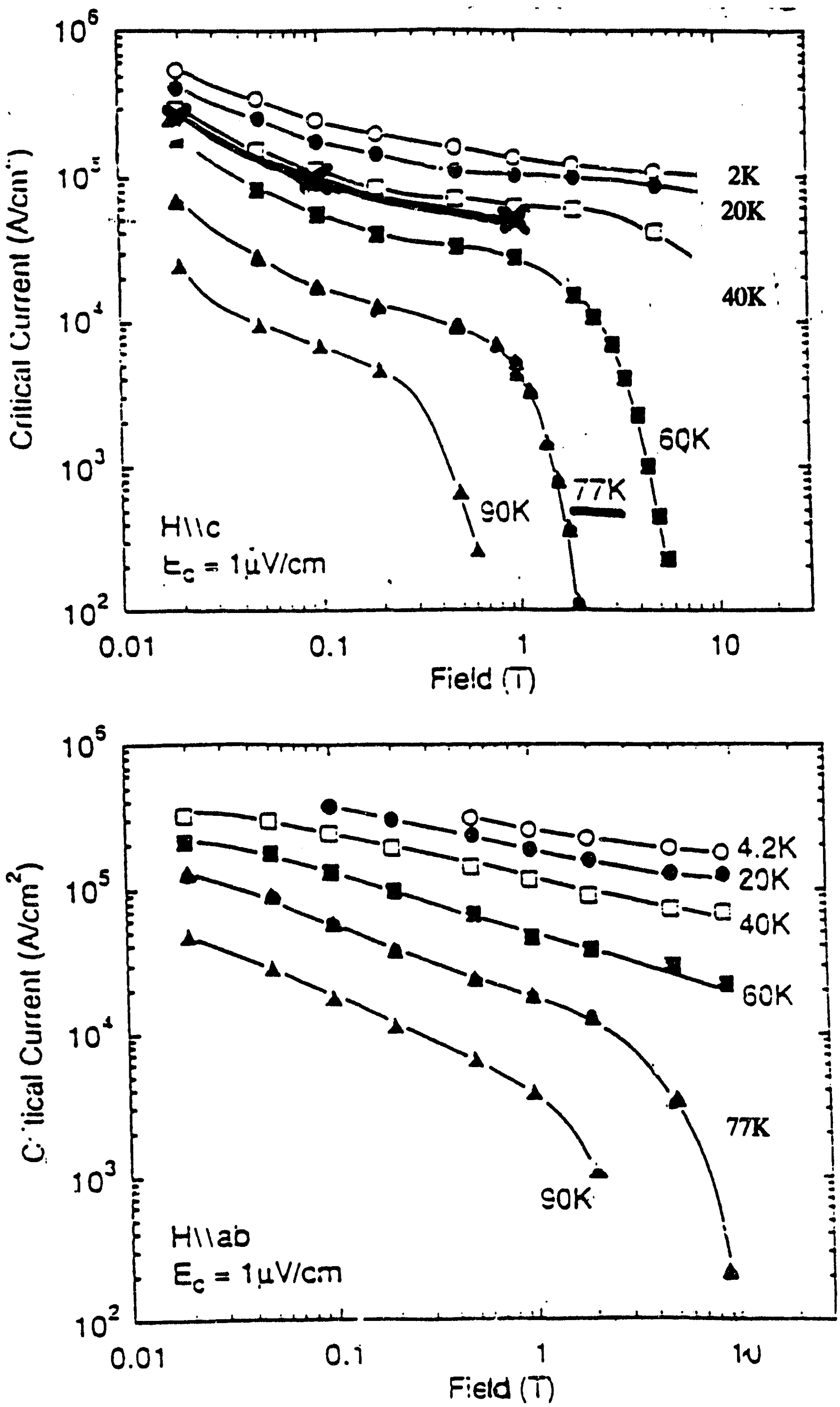
- *High temperature properties are strongly limited by the intrinsic material anisotropy.*

High-Temperature Superconducting Applications: Wire Performance Requirements

Application	Industry driven device goals							
	J_c (A/cm²)	Field (T)	$Temp_{op}$ (K)	I_c (A)	Wire length (m)	Strain (%)	Bend radius (m)	Cost ($/kAm)
Fault-current limiter	10^4-10^5	1-3	20-77	10^3-10^4	100	0.2	0.1	10-100
Large motor (1000 Hp)	10^5	4-5	0-77	500	1,000	0.2-0.3	0.05	10
Generator (300 MVA)	5×10^4 [(a)]	5	20-50	1,000	2,000	0.2	0.1	10
SMES (1 MWh)	10^5	5-10	20-77	10^4	1,000	0.2	1	—
Transmission cable	10^4-10^5	<0.2	77	25-30 [(b)]	100	0.4	2	10-100

(a) Minimum for high-temperature superconducting wire alone

(b) Current for individual wire. Cables, with multiple wires, require current of 5,000 A.



Tl-1223 (STO)
x -- T. Doi et al.
B|| c @ 77K

"Thick film"
c-axis featuring
DeLuca et al.

Jc>10[5] A/cm[2]
@ 77K, H61

Figure 7. Critical current density versus applied field for H || c and H || ab at 77 K for Tl-1223 film applied by spray pyrolysis and reacted using a two-zone method. (Due to DeLuca et al. reference 49)

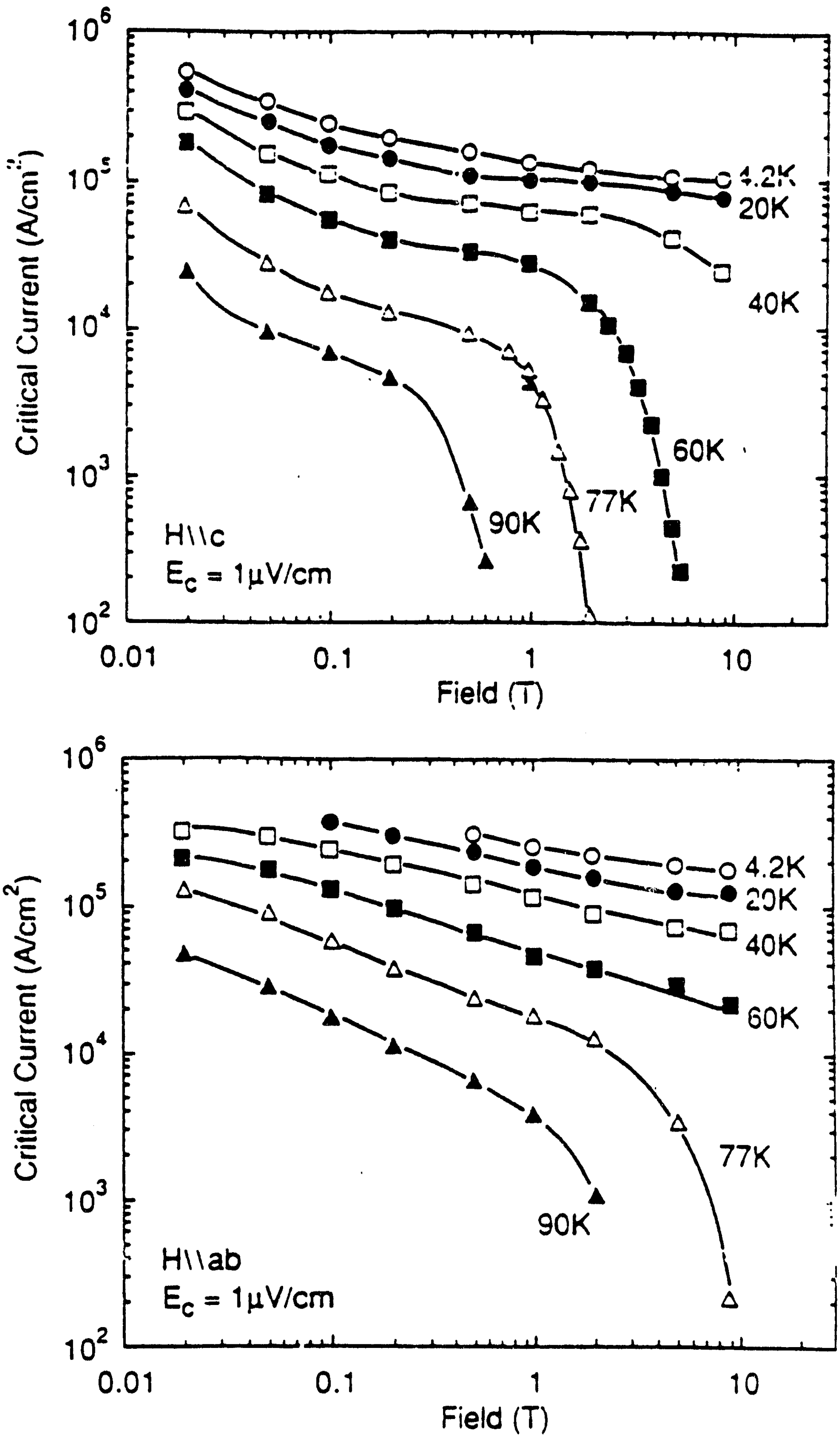
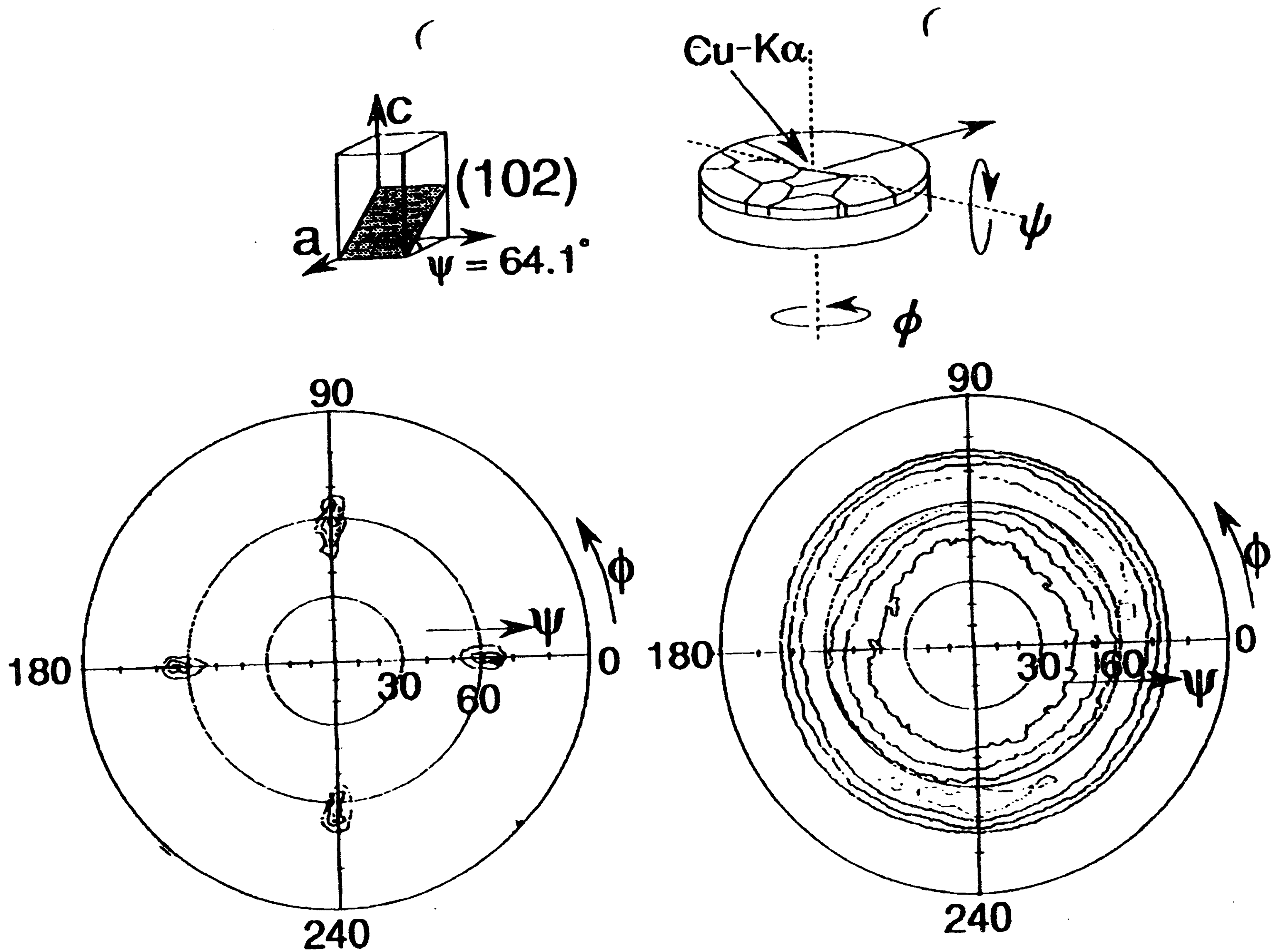


Figure 7. Critical current density versus applied field for H || c and H || ab at 77 K for Tl-1223 film applied by spray pyrolysis and reacted using a two-zone method. (Due to DeLuca et al. reference 49)



(a) Tl-1223 on STO

(b) Tl-1223 on Ag

Fig. In-plane crystal orientations of $TlBa_{1.6}Sr_{0.4}Ca_2Cu_3O_x$ films on STO and Ag substrates.

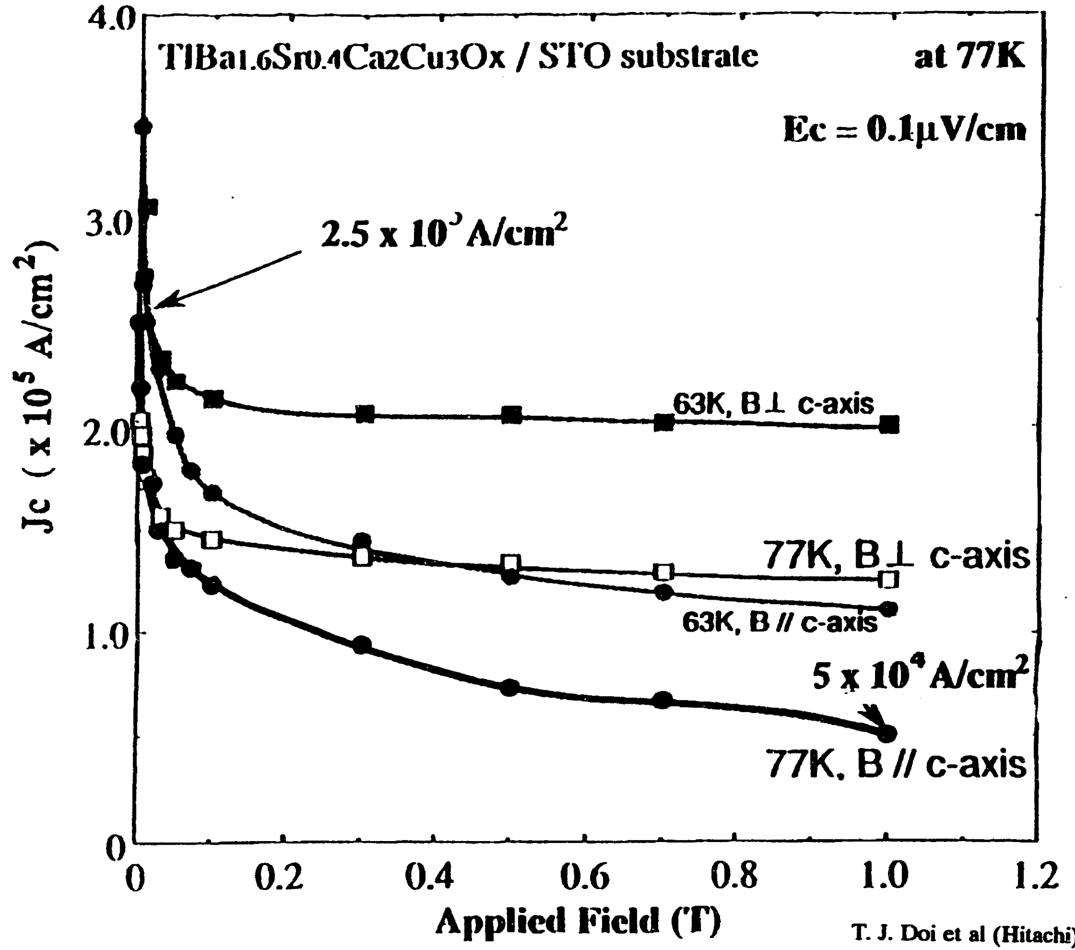


Fig. The magnetic field dependence of $TlBa_{1.6}Sr_{0.4}Ca_2Cu_3O_x$ on STO

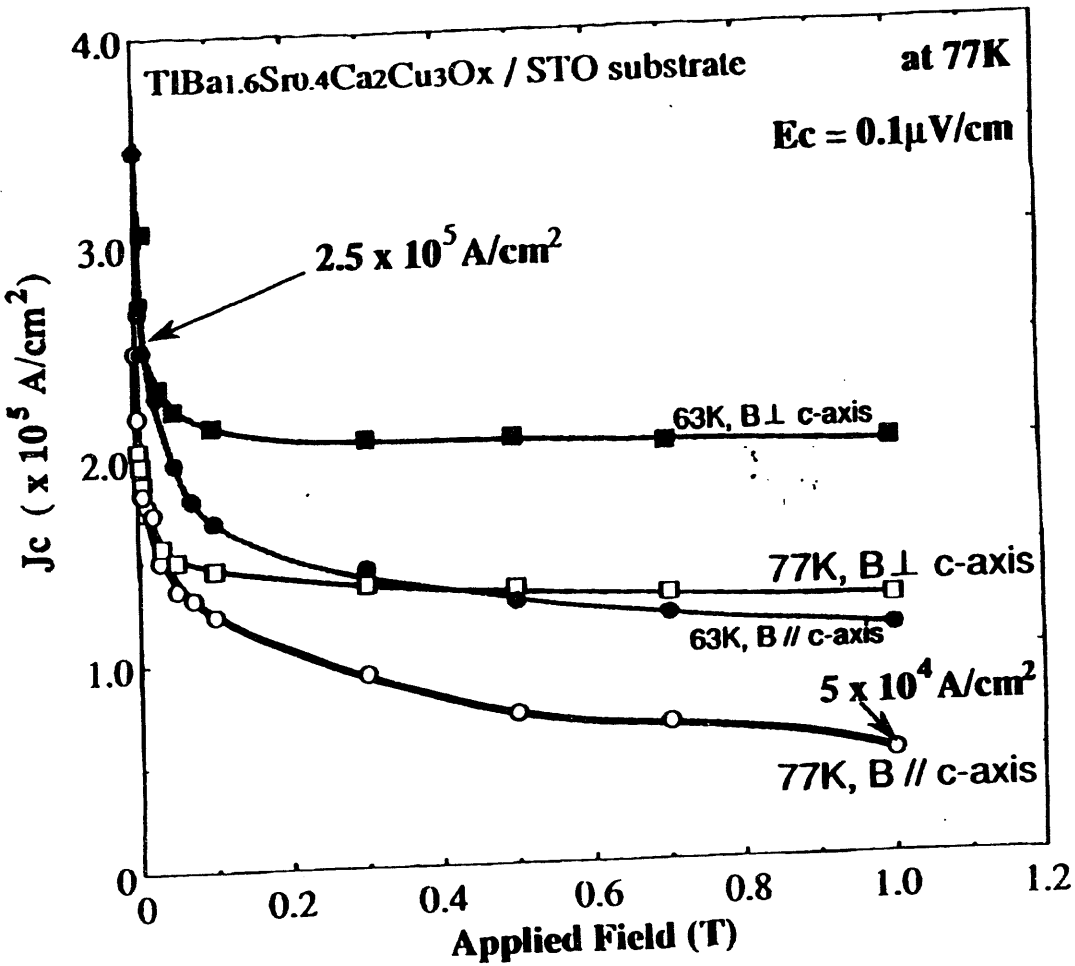
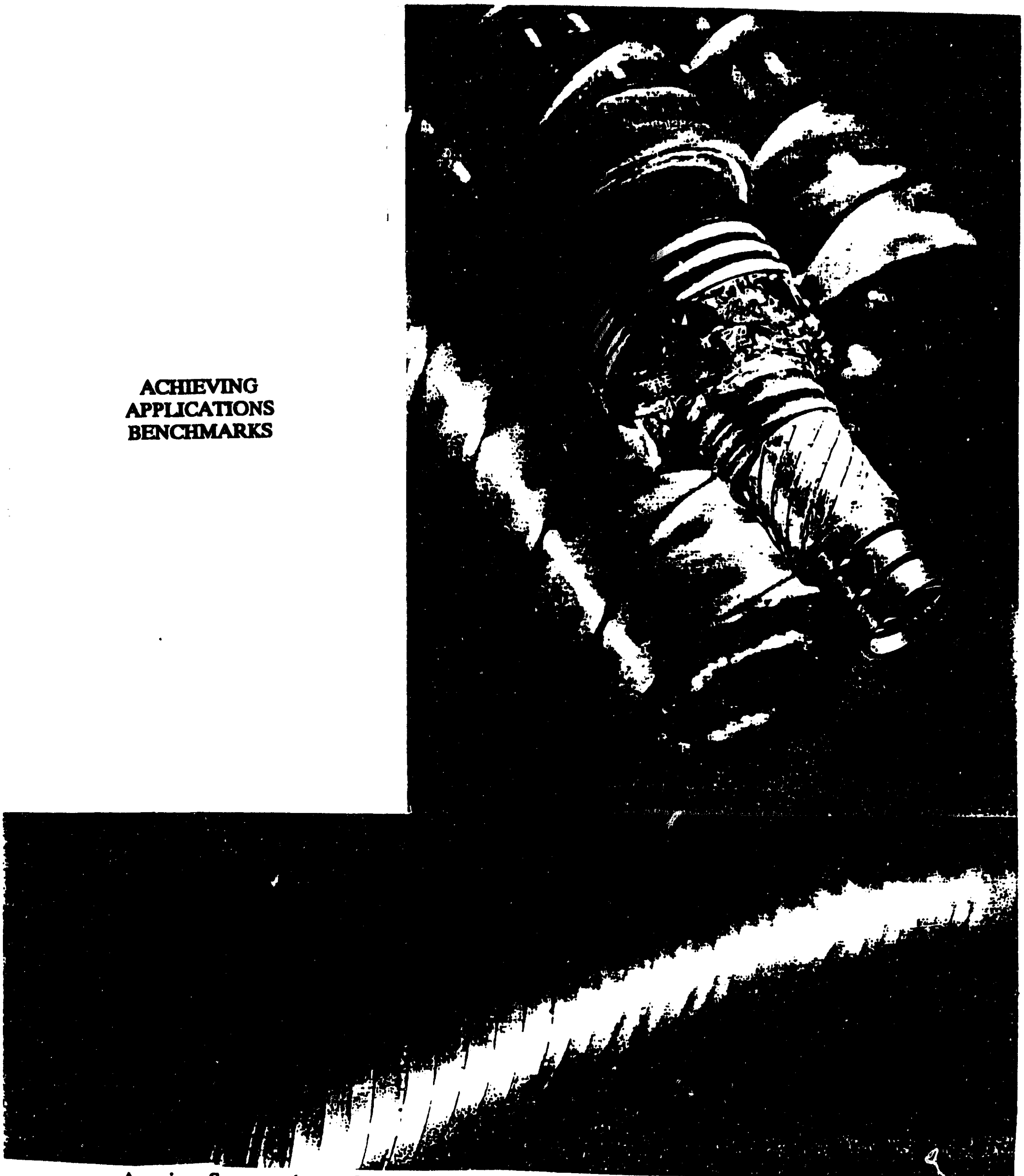
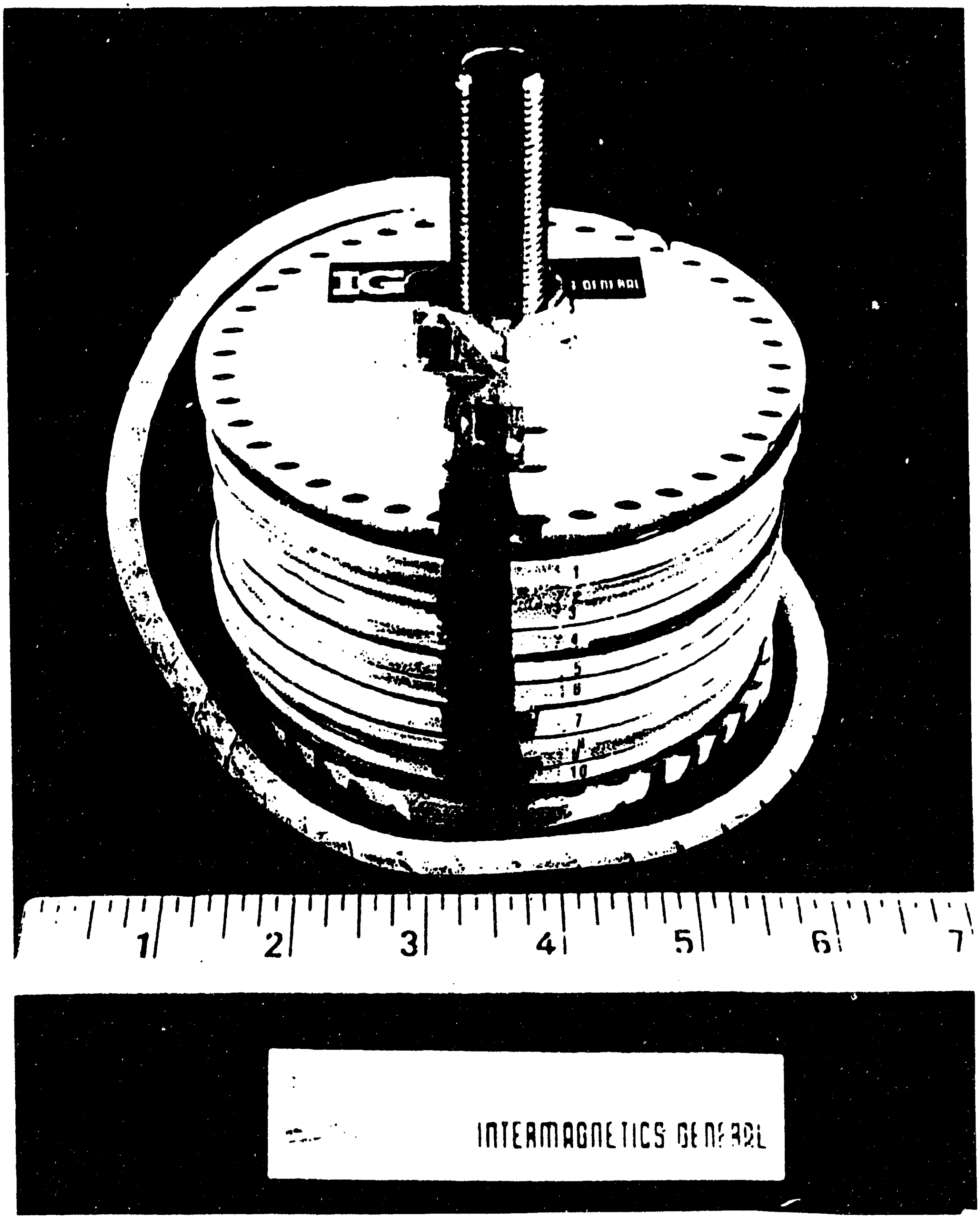


Fig. The magnetic field dependence of $TlBa_{1.6}Sr_{0.4}Ca_2Cu_3O_x$ on STO.

ACHIEVING APPLICATIONS BENCHMARKS



American Superconductor Corporation/Pirelli/EPRI
2300 A (1 m)
Goal (30 m) late 1994



2.6 T (4.2 K) → 1.8 T (27 K) → 0.36 T (77 K)

COMPARISON OF VARIOUS COILS

Organization	Material	T (K)	B(T)	ID (CM)	L (M)	AMP-Turns	Type
Furukawa	Bi2212	4.2	1.65	1.0	22	43,000	Solenoid
NRIM	Bi2212	4.2	2.00	1.4			Pancake
Kobe Steel	Bi2212	4.2	1.60	1.3	450		Pancake
IGC	Bi2223	4.2	2.6	2.5	480	163,800	Pancake
Sumitomo	Bi2223	4.2	2.00	4.0			Pancake
ASC	Bi2223	4.2	0.30		293	17,822	Racetrack
Hitachi	TBSCCO	4.2	0.14	1.0			
Showa	Bi2223	20	1.50	1.0	96		Pancake
Kobe Steel	Bi2212	20	0.62	1.3	450		Pancake
Sumitomo	Bi2223	20	1.0	4.0			Pancake
ASC	Bi2223	20	0.23		293		Racetrack
IGC	Bi2223	27	1.80	2.5	480	113,500	Pancake
IGC	Bi2223	77 K	0.35	2.5	480	22,400	Pancake
ASC	Bi2223	77 K	0.03		293	2,560	Racetrack

COMPARISON OF VARIOUS COILS

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Sumitomo	Bi2223	20	0.5	1.0			Pancake
ASC	Bi2223	20	0.23		293		Racetrack
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IGC	Bi2223	77 K	0.35	2.5	480	22,400	Pancake
ASC	Bi2223	77 K	0.03		293	2,560	Racetrack

Table 1: Superconductor properties of laboratory-scale conductors.

Conductor	Fill Factor	Jc (A/cm^2)	Je (A/cm^2)
a	18%	26,500	4,800
b	23%	23,000	5,300
c	28%	22,100	6,200
d	33%	20,300	6,700

Table 2: Superconductor properties of pilot production conductors

Length (m)	Ic (A)	Jc (A/cm^2)	Je (A/cm^2)	Ic (A)	Jc (A/cm^2)	Je (A/cm^2)
	(1 μV/cm)	(1 μV/cm)	(1 μV/cm)	(10^{-11} Ω-cm)	(10^{-11} Ω-cm)	(10^{-11} Ω-cm)
10	18.7	14,900	4,900	16.0	12,700	4,200
64	19.5	16,500	3,800	16.1	13,500	3,100
280	18.1	15,200	3,500	12.7	10,900	2,500
650	10.1	9,100	2,100	7.3	7,000	1,600

G. N. Riley et al. (American Superconductor Corporation)

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)	SC (%)
SHORT SAMPLE (PRESSED)	51	~45,000	9,000	20
SHORT SAMPLE (ROLLED)	33	~21,000	5,000	24
LONG LENGTH (34 m)	16	~11,000	2,500	24
LONG LENGTH (70 m)	23	~15,000	3,500	24
SHORT SAMPLE (ROLLED)	51	~29,000	7,800	27
COPPER			4,000	

PRADEEP HALDAR

CRITICAL CURRENT DENSITIES OF SHORT AND LONG TAPES AT 77 K.

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SHORT SAMPLE (ROLLED)	51	~29,000	7,800	27
COPPER			4,000	

PRADEEP HALDAR

IGC
H T S

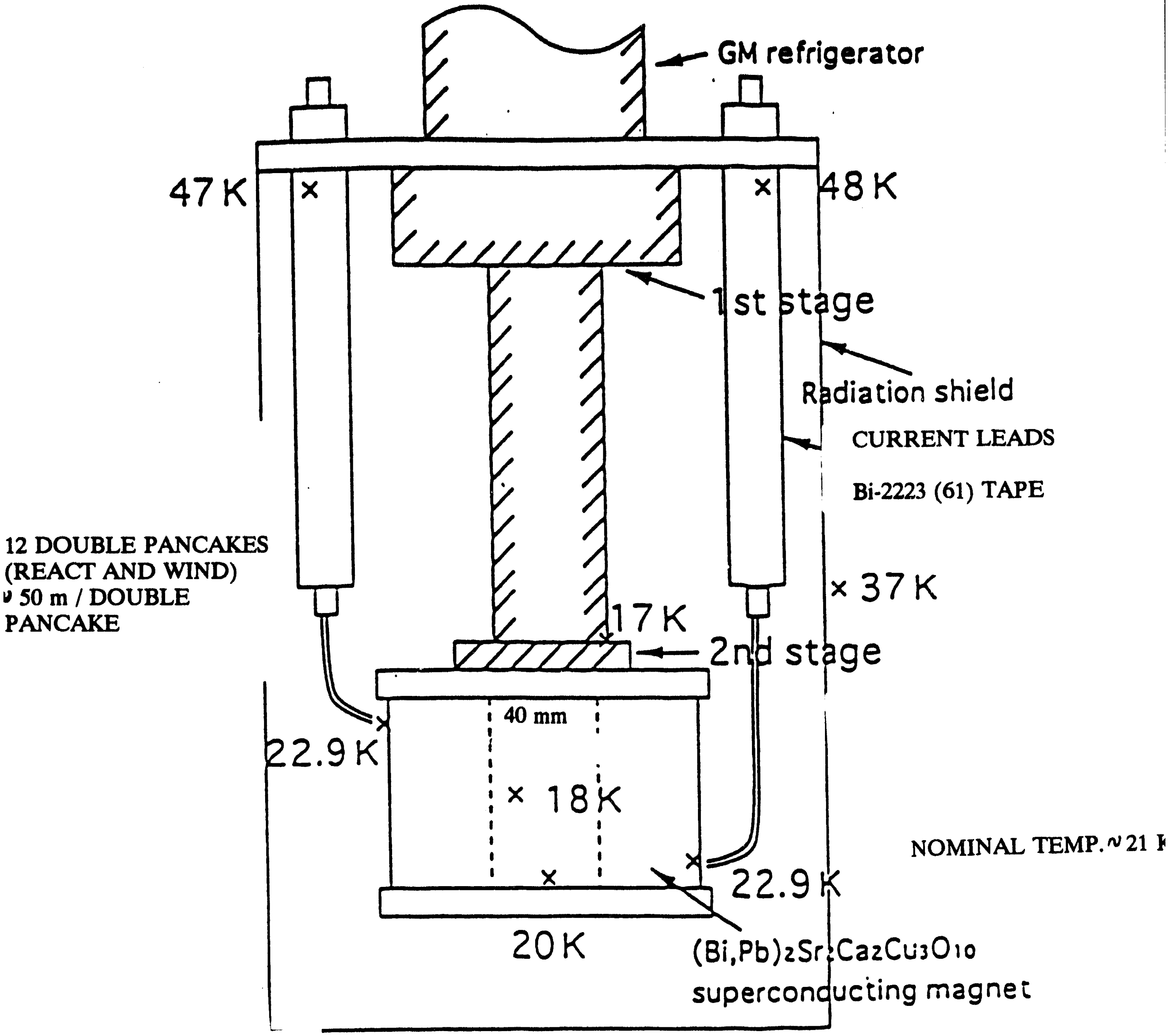
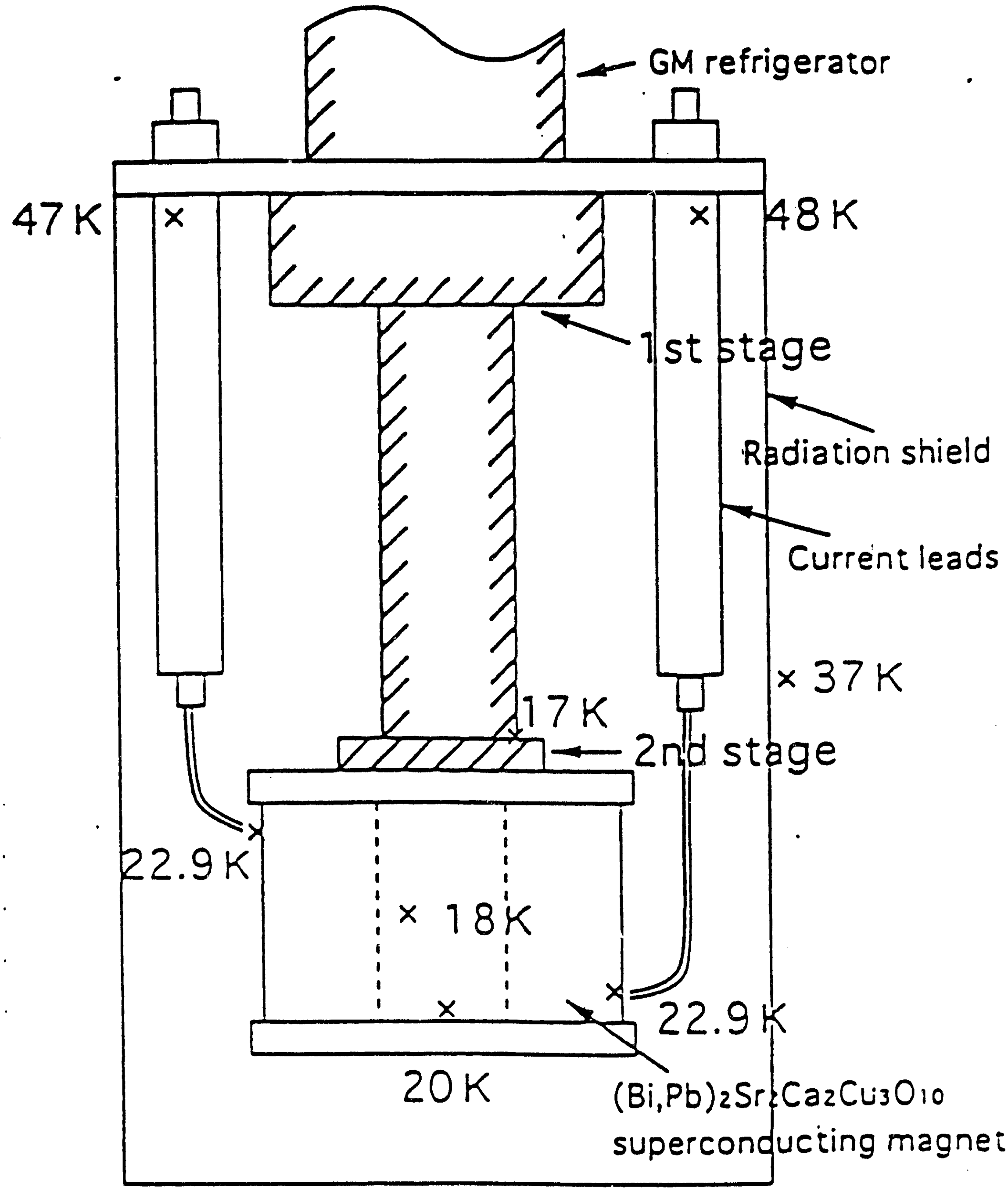


Fig.5 Temperature profile in the conduction–cooled high–Tc magnet system when the coil was operated at 30.8A (1.0 T) and held for 100h. K. Ohkura et al. (Sumitomo)



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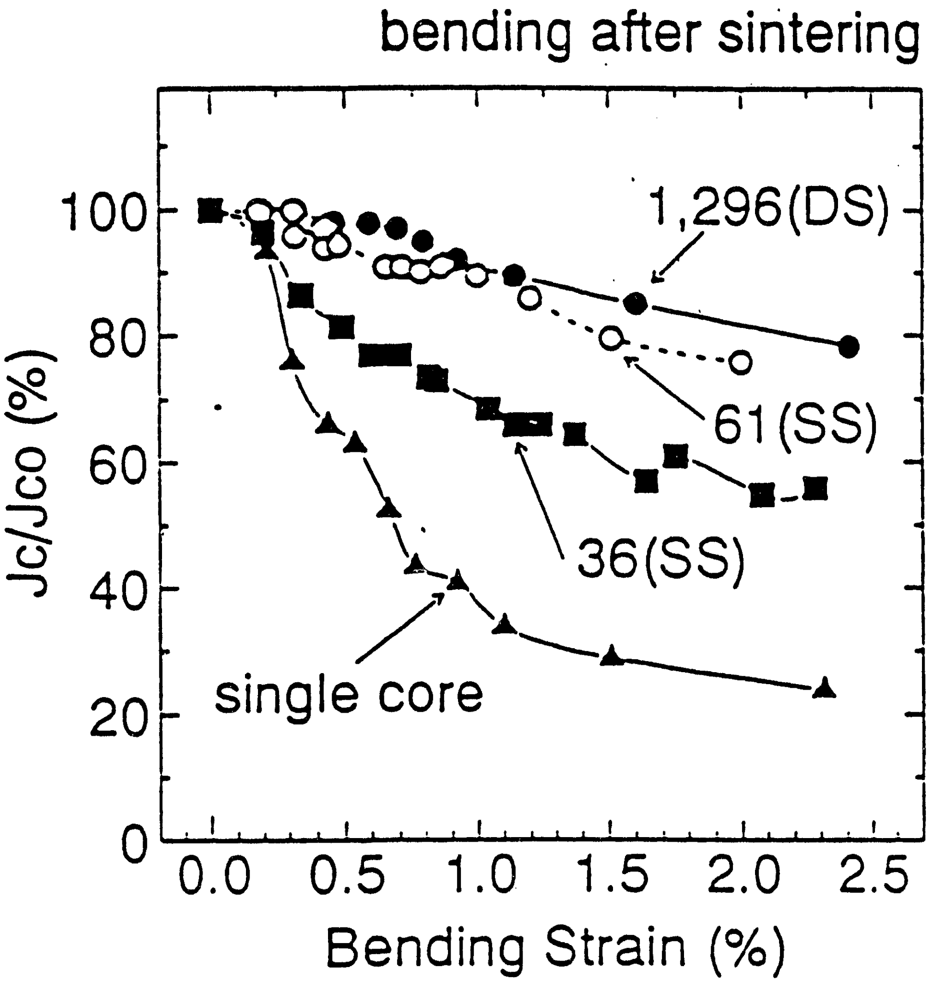


Fig.2 Bending strain characteristics of the high−Tc superconducting tape

K. Ohkura et al. (Sumitomo)

40-mm diam → 0.6% strain → Jc decrease ~5%
(minimum bend)

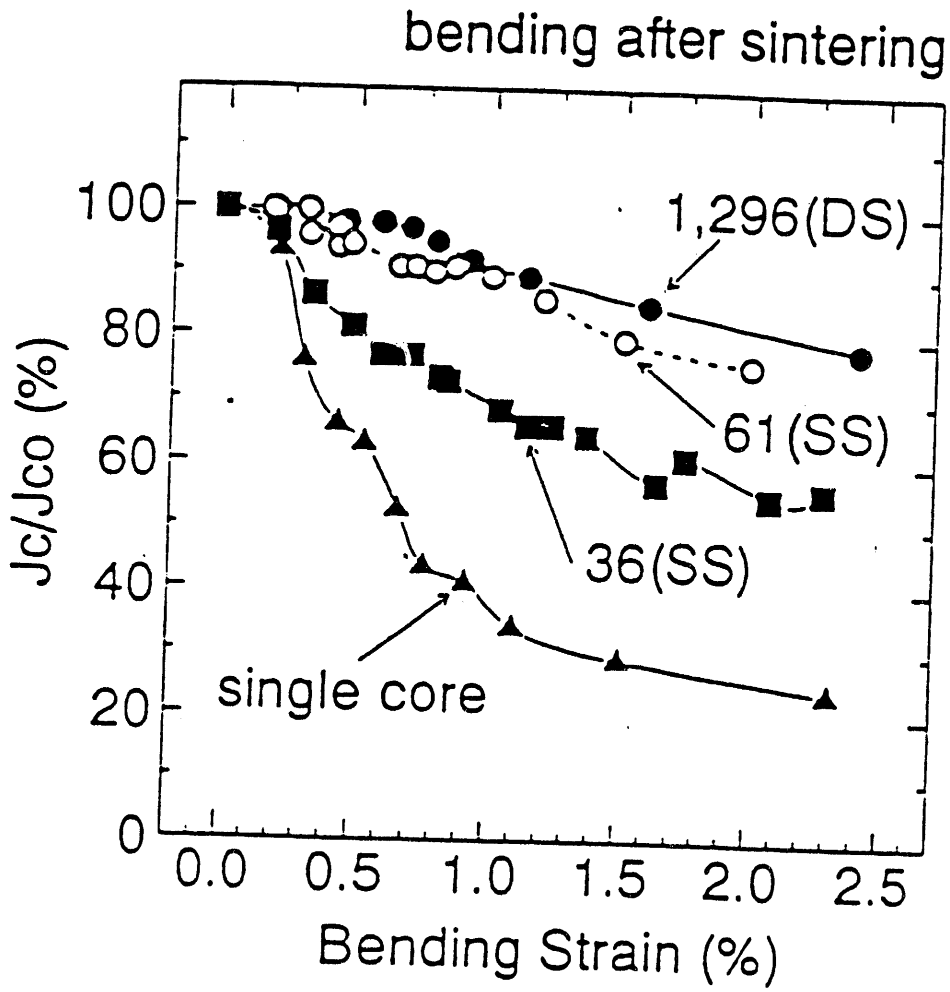


Fig.2 Bending strain characteristics of the high−Tc superconducting tape

LONG WIRE

Length(m)	Jc(A/cm²)	Ic(A)
100	20,500	21.0
518	13,500	17.7
1,080	4,020	2.4

Bi-2223 TAPE
(61 FILAMENT)

Table 1 The Ic characteristics of the long length high−Tc wire

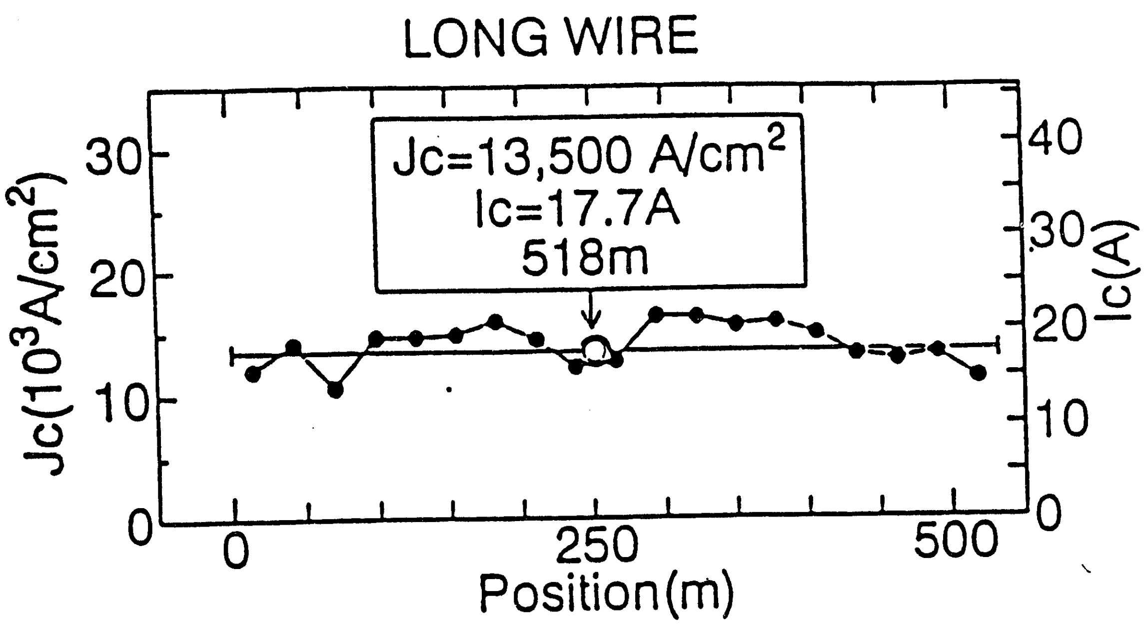
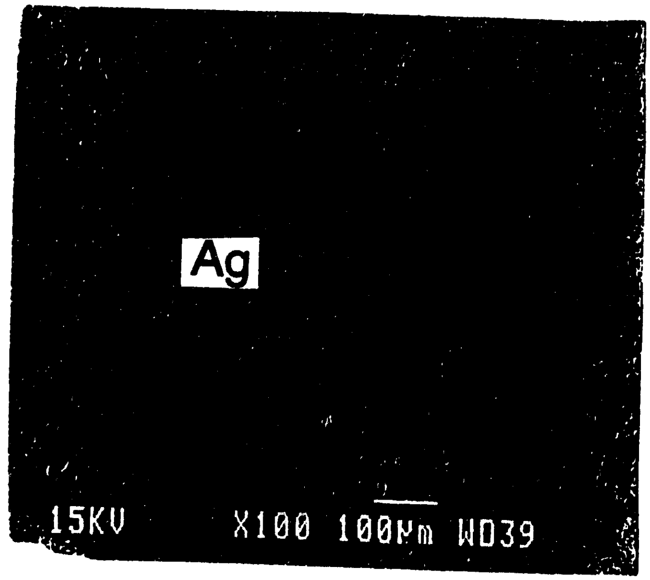


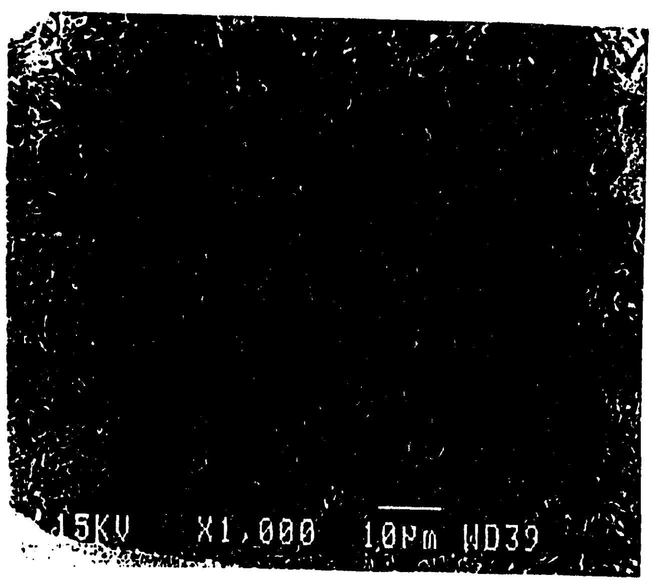
Fig.1 Ic distribution of high−Tc superconducting tape of 518 M

K. Ohkura et al. (Sumitomo)

Ag–Clad $TlBa_2Ca_2Cu_3O_x$ Tapes



Rolling direction ⟶



T. J. Doi et al. (Hitachi)

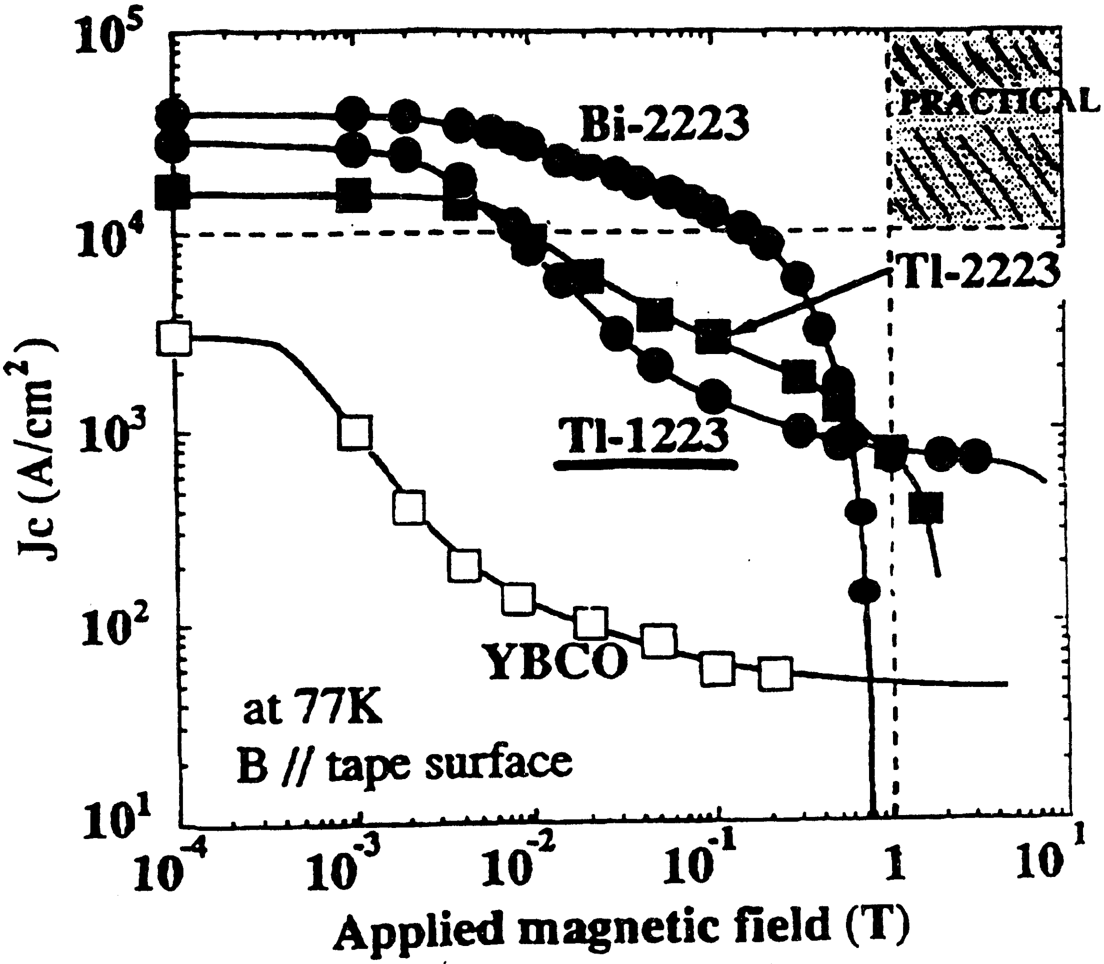


Fig. Transport Jc of HTS wires

"Pit Processed"

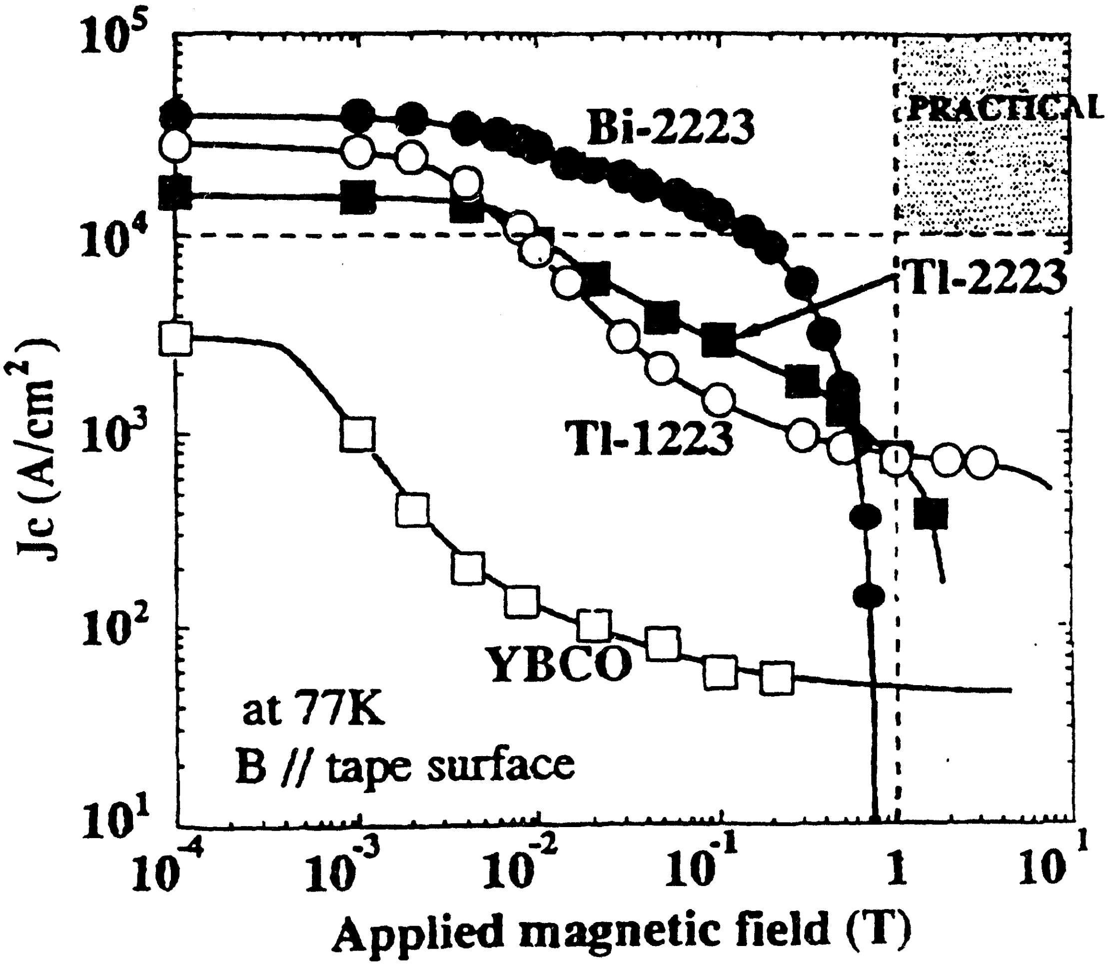
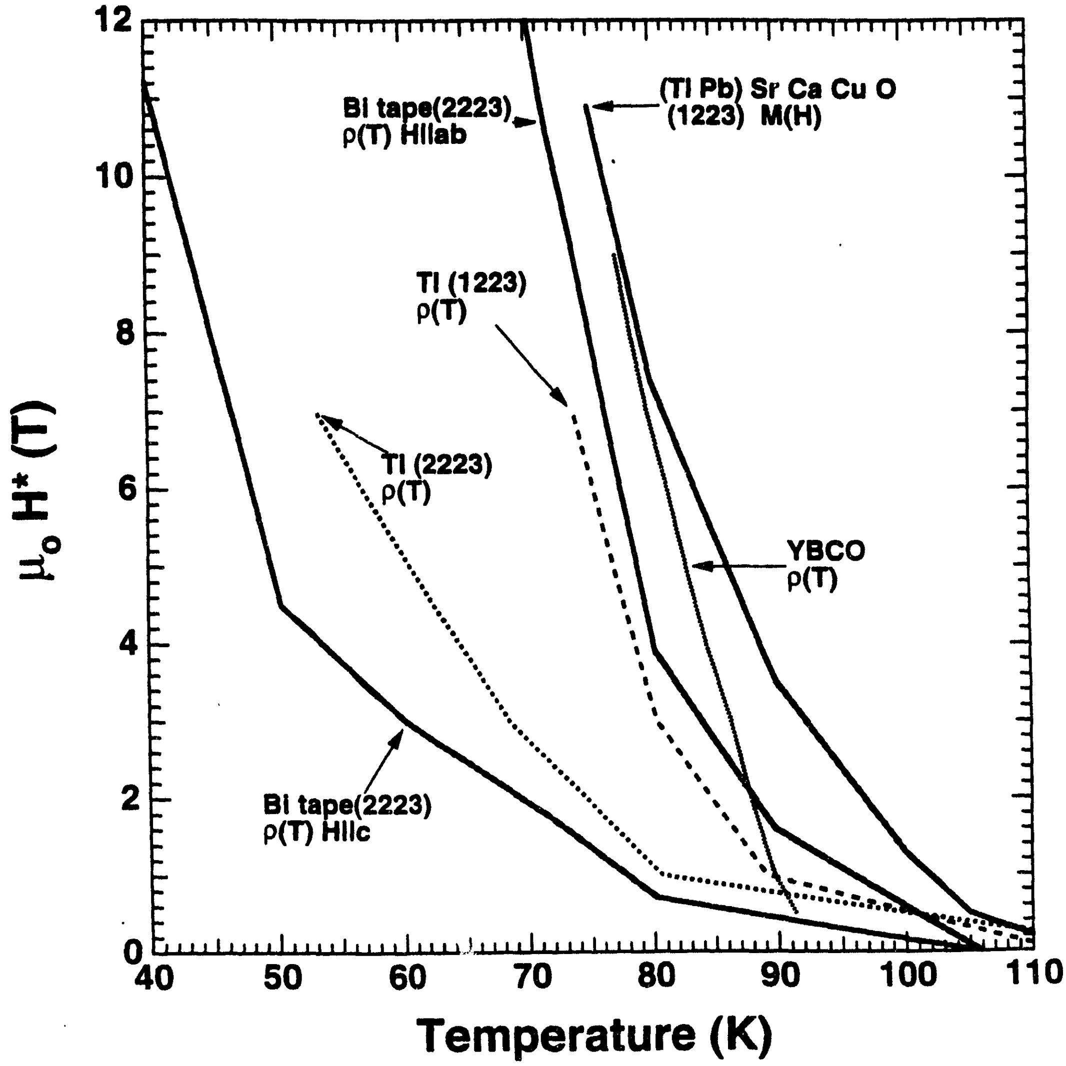


Fig. Transport Jc of HTS wires

Characteristic Magnetic Field Comparison



Current Density Requirements for Selected Superconducting Applications

	Overall [a] current density (A/cm^2)	Superconductor current density (A/cm^2)	Typical operating magnet field (T)
Generator	$1.5\text{-}3.0 \times 10^4$	2×10^5	2 - 5
High energy physics	$2\text{-}4 \times 10^4$	$2\text{-}3 \times 10^5$	5 - 7
MRI	1×10^4	1×10^5	0.5 - 2
Fusion + SMES	5×10^3	5×10^4	≥ 8
Strip lines & Interconnects	NA	$10^5 - 10^6$	(Low field) <0.1T
Digital devices	"	$10^3 - 10^5$	"
SQUID Sensors	"	$1 - 10^3$	"
Shielding	"	$10^3 - 10^4$	"

[a] This current density is an average for a distributed area which includes conductor stabilizer insulation and /or potting and cooling interstices.

SECTION V

WIRE CHARACTERIZATION ISSUES AND NEEDS

WIRE CHARACTERIZATION ISSUES IN THE DEVELOPMENT OF CERAMIC COMPOSITE SUPERCONDUCTORS

PRESENTATION MATERIAL PREPARED BY THE ARGONNE NATIONAL LABORATORY ENERGY TECHNOLOGY DIVISION*

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LOS ALAMOS NATIONAL LABORATORY
OAK RIDGE NATIONAL LABORATORY
STATE UNIVERSITY OF NEW YORK (BUFFALO)
UNIVERSITY OF WISCONSIN

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*RESEARCH SPONSORED BY THE U.S. DEPARTMENT OF ENERGY, ENERGY EFFICIENCY AND RENEWABLE ENERGY AS PART OF A DOE PROGRAM TO DEVELOP ELECTRIC POWER TECHNOLOGY.

Bi-2223 Two-Powder Process

Form Pb-doped Bi-2212.
$(Bi_{1.8}Pb_{0.4}Sr_{2-x}Ca_{1+x}Cu_{2.0}O_8)$

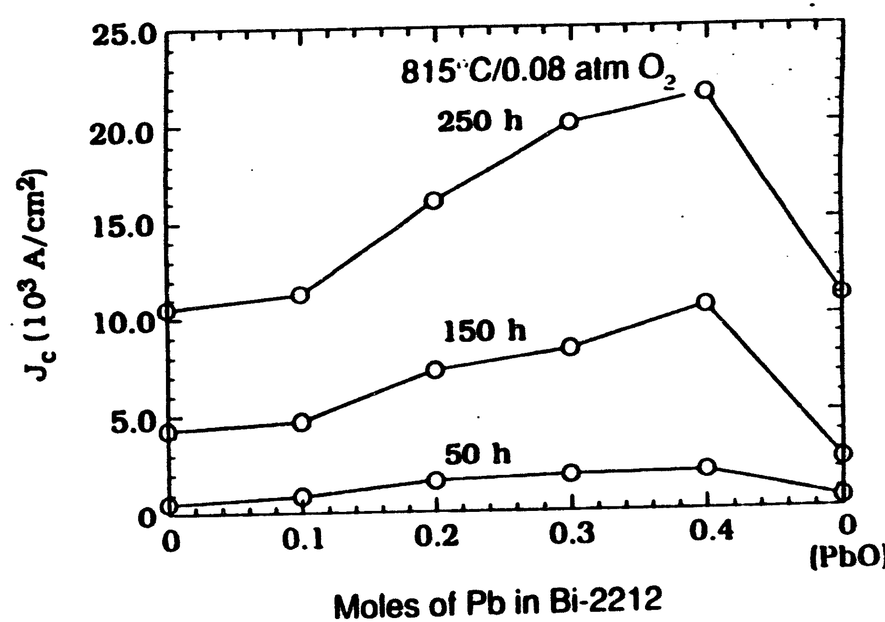
Form 2nd phase.
$(Sr_xCa_{1-x}CuO_2)$

⇓

Blend Bi-2212 and 2nd phase powders.
$(Bi_{1.8}Pb_{0.4}Sr_{2-x}Ca_{1+x}Cu_{2.0}O_8$ and $Sr_xCa_{1-x}CuO_2)$

⇓

Prepare tape conductor by powder–in–tube process.

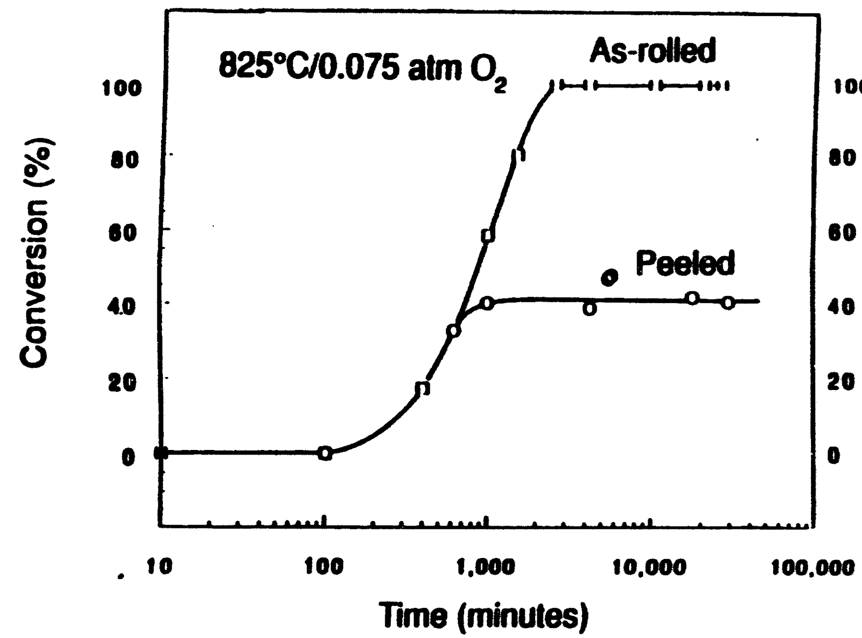


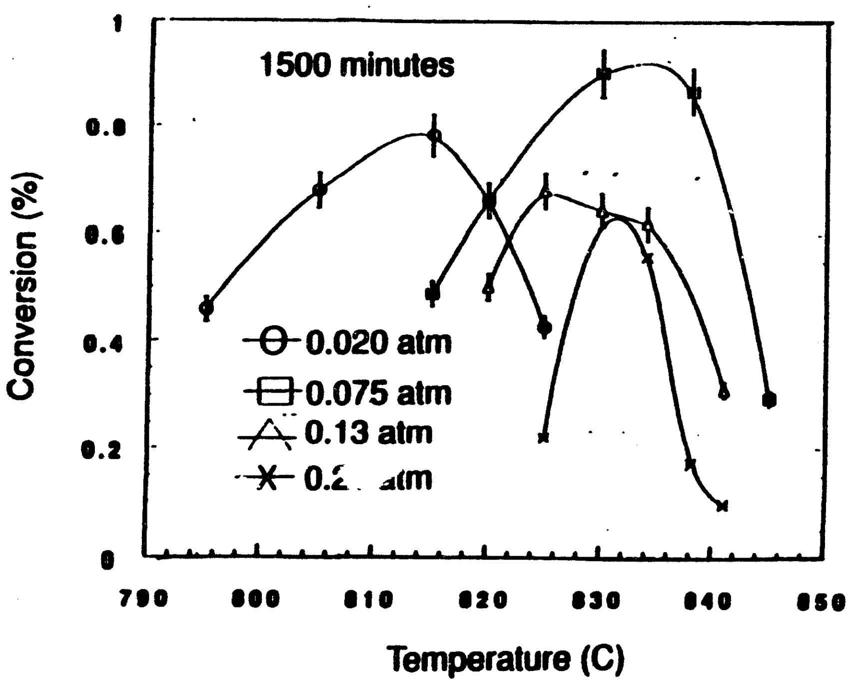
REMAINING ISSUES

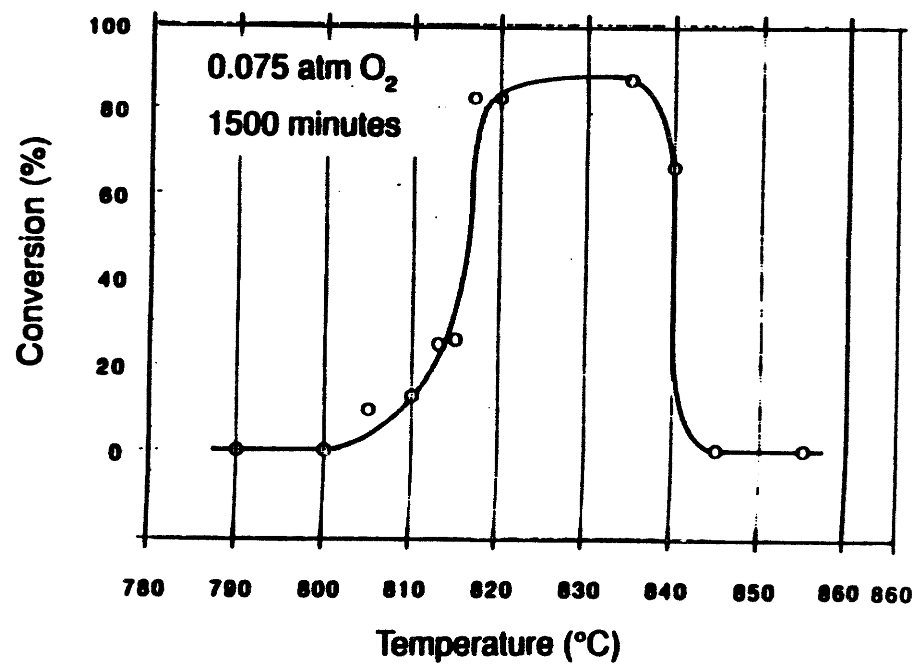
- THERMOMECHANICAL PROCESS OPTIMIZATION
- CRACKING/POROSITY CONTROL
- STOICHIOMETRY OPTIMIZATION
- LEAD DEPLOYMENT IN POWDER CONSTITUENTS

Bi-2223 COMPOSITE CONDUCTORS: HEAT TREATMENT PARAMETERS

- HEAT TREATMENT TIME
  - INDUCTION PERIOD
  - SIGMOIDAL KINETICS
- HEAT TREATMENT TEMPERATURE
  - RANGE OF RAPID KINETICS
  - PRELOAD TREATMENT OF POWDER
- OXYGEN PARTIAL PRESSURE
  - Bi-2223 STABILITY RANGE (WIDTH)
  - SECOND PHASE CHEMISTRY AND MICROSTRUCTURE



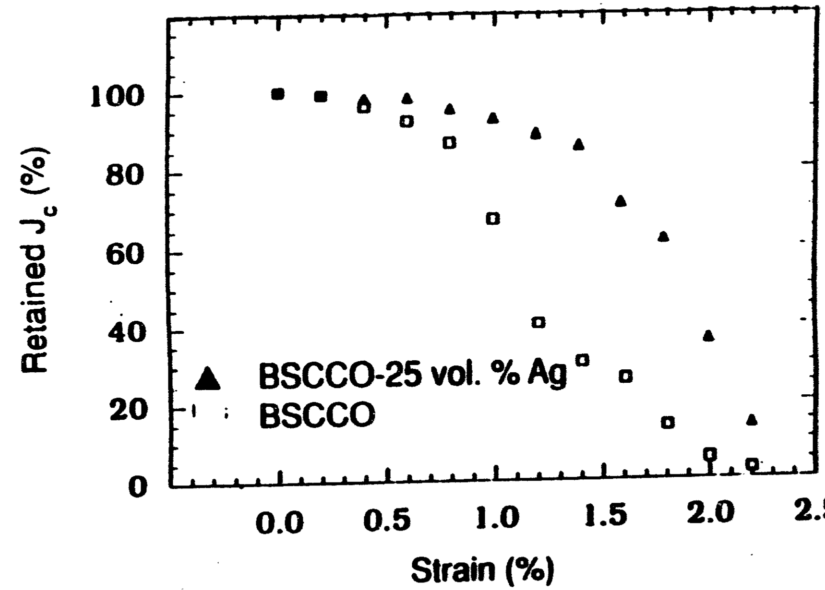


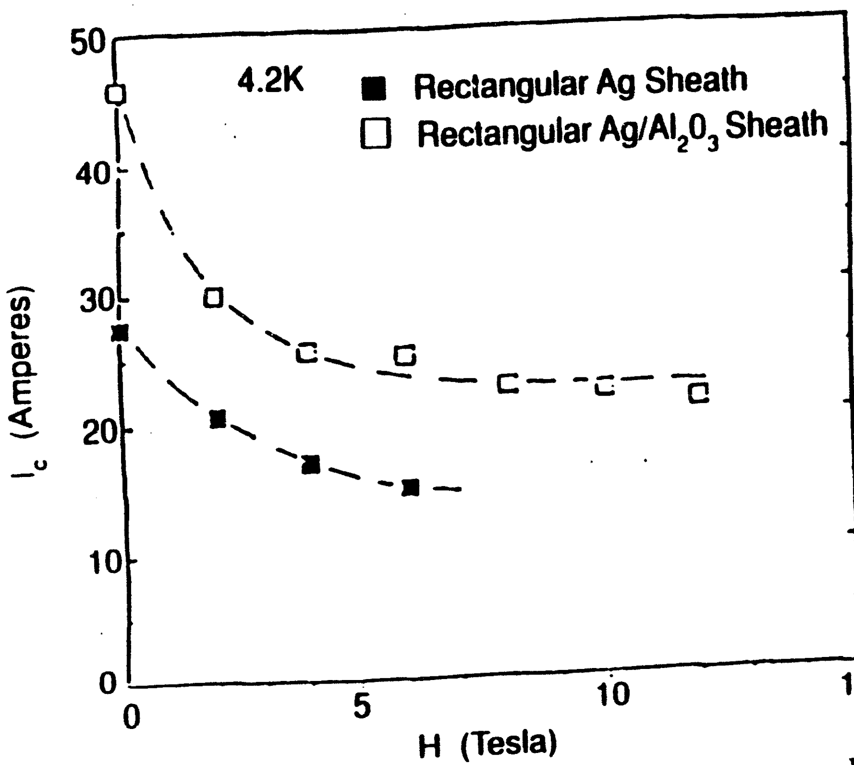


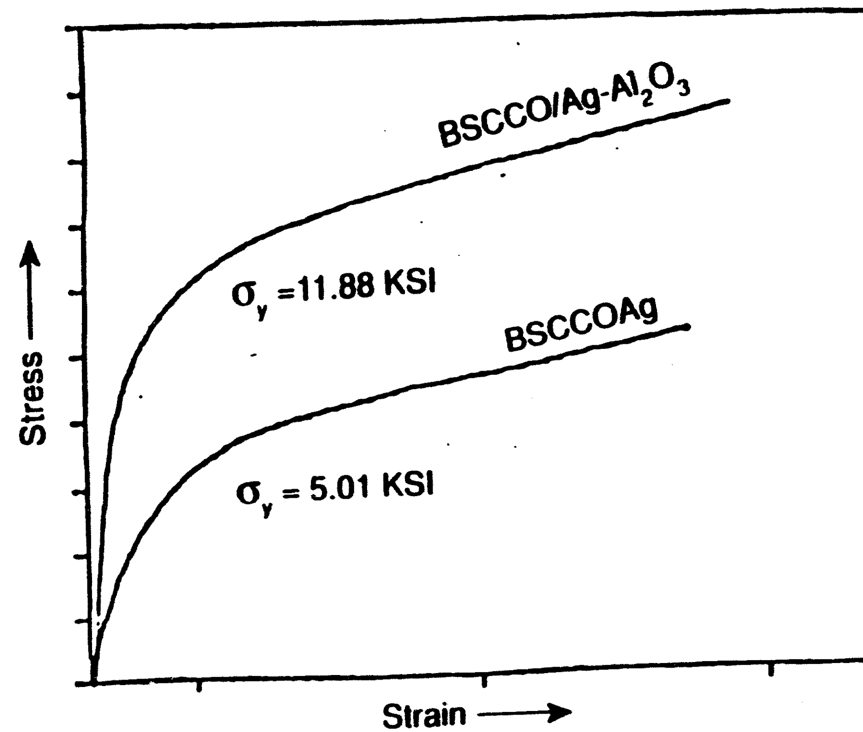
W/ASC

ENHANCEMENT OF COMPOSITE CONDUCTOR STRESS TOLERANCE

- J_c DECREASES WITH INCREASING TENSILE/BENDING STRAIN (ε_{CRIT}~0.2%)
- ADDITION OF Ag OR Ag_2O TO POWDER INCREASES STRAIN TOLERANCE
- MODIFICATION OF SHEATH MATERIAL (e.g., Ag-Al_2O_3) CAN INCREASE CONDUCTOR STRENGTH AND REDUCE FIELD DEPENDENCE OF J_c







W/IGC

AIIM

Association for Information and Image Management
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 mm

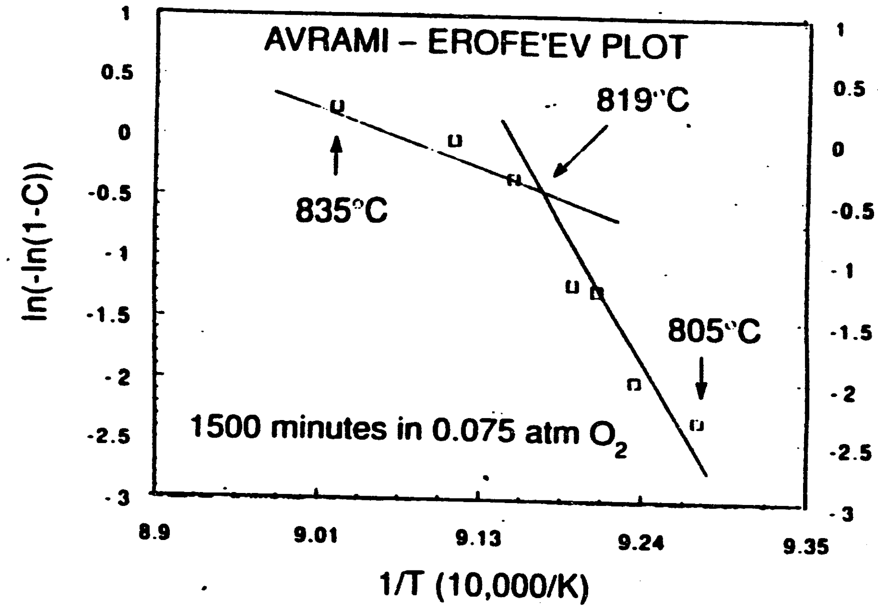
1 2 3 4 5

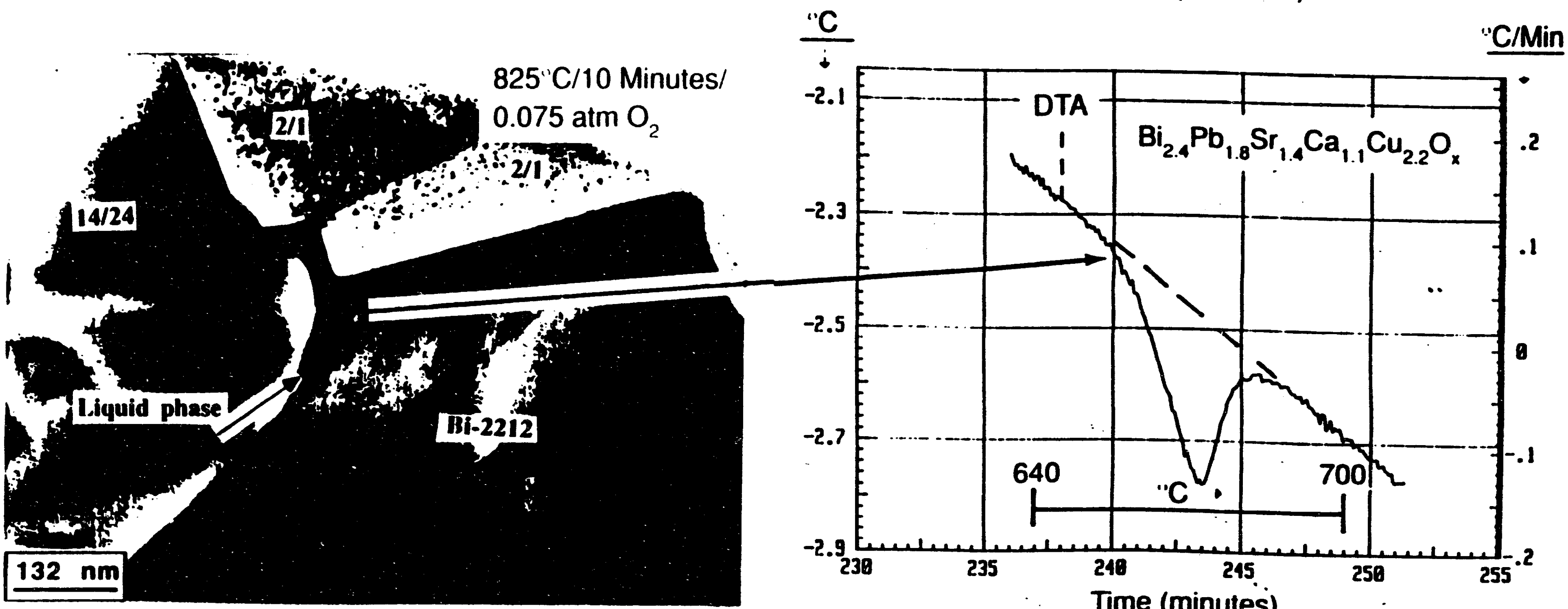
Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

Bi-2223 COMPOSITE CONDUCTORS: CHARACTERIZATION OF THE "LIQUID" PHASE

- **EVIDENCE FROM QUENCHED SAMPLES**
- **EFFECT ON REACTION KINETICS**
  - **ENHANCED DIFFUSION RATES**
  - **DISSOLUTION OF SECOND PHASES**
- **EFFECT ON MICROSTRUCTURE**
  - **CRACK HEALING**
  - **SECOND PHASE GROWTH**
- **RELATIONSHIP TO CRITICAL CURRENT**

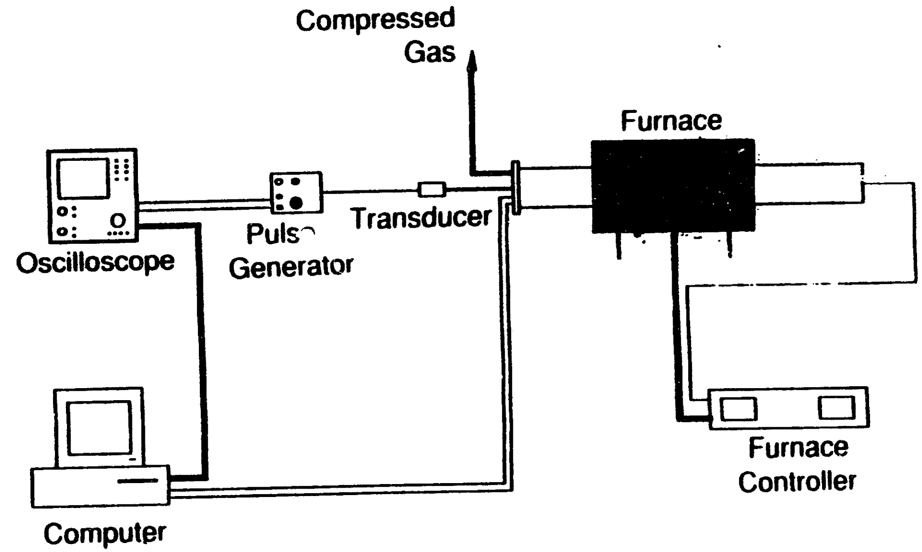




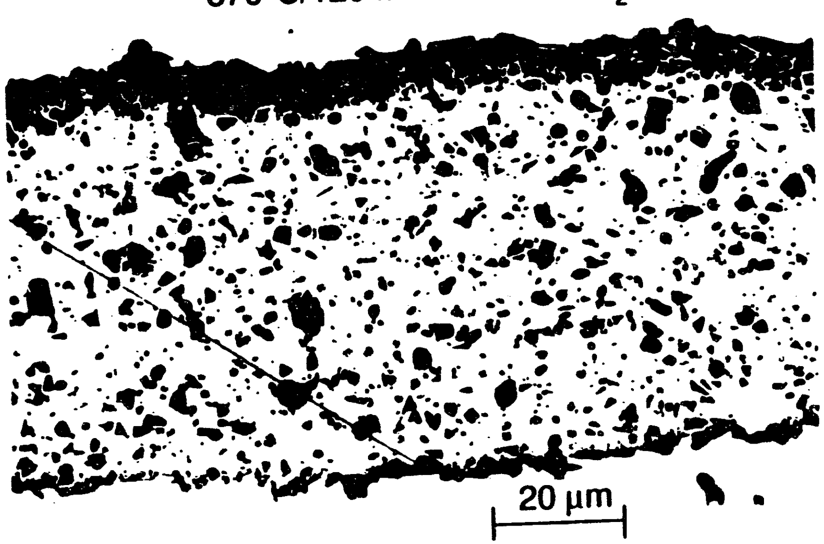
Tl-BASED SUPERCONDUCTORS

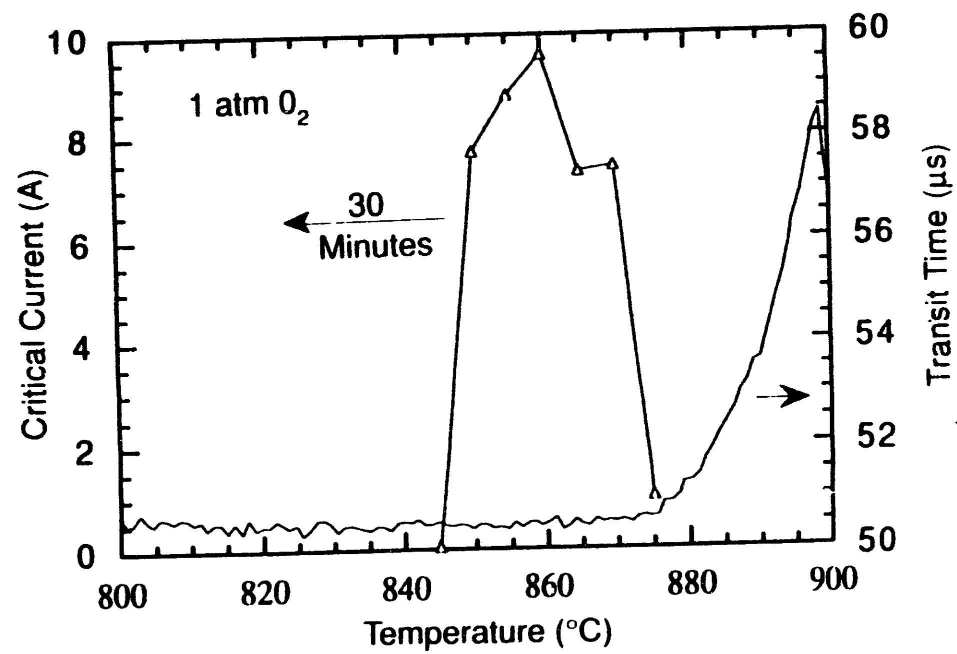
- LIQUID FORMATION CHARACTERIZED BY ACOUSTIC VELOCITY MEASUREMENT (TECHNIQUE UNDER DEVELOPMENT AT ANL)
- HIGHEST J_c OBTAINED BELOW POINT OF INCONGRUENT MELTING
- EVIDENCE OF MANY SECOND PHASES AND REACTION BETWEEN Ag AND TBCCO NEAR MELTING TEMPERATURE

Acoustic Velocity Measurement Apparatus



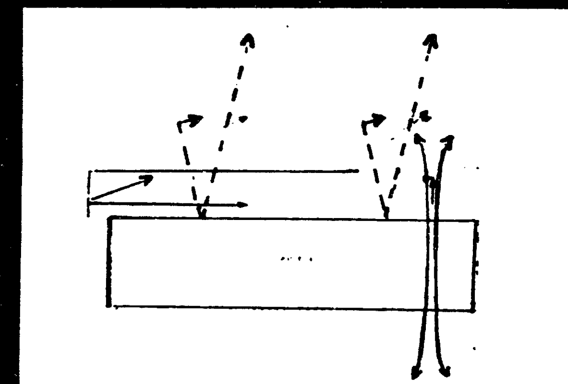
870°C/120 Minutes/1 atm O_2

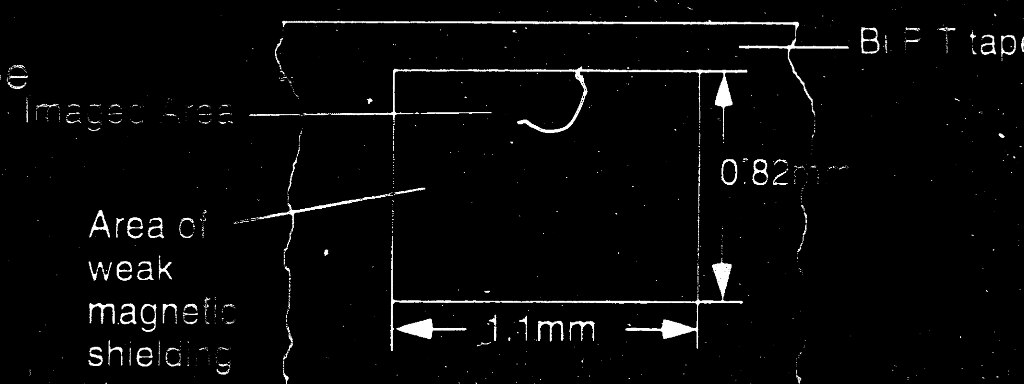




- Time and Spatially Resolved Images of Magnetic Flux Patterns
- Ideal Technique for Investigation of Uniformity of Superconducting Properties
- Example: Bi PIT - tape in perpendicular field evidence for weak critical current along the center of the tape

Magneto-optical technique

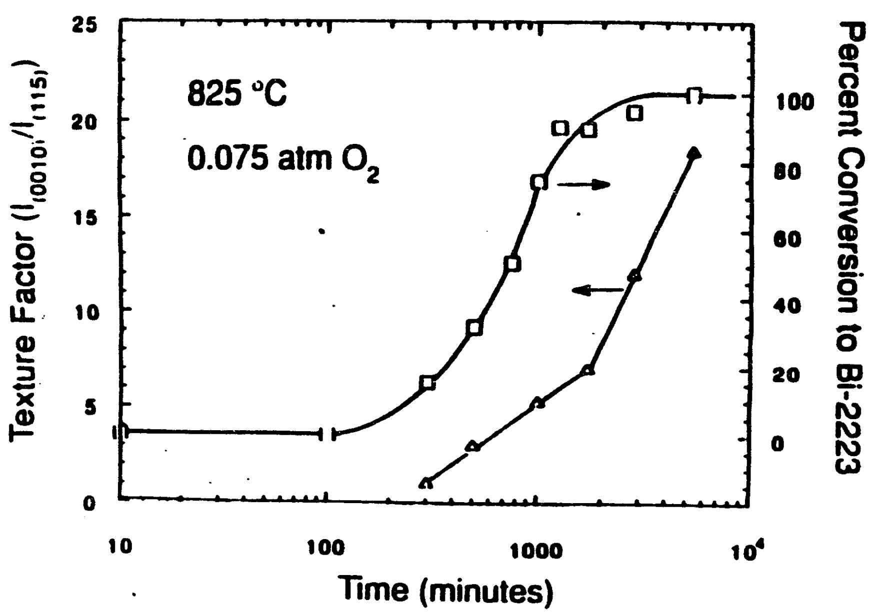


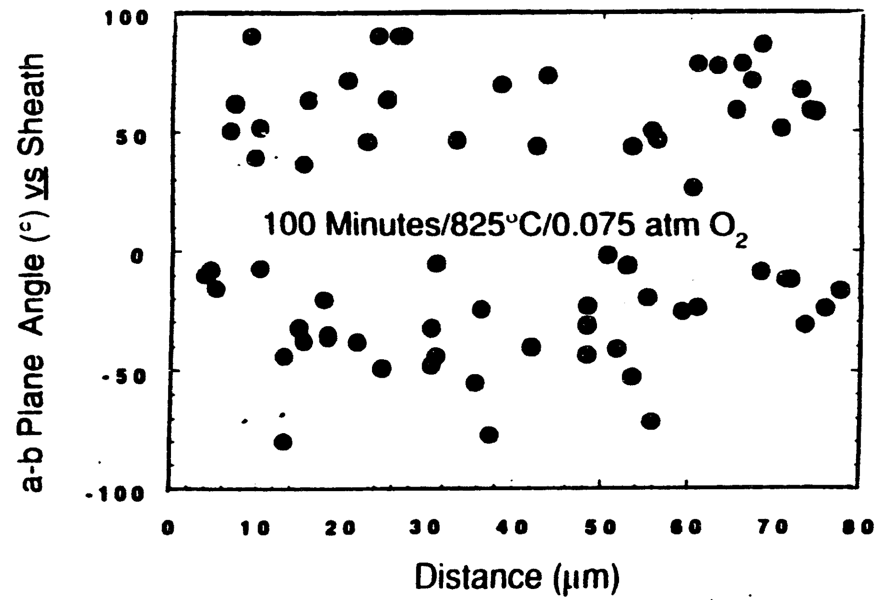


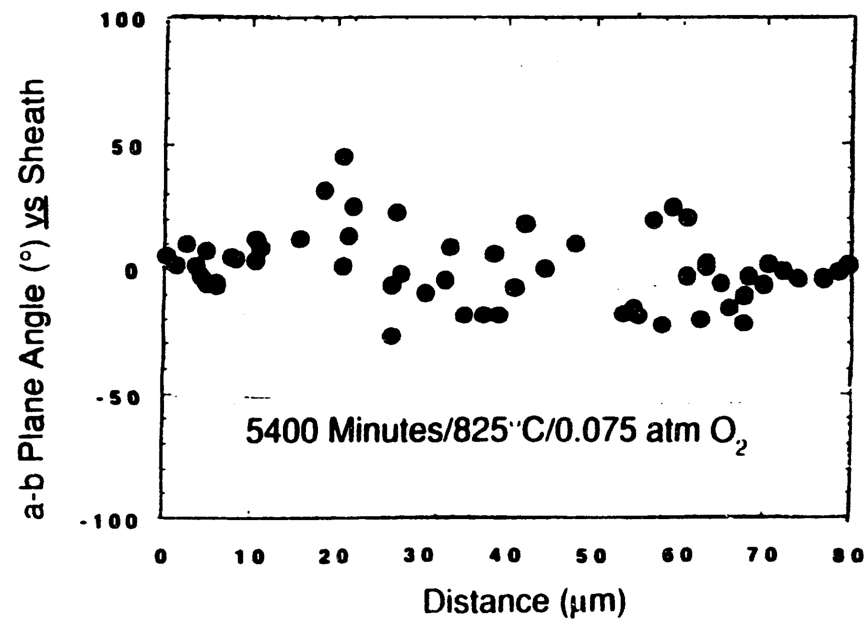
T=20K, H=120G Increasing

REACTION INDUCED TEXTURE IN BSCCO/Ag COMPOSITE CONDUCTORS

- **C-AXIS TEXTURE DEVELOPS DURING HEAT TREATMENT OF AS-ROLLED Bi-2223/Ag MONOFILAMENTS WITHOUT ADDITIONAL ROLLING/PRESSING**
- **THE EFFECT APPEARS TO BE CAUSED BY THE CONSTRAINING ENVIRONMENT OF THE SHEATH**







W/ASC

WIRE CHARACTERIZATION ISSUES

- Powder Preparation
  - synthesis method
  - preload heat treatment
  - stoichiometry/microstructure

- Conductor Processing
  - pO_2, temperature, time
  - heat treatment/reduction synergism
  - taming the liquid phase

- Process Monitoring/Control
  - "litmus" test
  - in situ interrogation methods

- J_c Characterization
  - where is current flowing?
  - macroscopic vs microscopic disruptions

Textures in Bulk HTS Superconductors

1) Hot pressed YBCO

2) Cold pressed Bi 2223

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D. Phillips, LANL for compression experiments
NSF (Earth Sciences)
INCOR
UERG Univ. Calif.

Texture Determination in HTS Bulk Materials

HTS ceramics of various compositions have in common a highly anisotropic crystal structure with Cu atoms positioned on planes parallel to (001). Without knowing the exact mechanism it is agreed that in single crystals high electrical conductivity is restricted to this plane. This is, for example, documented by epitaxial films with almost perfect crystal alignment. Conductivity parallel to the film surface is high if the c-axis [001] is aligned perpendicular to the film and low if an a-axis [100] is perpendicular to the film. Much of the film development consists in producing relatively thick films with a high [001] alignment.

Anisotropy also haunts bulk materials. One of the compounds with the most favorable high temperature properties, YBCO, has not been very successful for bulk materials because of the difficulty in producing an alignment of the crystal lattice. More successful have been experiments with Bi2223, Bi2212 and some Tl compounds which consist of non-equiaxed grains. The best conducting properties have been observed in tapes and wires with a relatively good crystal alignment, as evidenced by visual inspection of the microstructure. This alignment, known as "texture", has become accepted as an important factor and "texturing" has become a popular buzword. Clearly it is not the only significant factor - chemical and structural properties as well as grain contact are initially more limiting - but a good texture is a necessary ingredient for any high performance wire or tape. It is surprising how little quantitative data on textures of HTS ceramics is available. The literature abounds with qualitative estimations of microstructures and at best diffraction peak ratios in x-ray powder patterns.

Texture research is a well established field and has reached a sophisticated level of quantification, both in metallurgy and geology (1,2). Textures are measured as pole figures with x-ray, neutron or electron diffraction. From these pole figures the orientation distribution function (ODF) is determined mathematically and the relationship between crystal and sample frame are expressed as normalized orientation densities. A density of 1 m.r.d. (multiples of a random distribution) signifies uniform orientation density, an ODF with a maximum of 5 m.r.d. is a weak texture, one with a maximum of 20-50 m.r.d. a strong texture. Information from textures is twofold: First textures enable us to evaluate properties such as mechanical strength, thermal conductivity, elastic properties, ductility. Secondly textures contain characteristic information about the formation process and can be used to derive mechanisms. Since they include an assembly of crystallites, rather than a few grains as studied with the TEM they are statistically more representative of the bulk material and can often be interpreted more confidently as the large literature on metals and geological materials illustrates (3). Both aspects are significant for HTS. Quantitative texture analysis is fully developed and applicable now (4,5), even though not quite a routine for HTS compounds. However, it is necessary to educate physicists who have been the main investigators of HTS materials, to teach them a new language and make them familiar with the possibilities of texture analysis.

Over the last years at Berkeley efforts were made to quantify texture determination of thin films (6-8), of hot pressed YBCO (9) and of coldpressed Bi2223 powders (10,11). The latter research is particularly significant for HTS wires and tapes and established that in these materials deformation occurs largely by rearrangement of rigid platelike particles during compaction, rather than by intracrystalline ductile deformation. This is analogous to phyllosilicate compaction in shales and slates. Evidence for this is that with increasing compaction textures level off at 5-7 m.r.d. due to grain interaction and do not increase as would be expected from ductile dislocation processes. Other evidence is the microstructure, residual porosity and the fact that texture development is only observed in polycrystals with non-equiaxed grains. Modifications of rigid particle rotation models (12-14) can be used to interpret texture development (11). Such a model explains why no stronger textures are produced in rolled tapes deformed to much higher strains. Analogy with phyllosilicates also suggests that much stronger textures with (001) pole densities could be obtained by compaction and deformation at high temperature, where recrystallization and diffusion alleviate interferences at grain boundaries (15). Such conditions would also improve grain contacts.

While quantitative x-ray measurements remain the routine method of texture analysis, one should explore local textures by SEM-EBSP measurements which have recently been successfully applied to ceramics (16,17).

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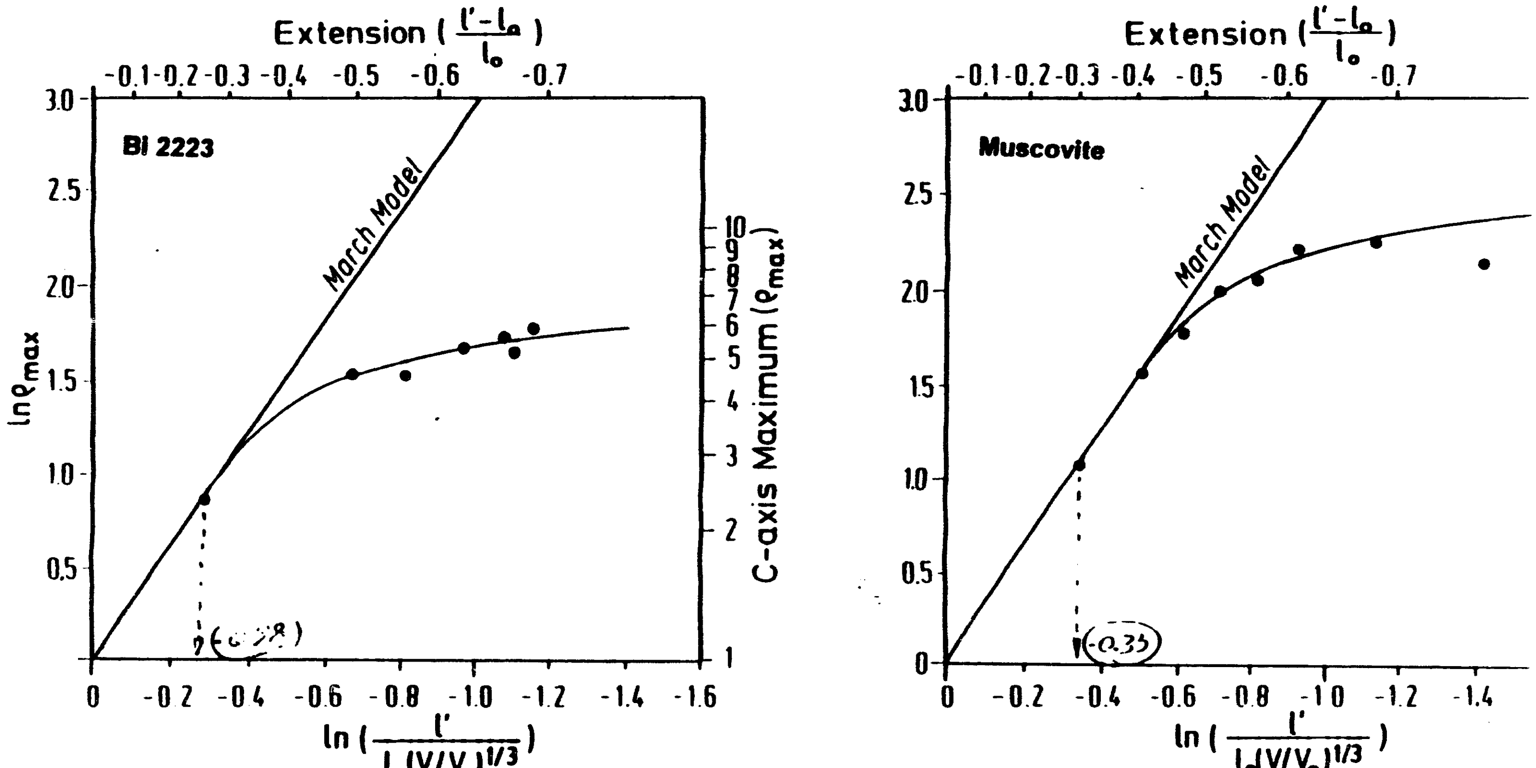

Figure 1 March strain determined from the (001) pole density as a function of observed compaction strain from cold pressed 2223 powders and muscovite (from Tullis, 1976).

Preferred orientation in experimentally deformed $YBa_2Cu_3O_{6+x}$

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Neutron diffraction data document that [001] axes of $YBa_2Cu_3O_{6+x}$ in an experimentally deformed polycrystalline aggregate are preferentially aligned parallel to the compression direction. Preferred crystallographic orientation strongly affects oxygen stoichiometry results determined by structure refinement analysis of neutron diffraction data and appropriate corrections are necessary.

There have been several reports which suggest that pressed pellets of $YBa_2Cu_3O_{6+x}$ polycrystals display grain-shape anisotropy.[1-4] In this communication we document strong crystallographic preferred orientation in a sample which has been deformed at high temperature and high confining pressure and which has anisotropic electrical properties.[4,5]

A $YBa_2Cu_3O_{6+x}$ powder was prepared using the amorphous citrate process.[6] The material was then cold pressed to approximately 70 MPa into cylinders of 6 mm diameter and 20 mm length using a steel dye, presintered in air at 800 °C for 10 h, then annealed at 450 °C in oxygen for 20 h. Following this procedure the 75% dense, 1–2-μm grain-size powder compact was hydrostatically compacted under 1.0 GPa confining pressure at 900 °C for 1 h. Subsequently it was deformed in a solid medium deformation apparatus at pressure and temperature and a strain rate of $10^{-5}\ s^{-1}$ and shortened 35% in axial compression. After deformation, the material is fully dense and textured.[5]

At this stage the experimentally deformed polycrystalline aggregate of $YBa_2Cu_3O_{6+x}$ is oxygen deficient and nonsuperconducting. Following a 10 day anneal at 450 °C in a pure O_2 atmosphere it exhibits anisotropic properties.[4,5] Most of the sample was used for resistivity and susceptibility measurements, and only a fragment of about 2×3×5 mm was available for the texture analysis. It is difficult to determine the preferred orientation of perovskite-related structures with x-ray pole figure goniometry, because angular resolution is not adequate to resolve closely spaced diffraction peaks. Furthermore, transmission geometry, which could be used to measure the low angle (001) diffraction peak, is not very accurate due to strong absorption. We had the opportunity to use a position sensitive detector with the D1B instrument at the high flux reactor at the Institut Max von Laue-Paul Langevin (ILL), in Grenoble, France. This facility had previously been proved suitable for high-resolution texture analysis of complex geological materials.[8-10] The radiation used is a monochromated beam of neutrons with a wave-

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Textures of laser ablated superconducting thin films of $YBa_2Cu_3O_{7-\delta}$ as a function of deposition temperature

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The preferred orientation of a series of laser deposited superconducting thin films of $YBa_2Cu_3O_{7-\delta}$ on $LaAlO_3$ substrate has been examined. X-ray measurements (pole figures, χ-scans, ω-scans, rocking curves) reveal an increasingly strong preferred orientation of the polycrystalline material with c-axes perpendicular to the substrate surface as deposition temperature increases. At low temperatures c-axes are predominantly parallel to the substrate surface. Characteristic parameters of the texture types were derived from those measurements. With higher temperatures twinning on (110) was observed. The different texture types are interpreted in terms of a layered film structure.

I. INTRODUCTION

The superconducting property in $YBa_2Cu_3O_{7-\delta}$ high temperature superconductors is restricted to the crystallographic (001) plane and therefore a strong preferred orientation in a polycrystalline material is crucial in order to reach a high transition temperature. Recently the deposition of thin film on a single crystal surface has been established as a promising technique.[1] The lattice parameters of the substrate are usually chosen close or equal to those of the desired perovskite structure of $YBa_2Cu_3O_{7-\delta}$ and cause an oriented growth of the film material on the substrate surface (epitaxy). Besides other factors (e.g., substrate material, surface quality) the quality of the preferred orientation in the deposited material is influenced by the deposition temperature. In order to determine a quantitative relationship between preferred orientation and deposition temperature we examined a series of six samples of $YBa_2Cu_3O_{7-\delta}$ deposited at various temperatures (650 to 775 °C in roughly 25° increments) on a single crystal of $LaAlO_3$ using a laser ablation technique. In previous studies[2–6] it was shown that $LaAlO_3$ is a good substrate candidate for epitaxial growth of $YBa_2Cu_3O_{7-\delta}$.

The orthorhombic structure (space group *Pmmm*) of $YBa_2Cu_3O_{7-\delta}$[7] and the rhombohedral structure (space group $R\bar{3}m$) of $LaAlO_3$[8] are both pseudocubic perovskite structures with similar lattice parameters for corresponding crystallographic settings, specifically $a_{substrate} = b_{substrate} = c_{substrate} \approx 2 \times a_{film} \approx 2 \times b_{film} \approx 2/3 \times c_{film}$ (Table I). We used a substrate that was oriented with one of its {001} planes parallel to the surface and the other

TABLE I. Lattice parameters and principal lattice spacings with relative intensities for x-ray diffraction for film and substrate.

	$YBa_2Cu_3O_{7-\delta}$ (orthorhombic)			$LaAlO_3$ (rhombohedral)	
a (Å)	3.82			7.58	
b (Å)	3.89			7.58	
c (Å)	11.68			7.58	
α [°]	90			90.08	
β [°]	90			90.08	
γ [°]	90			90.08	

hkl	*d*-spacing (Å)	Int.	*hkl*	*d*-spacing (Å)	Int.
001	11.68	< 1	100	7.58	...
002	5.84	4	101	5.36	...
003	3.89	10	111	4.37	...
010	3.89	?	200	3.79	80
100	3.82	4	210	3.39	...
012	3.24	3	211	3.09	...
102	3.20	5	202	2.68	100
004	2.92	< 1			
013	2.75	55			
103	2.73	100			
110	2.73	?			

two roughly perpendicular to it. Two textures may form due to epitaxial growth: the "$c\perp$"-texture with the c-axis of the film material perpendicular to the substrate surface [Fig. 1(a)] and the "$a\perp$"-texture with the c-axis parallel to the substrate surface [Fig. 1(b)]. The $c\perp$-texture forms by alignment of (003) of the film with (002) of the substrate (plane parallel to the substrate surface) and

J. Appl. Cryst. (1992). 25, 524–530

Advantages of Monochromatic X-rays for Texture Determination of Superconducting Thin Films

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(*Received* 28 *January* 1992; *accepted* 13 *March*, 1992)

Abstract

X-ray pole-figure measurements traditionally employ β-filtered radiation. The remaining continuous spectrum can introduce serious artifacts in strong textures. It is shown that spurious peaks form in textures of epitactic YBCO films and that background determination may be ambiguous. These difficulties can be avoided by using monochromatic radiation with a graphite monochromator between the X-ray tube and the specimen.

1. Introduction

Over many years routine procedures have become established for texture determination with an X-ray pole-figure goniometer (Schulz, 1949; Wenk, 1985). Some modifications, especially for intensity corrections, are necessary for thin films (Wenk, Sintubin, Huang, Johnson & Howe, 1989). Recently there has been growing interest in texture analysis of high-temperature superconductors (HTS) because preferred orientation is closely linked to electrical properties (see, for example, Heidelbach *et al.*, 1992). In the case of laser-ablated films of $YBa_2Cu_3O_{7-\delta}$ (YBCO) on single-crystal substrates, textures are extremely strong and this has led us to develop special procedures that are advantageous for texture analysis in general.

Almost universally, X-ray pole-figure goniometers use Cu radiation and the intensity of the $K\beta$ (λ = 1.392 Å) component is reduced by filtering through an Ni foil with an absorption edge at 1.488 Å, which provides a strong $K\alpha$ component (λ = 1.542 Å) with a moderate continuous background. As Fig. 1 illustrates, a continuous contribution remains at wavelengths larger than $K\alpha$ and also at very short wavelengths. It will be shown here that this continuous component is not very significant if textures are weak but it introduces significant errors and artifacts if textures are strong. For such applications truly monochromatic radiation is recommended. This paper compares results of texture measurements of 40 nm thick YBCO films deposited by laster ablation at 1043 K on a (100) single-crystal substrate of $LaAlO_3$ (Heidelbach *et al.*, 1992), first for Ni-filtered Cu radiation and then for monochromatic X-rays produced with a graphite monochromator. Fig. 2 displays some differences between the radiations with precession photographs of a single crystal of garnet. These photographs represent (100) sections through the reciprocal lattice. In the case of monochromatic radiation one observes a discrete-point pattern (Fig. 2*a*). If the direct beam from an X-ray tube is used, each reciprocal-lattice point is

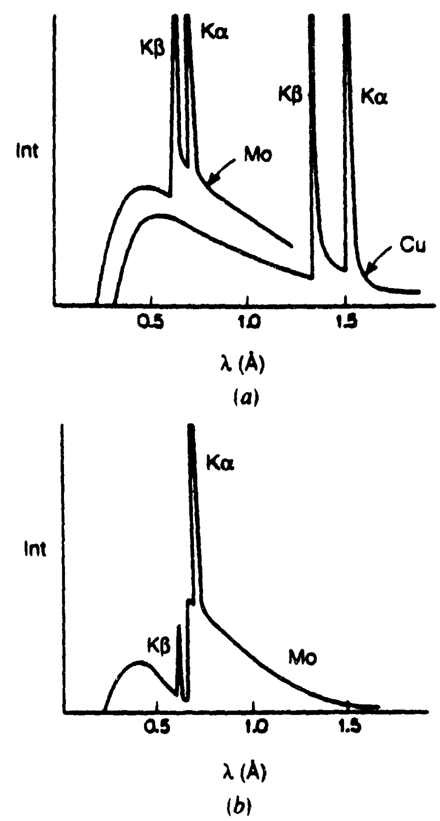

Fig. 1. X-ray spectra. (*a*) Mo tube (operated at 50 kV) and Cu tube (operated at 35 kV). (*b*) Mo spectrum if a 0.001 in Nb β filter is used.

0021-8898/92/040524-07$06.00

Mat. Sci. & Eng. A (submitted, 1994)

TEXTURE DEVELOPMENT IN PLATY MATERIALS. COMPARISON OF BI2223-AGGREGATES WITH PHYLLOSILICATE FABRICS

Sintubin, M.[1]*, Wenk, H.-R.*[2] *& Phillips, D. S.*[3]

Abstract

Quantitative texture data have been measured by x-ray diffraction on Bi2223 powders, cold pressed to different pellet strains. Comparisons of Bi2223-powders and geological phyllosilicate fabrics shows that both materials, characterised by a platy grain morphology, exhibit a similar texture development. This texture development is best explained by grain-shape induced rotation processes, which are limited by interactions of relatively rigid particles. With increasing compaction the orientation of platelets levels off at (001) pole densities of 5-6 m.r.d. By contrast intracrystalline slip mechanisms would produce much stronger textures at equivalent strains.

From analogy with phyllosilicates it is suggested that textures in Bi2223-compacts could be improved by hot pressing rather than cold pressing to alleviate incompatibilities at grain boundaries. Pole densities of 20 m.r.d. have been produced in experiments and observed in naturally deformed rocks. Such processing would also improve grain contacts. Of secondary importance is the size of the rigid, equiaxed, second phase particles which needs to be reduced to obtain stronger crystallite alignment.

For geological research Bi2223-compacts may serve as an experimental analogue, which approaches real phyllosilicate fabrics better than the materials used in experiments to date.

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In Situ Critical Current Measurements Under Mechanical Strains

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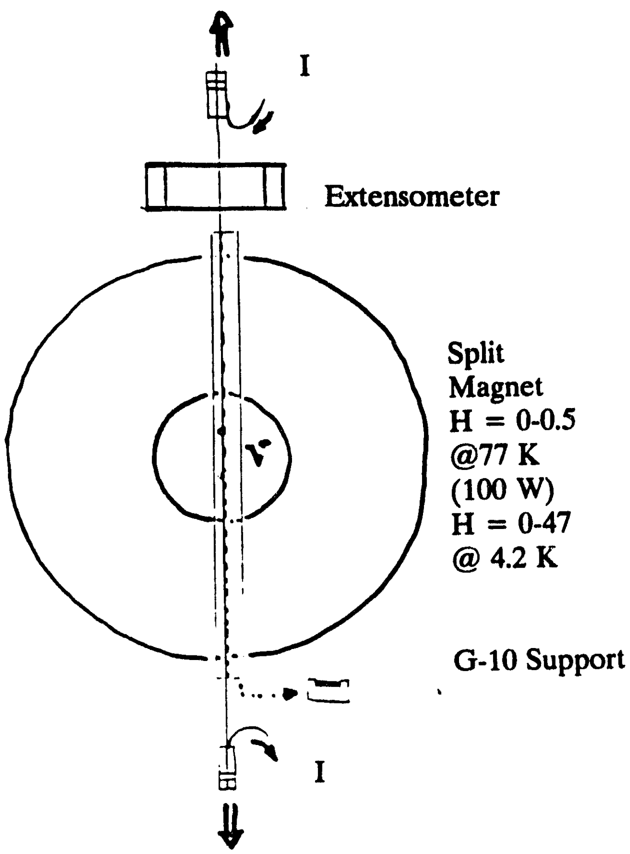
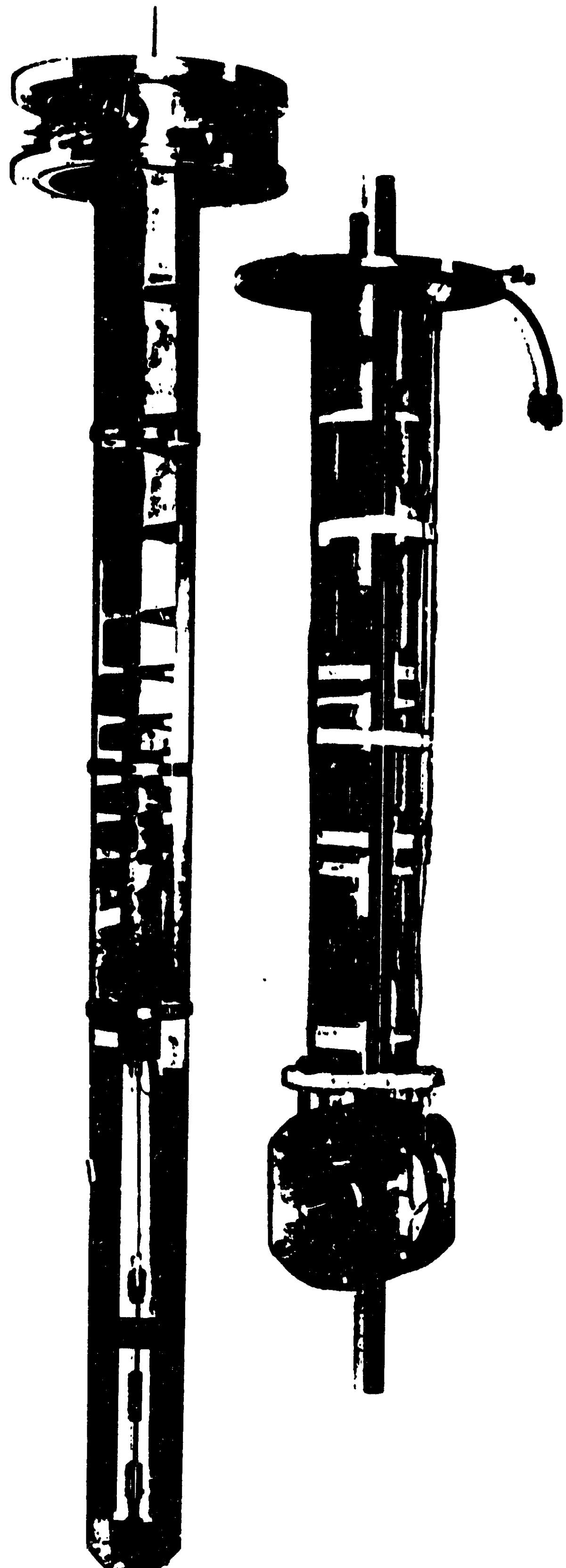
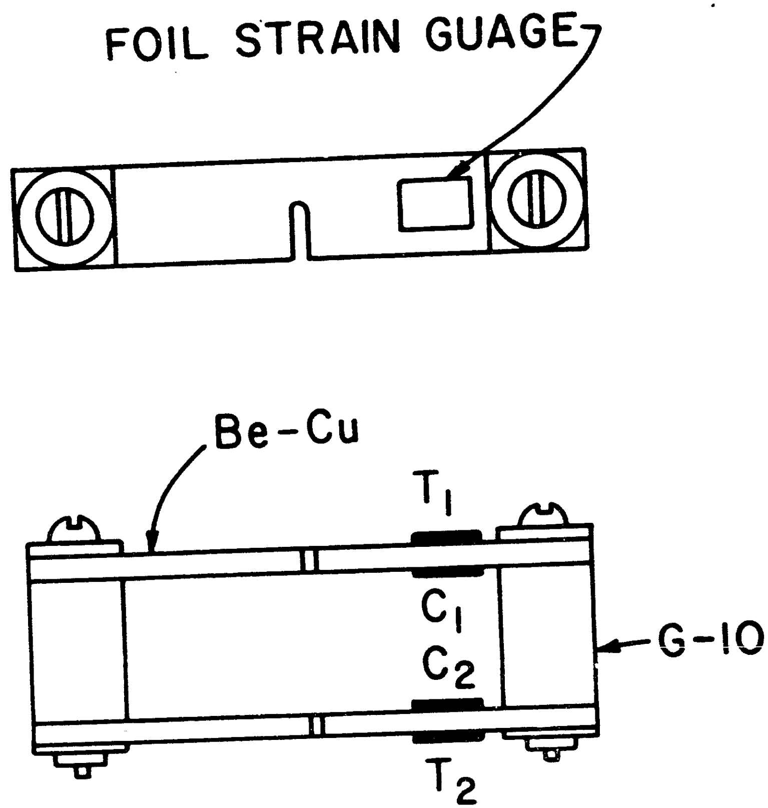
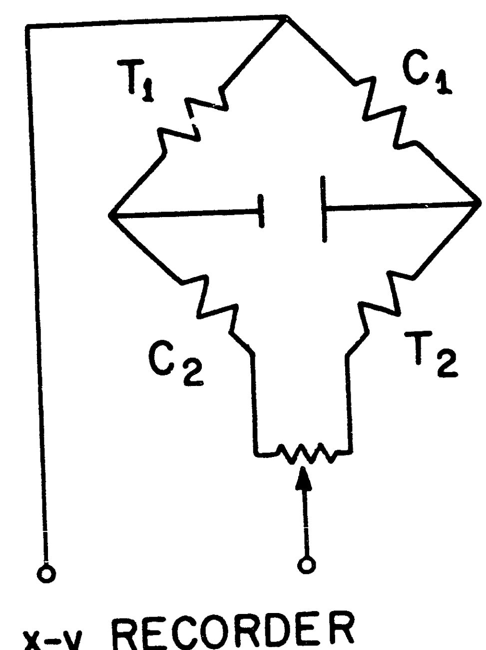
Presentation at
High Temperature Superconductivity
Wire Development Workshop
St. Petersburg, Florida
February 16, 1994



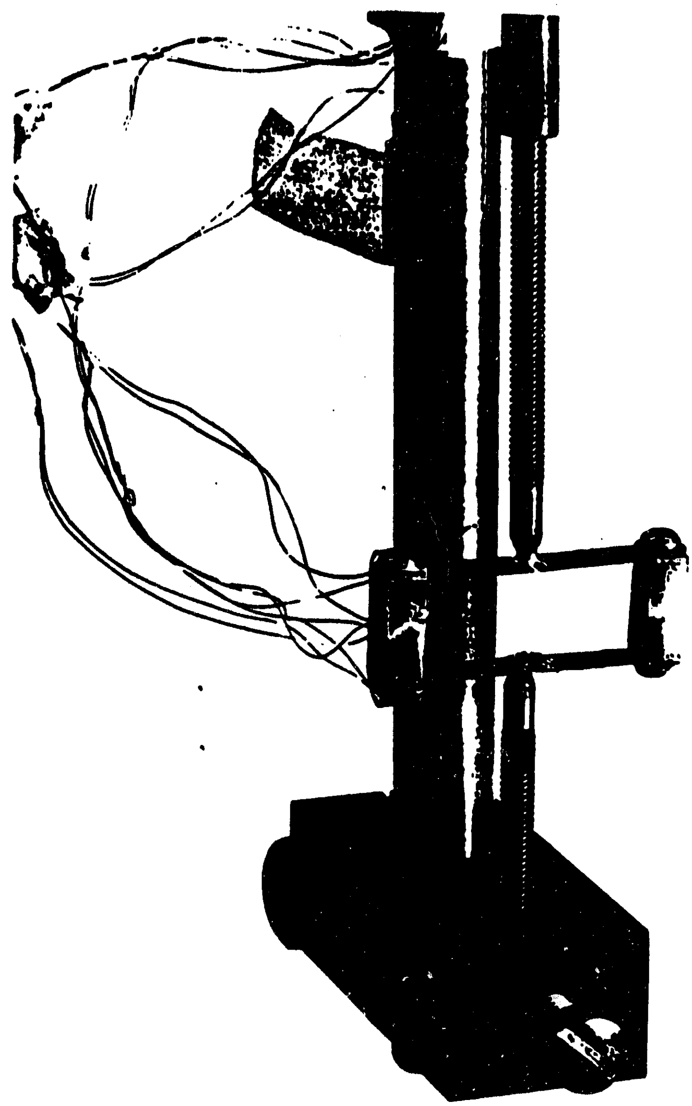


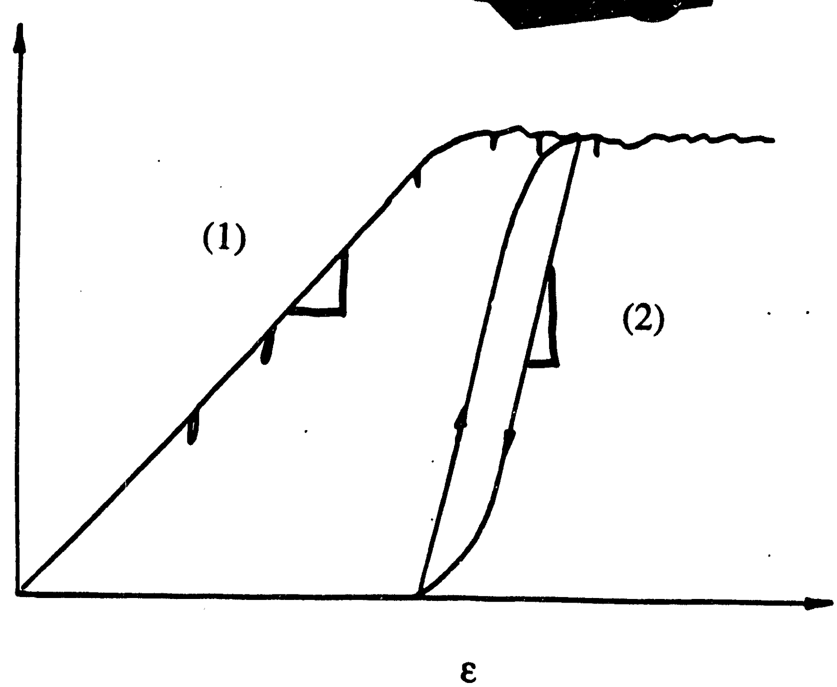


(a)



(b)




σ
(1)
(2)
ε

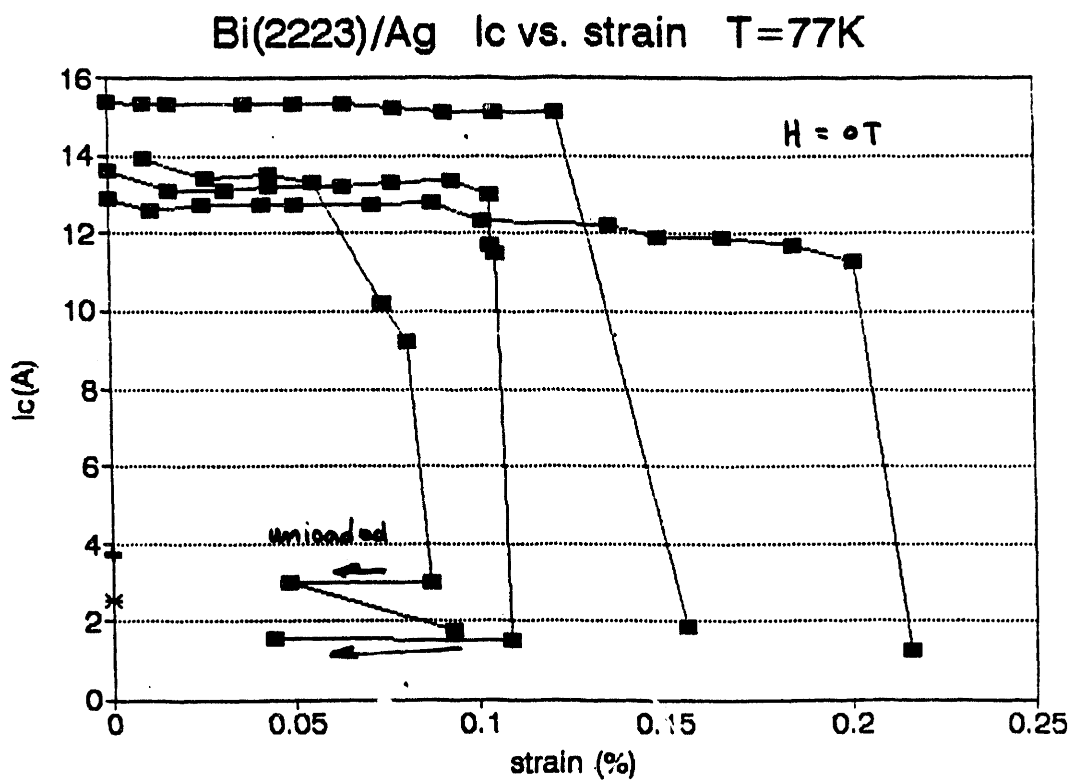
"Young's Modulus" of Bi (2223) Cores

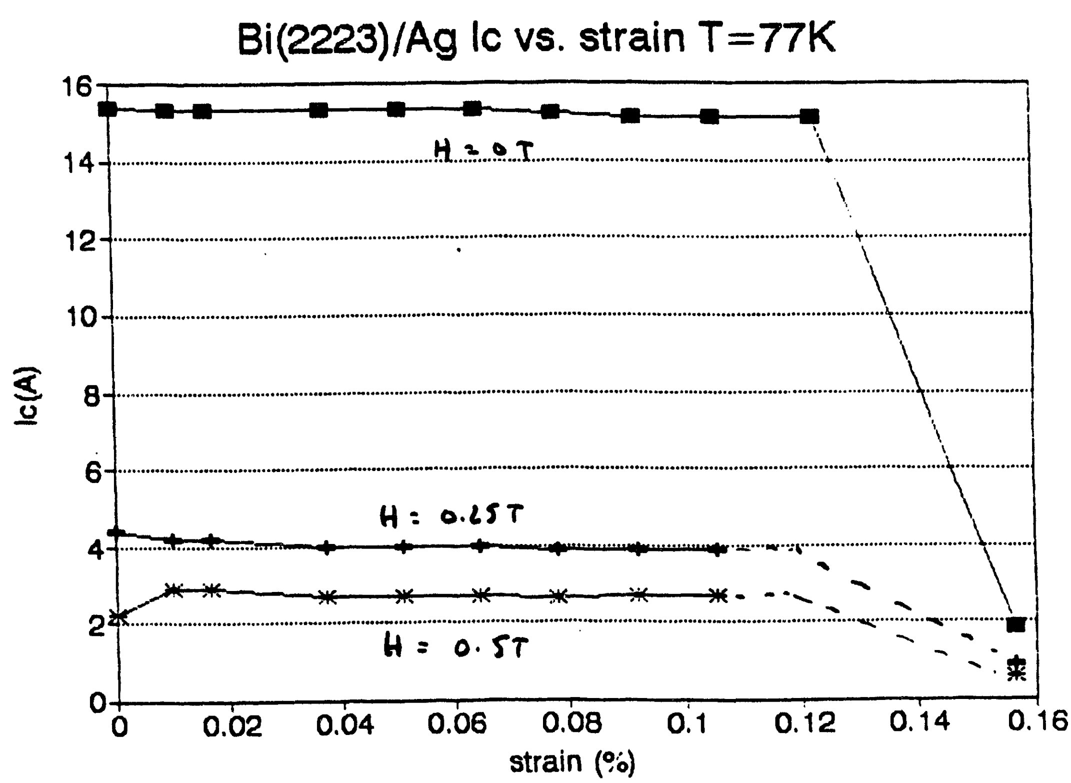
$$M_{Tape} \approx \left(\frac{\Delta\sigma}{\Delta\varepsilon}\right)_{unload} = V_{CORE}\, M_{CORE} + V_{Ag}\, M_{Ag}$$

where $V_c + V_{Ag} = 1$

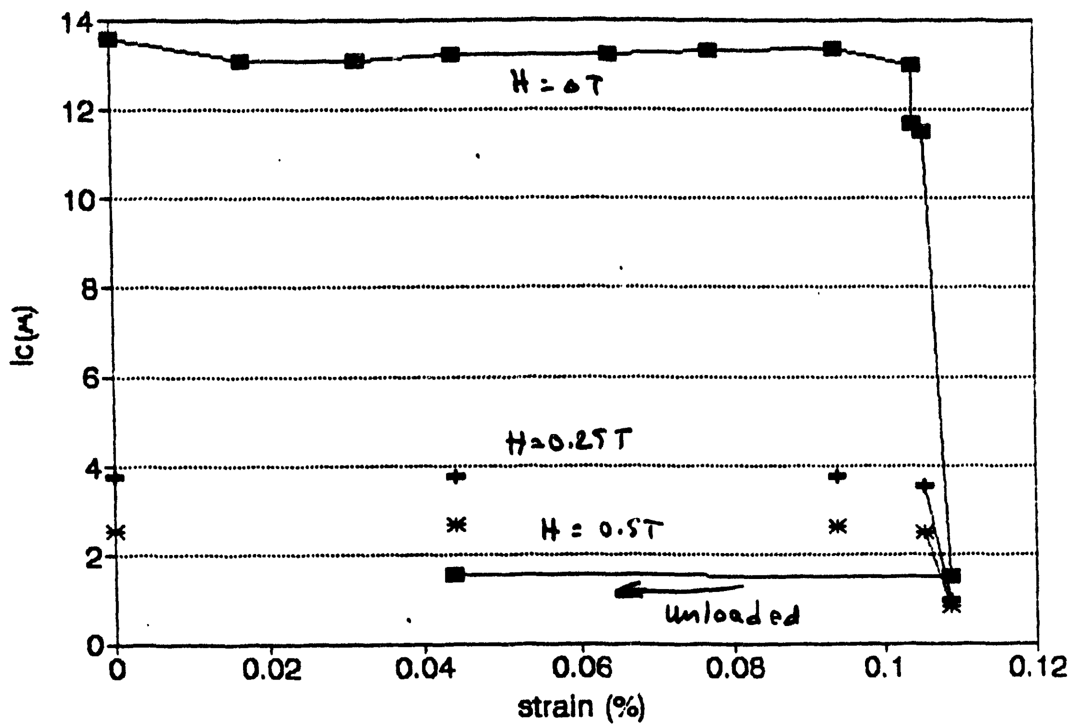
and $M_{Ag} \approx 70$ GPa

Tape 2	36.4GPa
6	30.7
7	77.8
9	72.1

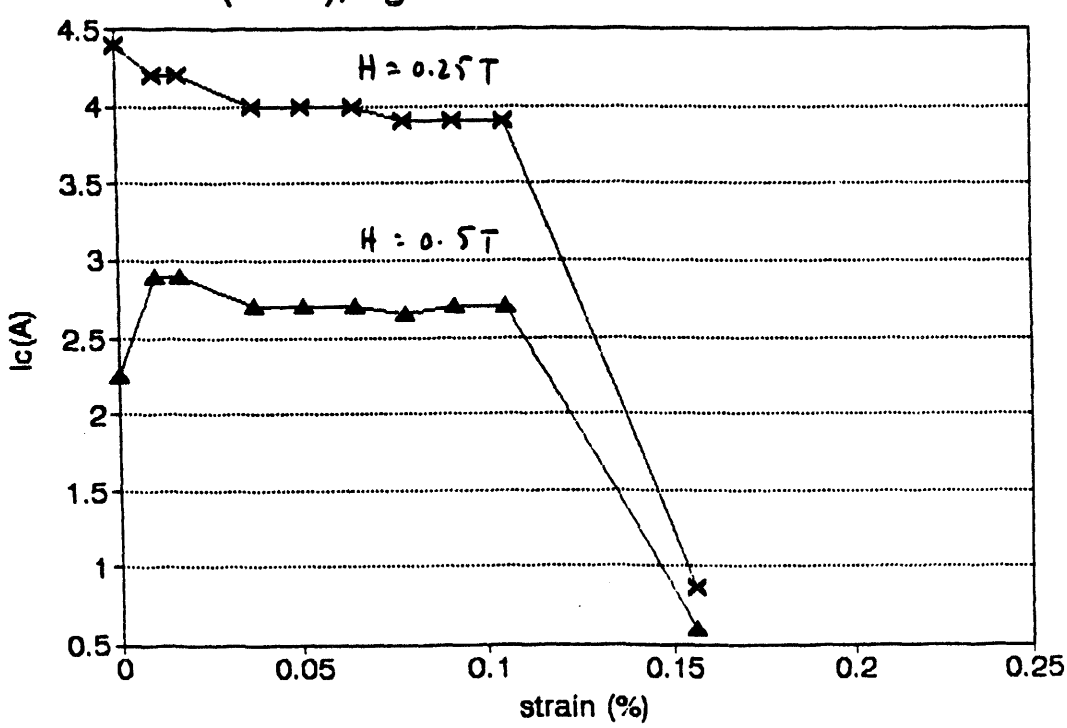

Bi(2223)/Ag Ic vs. strain T=77K
H = 0T
unloaded
Ic(A)
strain (%)
16
14
12
10
8
6
4
2
0
0
0.05
0.1
0.15
0.2
0.25


Bi(2223)/Ag Ic vs. strain T=77K
H = 0T
H = 0.25T
H = 0.5T
Ic(A)
strain (%)
16
14
12
10
8
6
4
2
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16

Bi(2223)/Ag Ic vs. strain T=77K #9



Bi(2223)/Ag Ic vs. strain T=77K #2



Measurement Issues for Critical Current Density

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Los Alamos National Laboratory

and

American Superconductor Corporation
(Wire Development Group)

Department of Energy High Temperature
Superconducting Wire Development Workshop

February 16-17, 1994
St. Petersburg, Florida

Critical Current Density Measurement Issues - Outline

I. Introduction - Definitions

II. Superconductor *vs.* engineering values

III. Critical current criteria: Electric field *vs.* resistivity
   A. Examples for long lengths
   B. Dependence on parameters

III. Models for I-V (e-j) characteristics - *n*
   A. Flux creep limitations
   B. Variation in critical current density with position

IV. Other measurement issues
   A. Contact application/thermal cycling
   B. Current transfer length

V. Summary and conclusions

Introduction

- The ultimate performance of a superconductor in any current carrying application can be quantified by:

  1) the total current it may carry while still remaining "superconducting," the **critical current**, I_C, and

  2) the current per unit cross-sectional area it may carry while still remaining "superconducting," the **critical current density**, J_C

- These quantities are subject to the definition of "superconducting" and are functions of
  1) **temperature** T,
  2) **magnetic field** B,
  3) and, for some conductors, the **direction of the magnetic field** ϕ

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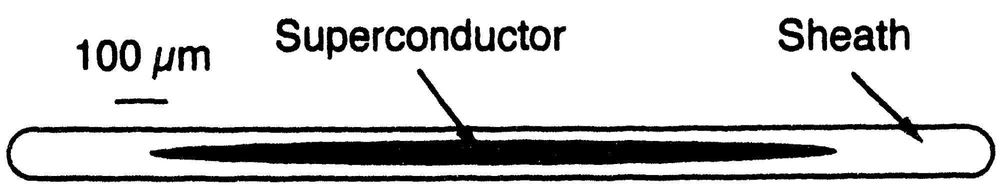
Superconductor vs. Engineering Values of J_C

- For High Temperature Superconductor (HTS) conductors, the configuration is typically a closed tape (Powder in Tube) or an open format (thick film)
- Schematic of a monofilament conductor cross section; the sheath is typically silver or a silver alloy and **Fill Factor** (ratio of HTS area to total area) is ~25%
- The **Engineering Cross Section** for J_C ($=J_e$) is the *total* area, yielding a lower value (~1/4) than the HTS J_C
- Superconductor $J_C = I_C /$ (HTS area)
- Engineering $J_C = I_C /$(Total conductor area)



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Critical Current Criteria

- **Electric Field Criterion** · Short sample (~ 1 cm) standard definition of I_c : current I at which an electric field e_c of 1 μV/cm is developed across the sample
- J_c or J_e can then be determined from I_c as discussed previously
- **Resistivity Criterion** - Applicable to short and long lengths but difficult to apply to short lengths because of voltage sensitivity limitations: current density J at which the sample develops a pre-determined resistivity ρ_c, typically 10^{-11} Ω-cm for HTS, based on either the HTS ($J_{c\rho}$) or the total cross section($J_{e\rho}$).
- Equivalently, by converting to resistance R based on the conductor geometry, $R = \rho$Length/Area, an I_c can be determined from the current/voltage curve

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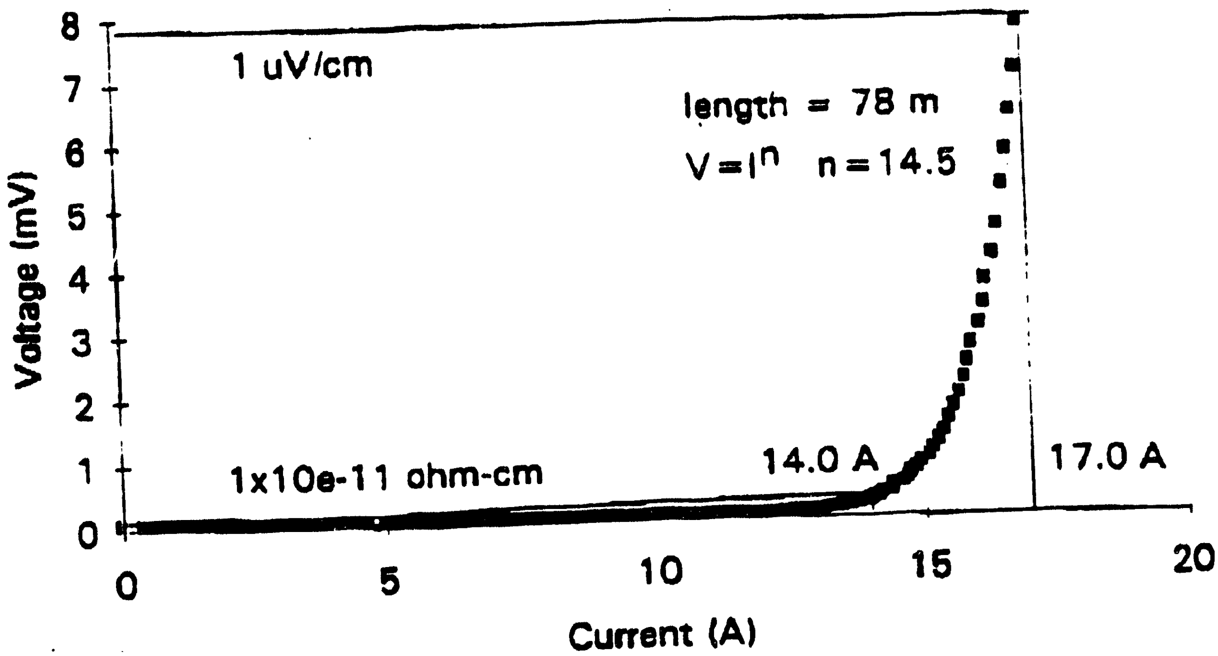
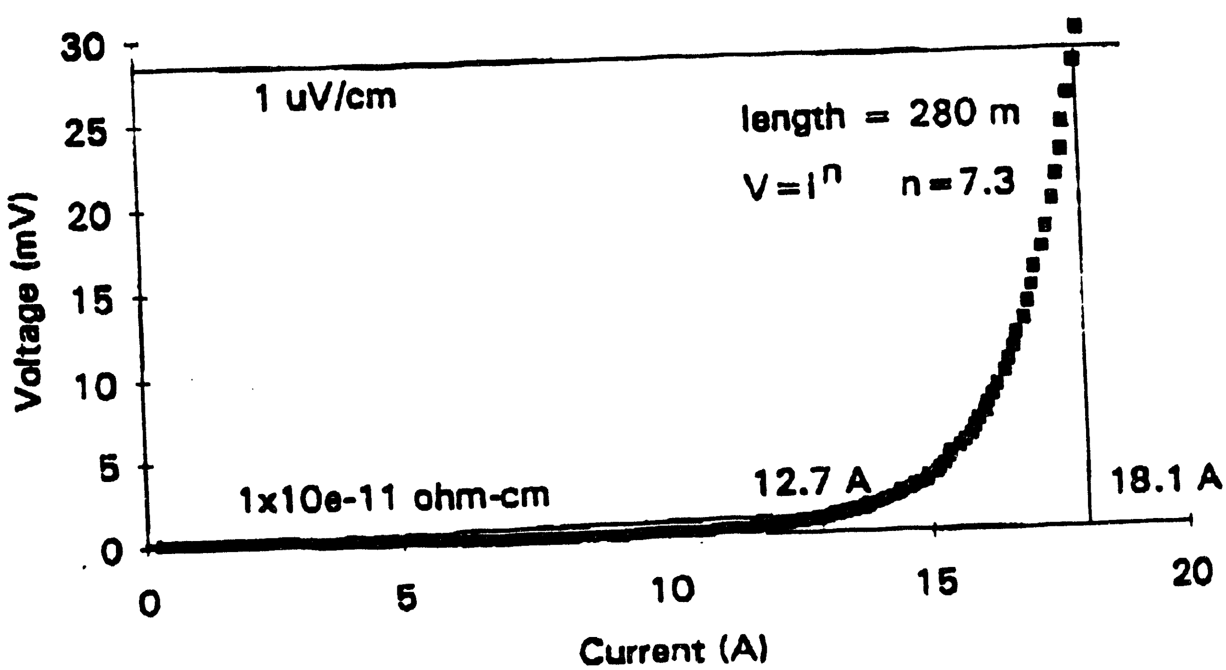
Pilot Production at American Superconductor Corporation

- Bi-2223
- 19 filament composite conductor
- 23% fill factor
- 100 m lengths
- Process Capability (over 250 to date)
- Conductor inventory for prototypes

American Superconductor CORPORATION

Long Length I-V Plots





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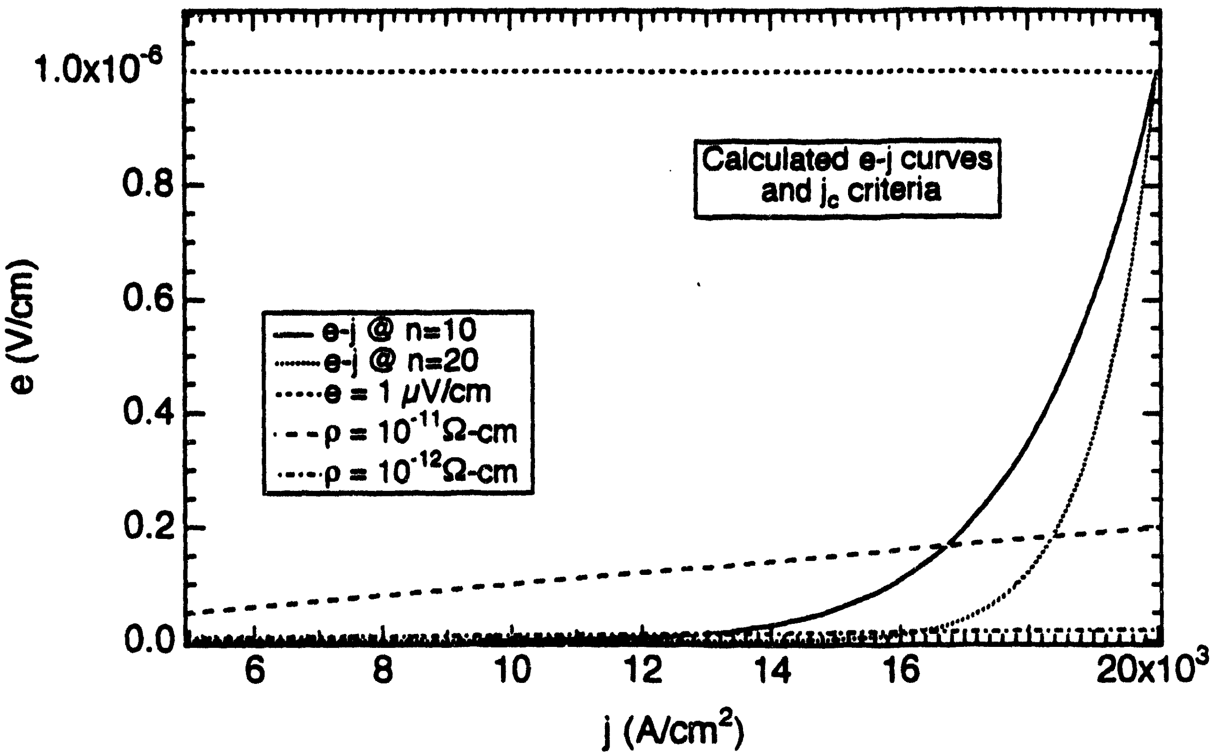
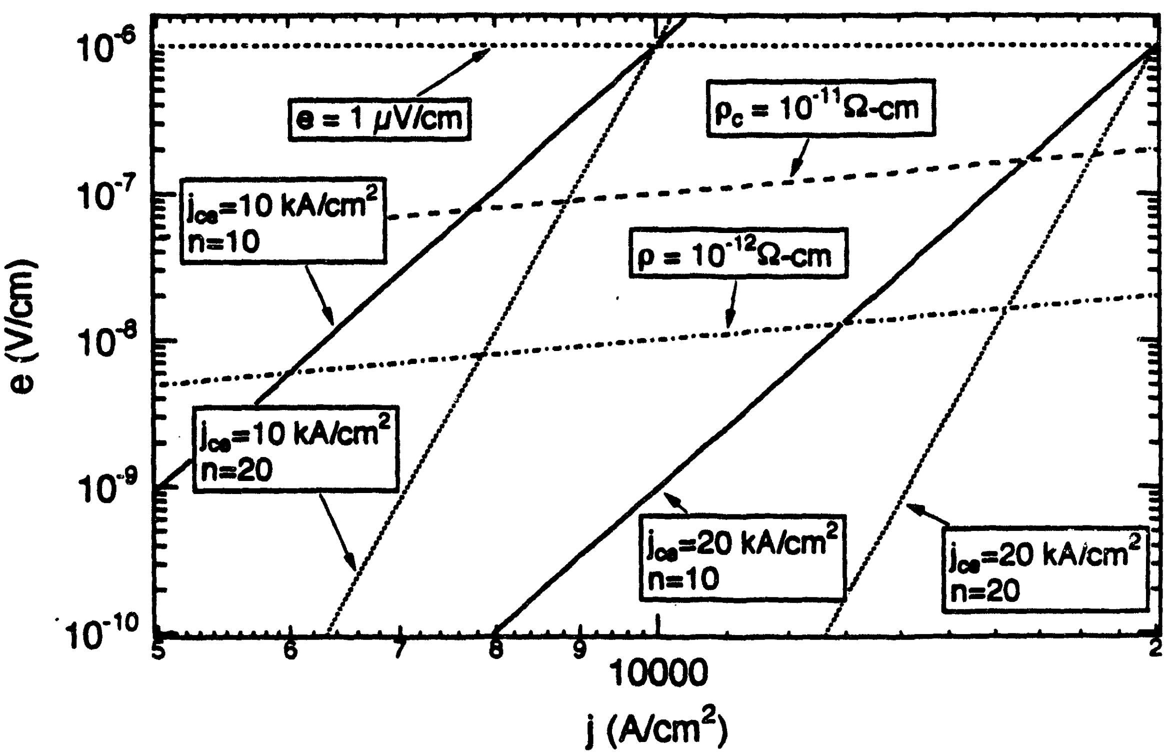


Calculated e-j curves and j_c criteria
e-j @ n=10
e-j @ n=20
e = 1 μV/cm
ρ = 10^{-11}Ω-cm
ρ = 10^{-12}Ω-cm
e (V/cm)
j (A/cm^2)



e = 1 μV/cm
ρ_c = 10^{-11}Ω-cm
j_{ce}=10 kA/cm^2 n=10
ρ = 10^{-12}Ω-cm
j_{ce}=10 kA/cm^2 n=20
j_{ce}=20 kA/cm^2 n=10
j_{ce}=20 kA/cm^2 n=20
e (V/cm)
j (A/cm^2)

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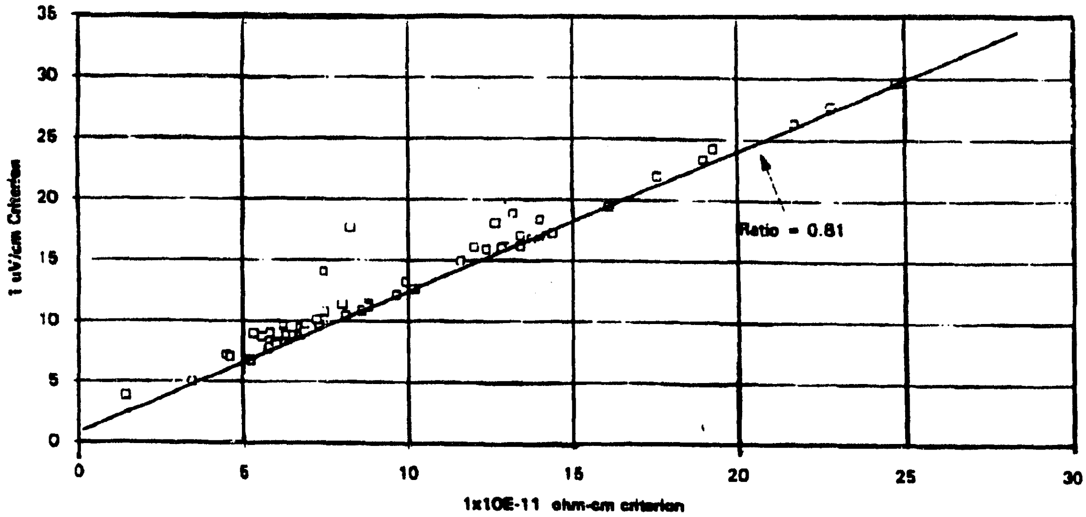
Ic Ratios (77K, self field) for Long Length Conductors



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Dependence of I_c, J_c, and J_e on Parameter Values

- The voltage-current (*V-I*) or electric field-current density (*e-j*) characteristics can be approximately represented by (neglecting current flow in the sheath):

$$e = e_o j^n$$

where e_o and n are obtained by fitting the data, or calculated as e_o ($= e_c / j_{ce}^n$) with e_c being the electric field criterion and j_{ce} the value of j_c at that field, and n is the exponent reflecting the power law behavior of the relationship

- j_{cp} and j_{ce} are then simply related by:

$$\frac{j_{cp}}{j_{ce}} = \left(j_{ce} \frac{\rho_c}{e_c} \right)^{\frac{1}{n-1}}$$

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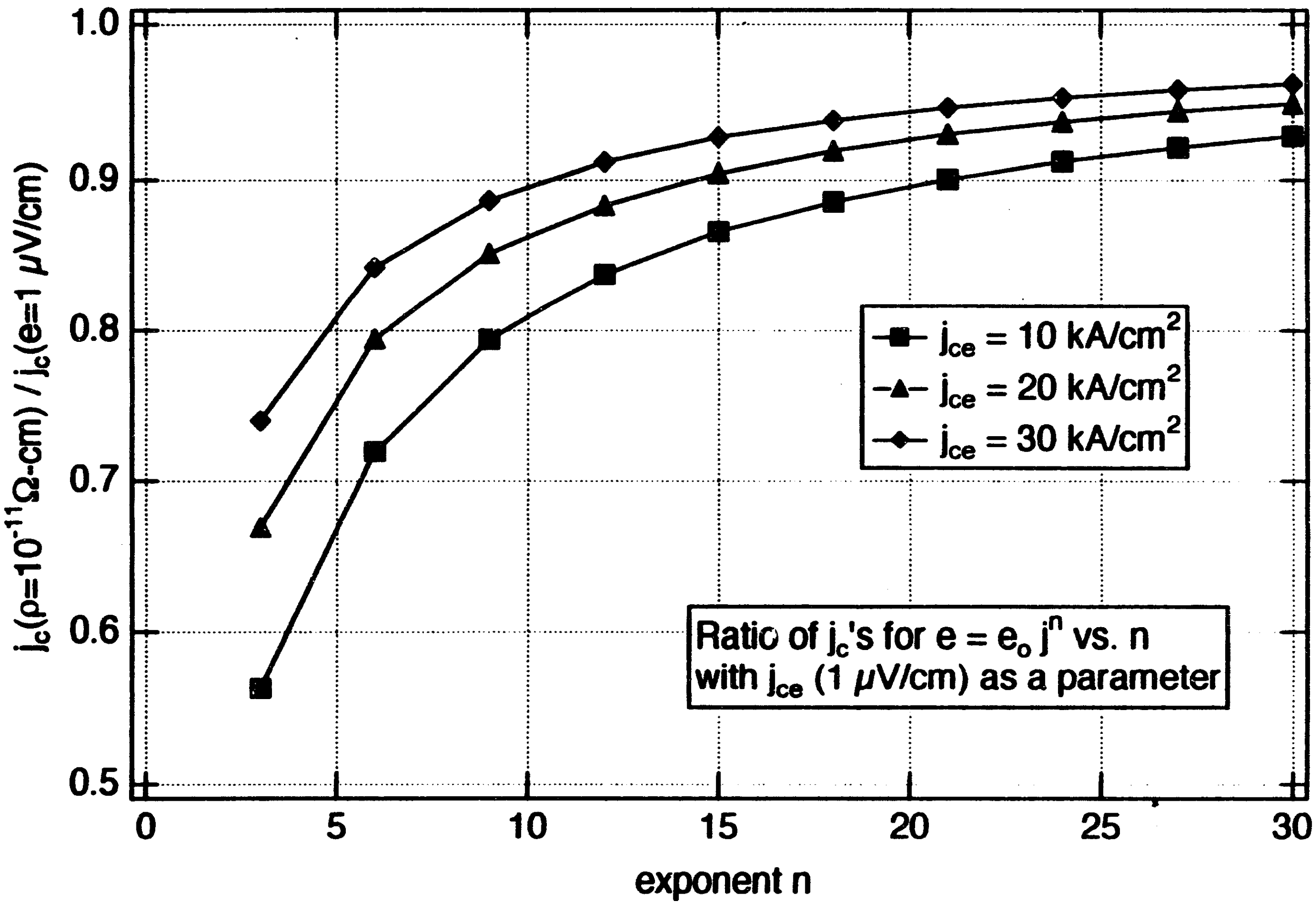

1.0
0.9
0.8
0.7
0.6
0.5
0
5
10
15
20
25
30
exponent n
$j_c(\rho=10^{-11}\Omega\text{-cm}) / j_c(e=1\ \mu V/cm)$
j_{ce} = 10 kA/cm^2
j_{ce} = 20 kA/cm^2
j_{ce} = 30 kA/cm^2
Ratio of j_c's for $e = e_o\, j^n$ vs. n
with j_{ce} (1 μV/cm) as a parameter

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Models for E-J characteristics

A. Flux Creep Model: $E(J) = E_c \exp[-U(J, B, T)/kT]$; where $U(J, B, T)$ is the flux creep barrier.

- Making the approximation $U = U_o \ln(J_c/J)$ (Vinokur *et al.* - Collective creep/vortex glass models) results in: $E(J) = E_c\,(J/J_c)^{U_o/kT}$ where $n = U_o(T, B)/kT$ and leads to an exponential decrease of J_{ce} with B and T
- Ries *et al.* and Gurevich *et al.* have applied this model to HTS systems.

B. n as measure of the variation of I_c with position x

- $I_c(x)$ may be caused by variation in area (sausaging, cracks, etc.) or in J_c (stoichiometry, defects, etc.)
- Many groups have used this model; recently Edelman and Larbalestier applied it to both monocore Nb-Ti wire and Bi-2223/Ag tape

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A. Gurevitch *et al.*, *Appl. Phys. Lett.* **62** (1688) 1993.

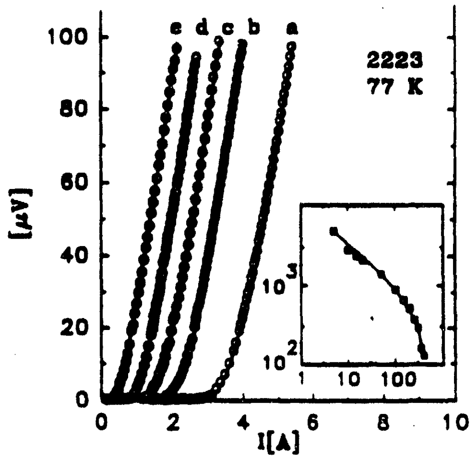
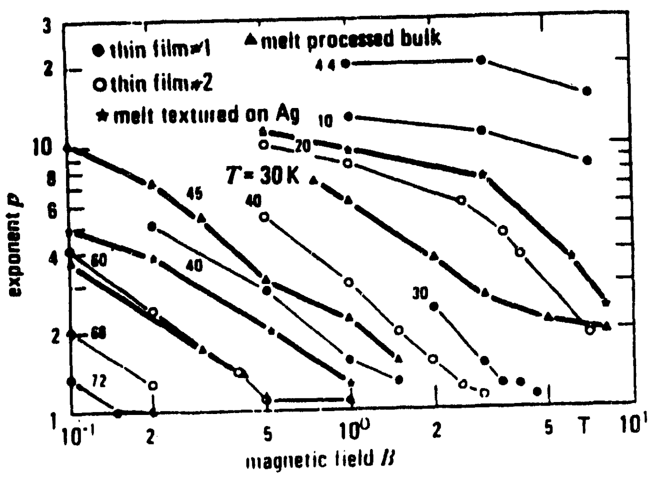


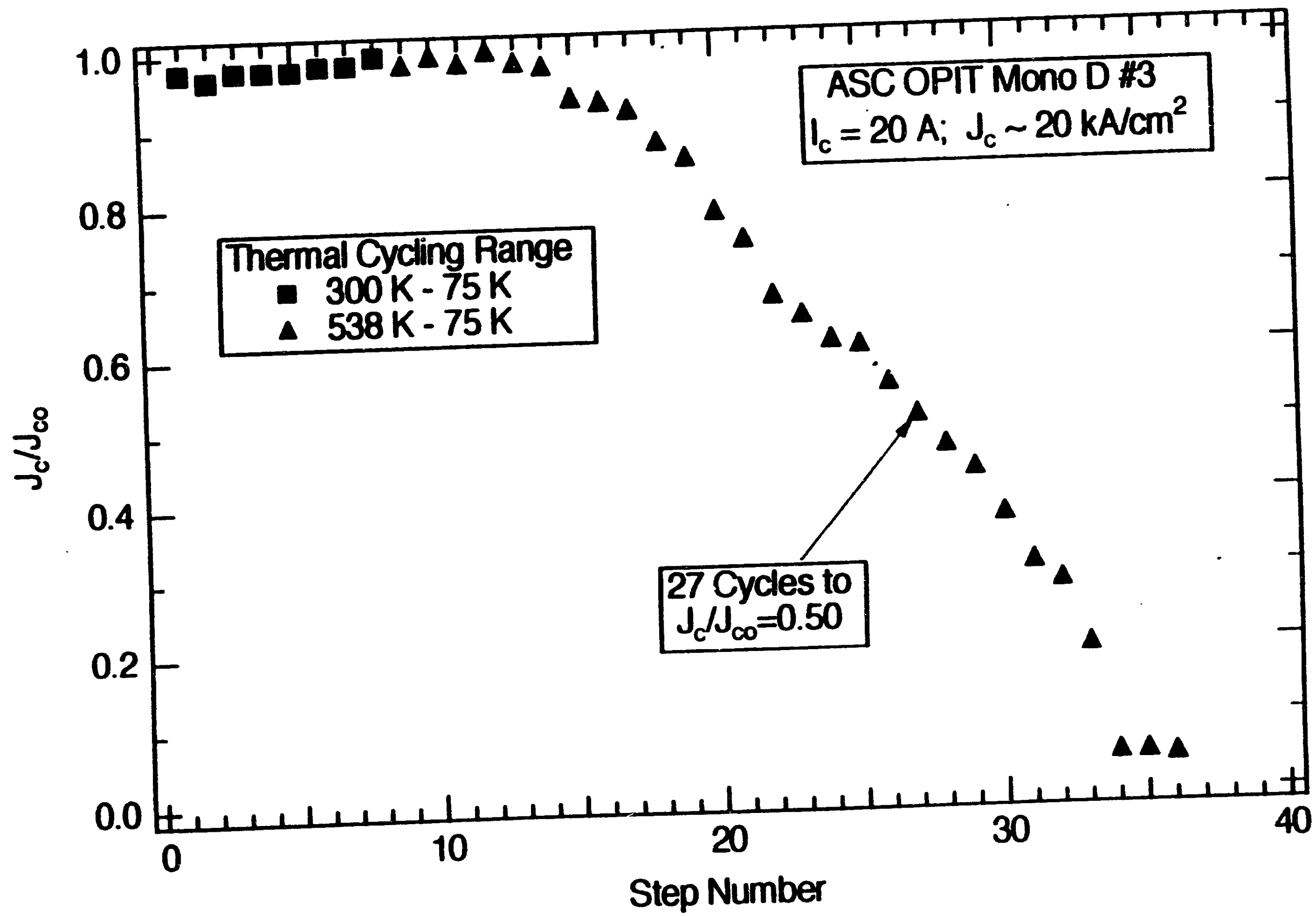
FIG. 2. V-I curves at 77 K and different B, the solid curves corresponding to Eq. (2). The upper figure concerns the 2212 tapes at: (a) 0 T, (b) 5 mT, (c) 10 mT, (d) 20 mT, and (e) 30 mT. Inset shows J_c [A/cm^2] versus B [mT] for different E_c: 1 μV/cm (open circles), and the extrapolation of the linear part of $I(V)$ down to the intersection with the I-axis (black squares). The lower figure concerns the 2223 tapes at: (a) 5 mT, (b) 10 mT, (c) 20 mT, (d) 50 mT, and (e) 200 mT. Inset shows J_c[A/cm^2] as a function of B [mT], where the solid curve corresponds to $J_0 b^{-1/2}(1-b)$ with $b = B/B^*$.

G. Ries, *et al.*, *J. Alloys and Compounds* **195** (379) 1993.



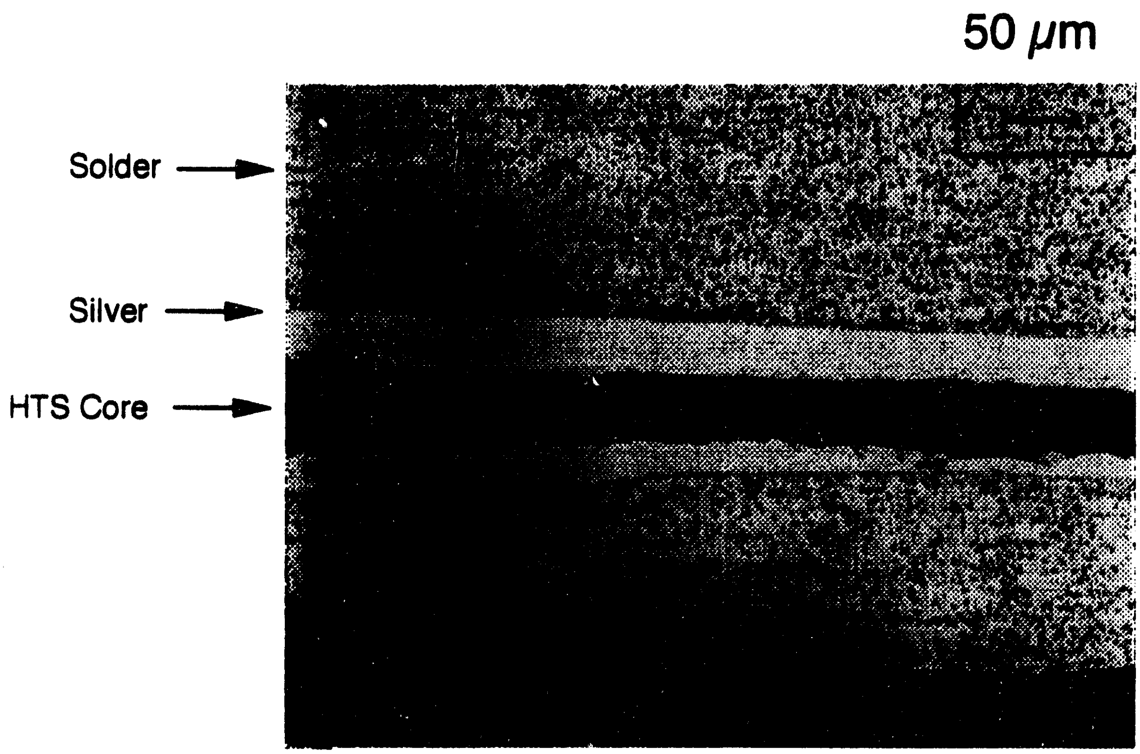
$e = j^{p}$

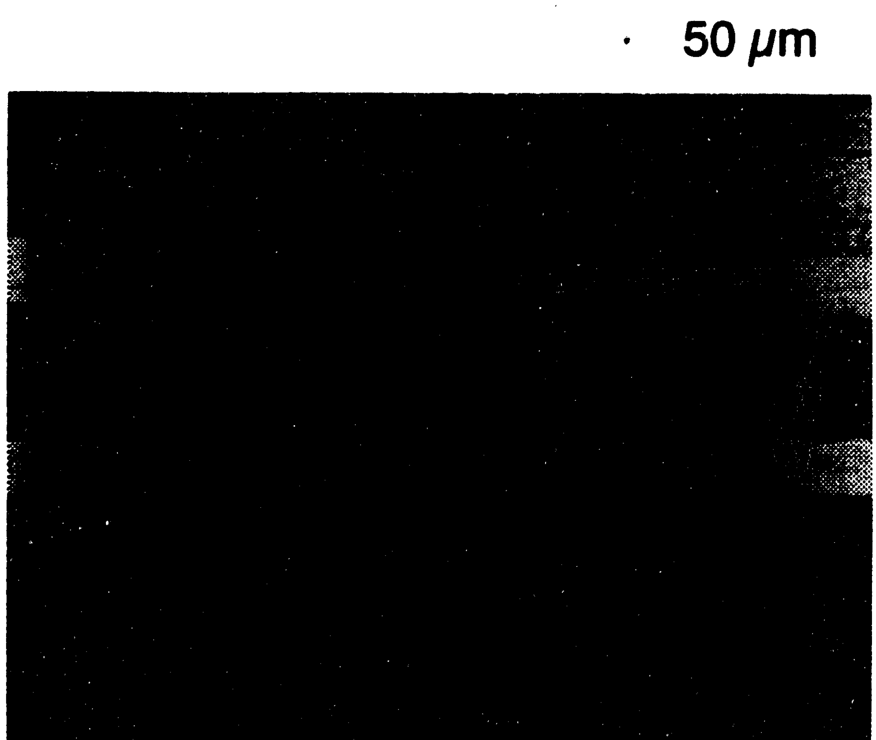
$(p \equiv n)$



ASC OPIT Mono D #3
I_c = 20 A; J_c ~ 20 kA/cm^2
Thermal Cycling Range
300 K - 75 K
538 K - 75 K
27 Cycles to
J_c/J_{co}=0.50
J_c/J_{co}
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
Step Number

Longitudinal Sections of Thermally Cycled Tape





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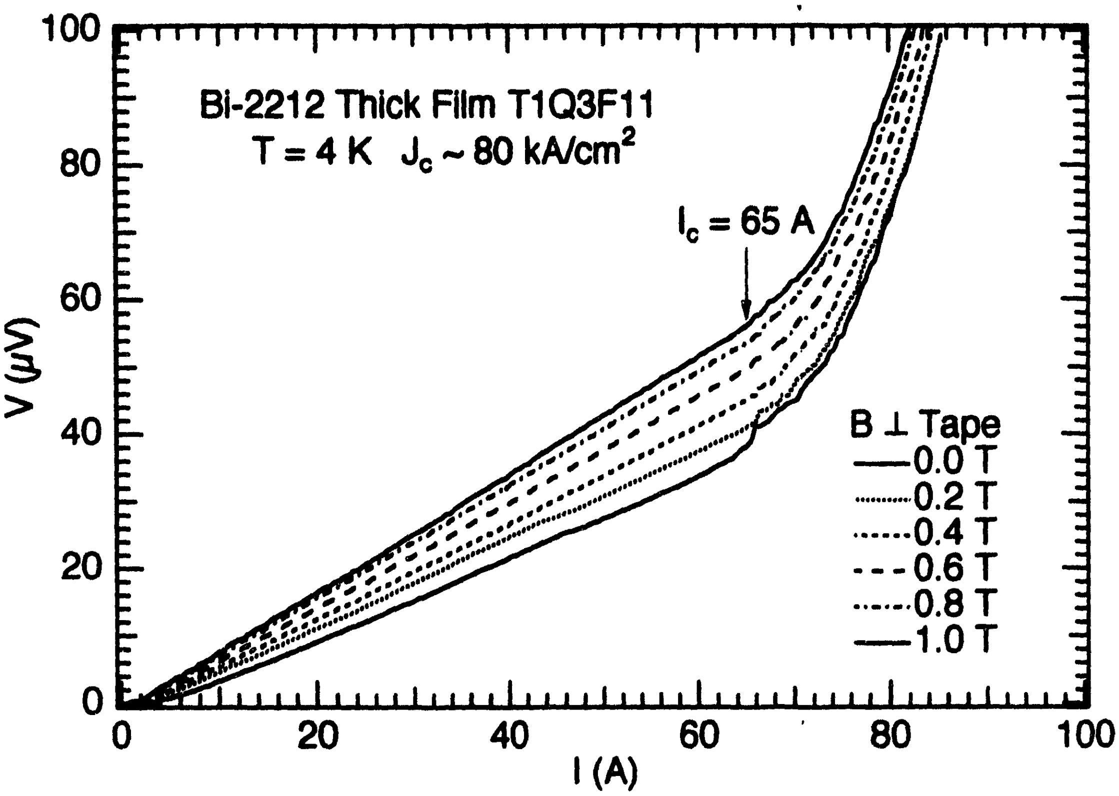
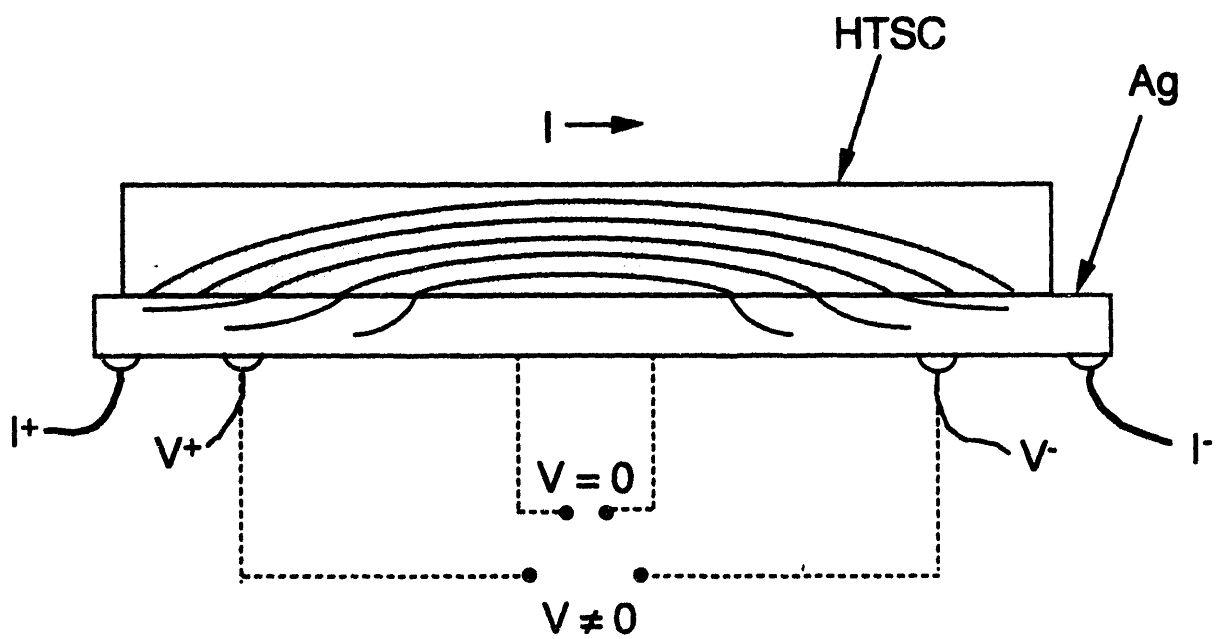
Current Transfer into Superconductor





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Summary

- Core *vs.* engineering (overall) critical current density values: J_c *vs.* $\boldsymbol{J_e}$ (more appropriate)
- Electric field vs. resistivity criteria for critical current density: J_{ce} *vs.* $\boldsymbol{J_{c\rho}}$ (or $\boldsymbol{J_{e\rho}}$) most appropriate for long length conductors
- Flux creep a major limitation at high temperature and modest fields; here $J_{c\rho}$ (or $J_{e\rho}$) is crucial to evaluation of conductor performance
- Mechanical issues of mounting and current transfer must be considered, especially for short lengths

Mechanical Properties Measurement of High-T_c Superconductors using a Mechanical Properties Microprobe

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Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831

OUTLINE

- Literature review of data on BSCCO
- Motivation for study
- Description of the Mechanical Properties Microprobe
- Results
  1. $YBa_2Cu_3O_{7-\delta}$
  2. PIT Bi-2212, Bi-2223
- Summary

Single Crystal Data for BSCCO

Material Dimensions (μm^3) Method	Modulus (GPa)	Reference
Bi-2212 (2000 X 20 X 2) Vibrating Reed	3-10	Jacobson et al., Phys. Rev. B47 (1993) 8312
Bi-2212 (3330 X 620 X 40) Vibrating Reed	70	Nes et al., Supercond. Sci & Tech., 4(1991) S388
Bi-2212 (400-1000) X (2-15) X (1-4) Stress-Strain by uniaxial loading	20	Tritt. et al., Physica C, 1991
Bi-2212 Brillouin Scattering	E_a = 125 E_c = 76	Boekholt et al., Physica C, 179 (1991) 101
Bi-2212 Brillouin Scattering	E_a = 130 E_b = 110	Wu et al., Phys. Lett., A148 (1990) 127
Bi-2212 Ultrasonic (100KHz)	100	Wang et al., Phys. Rev. , B41 (1990) 8981
Bi-2212 Brillouin Scattering	143	Baumgart et al., Physica C, 162-164 (1989) 1073
Bi-2212 Ultrasonic (100KHz)	165	Saint-Paul et al., Solid State Commun., 69 (1989) 1161
Bi-2223 (400-1000) X (2-15) X (1-4) Stress-Strain by uniaxial loading	E_a = 25	Tritt. et al., Physica C, 1991

For 2212

- E_{ab} : 3-10 GPa - 165
- E_c : 76 GPa

For 2223

- E_{ab} : 25 GPa

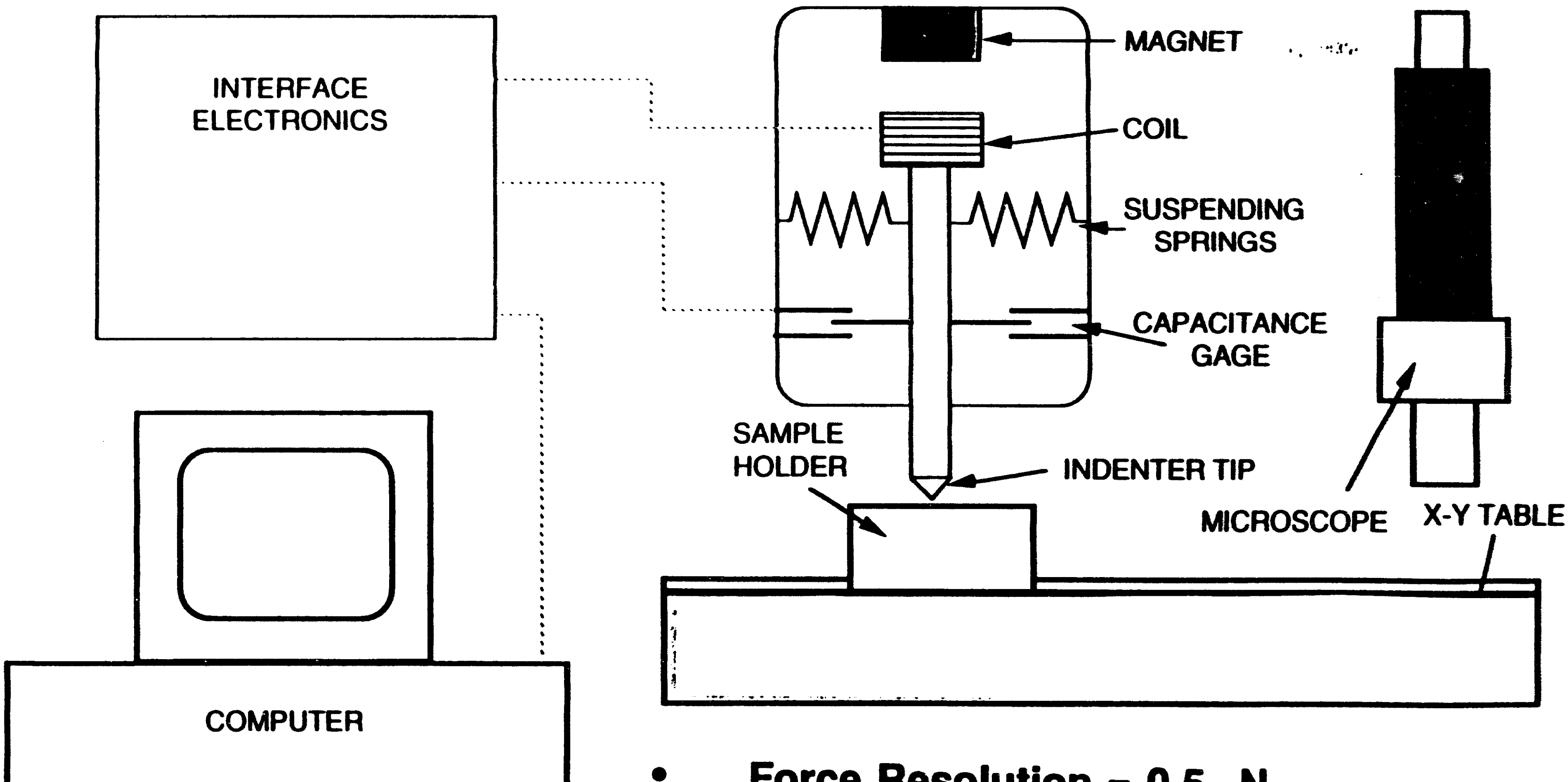
Summary of Data on Polycrystalline BSCCO

Material	E (GPa)
2201	42 ± 4; SD = 6
2212	50 ± 6; SD = 13
2223	59 ± 6; SD = 19

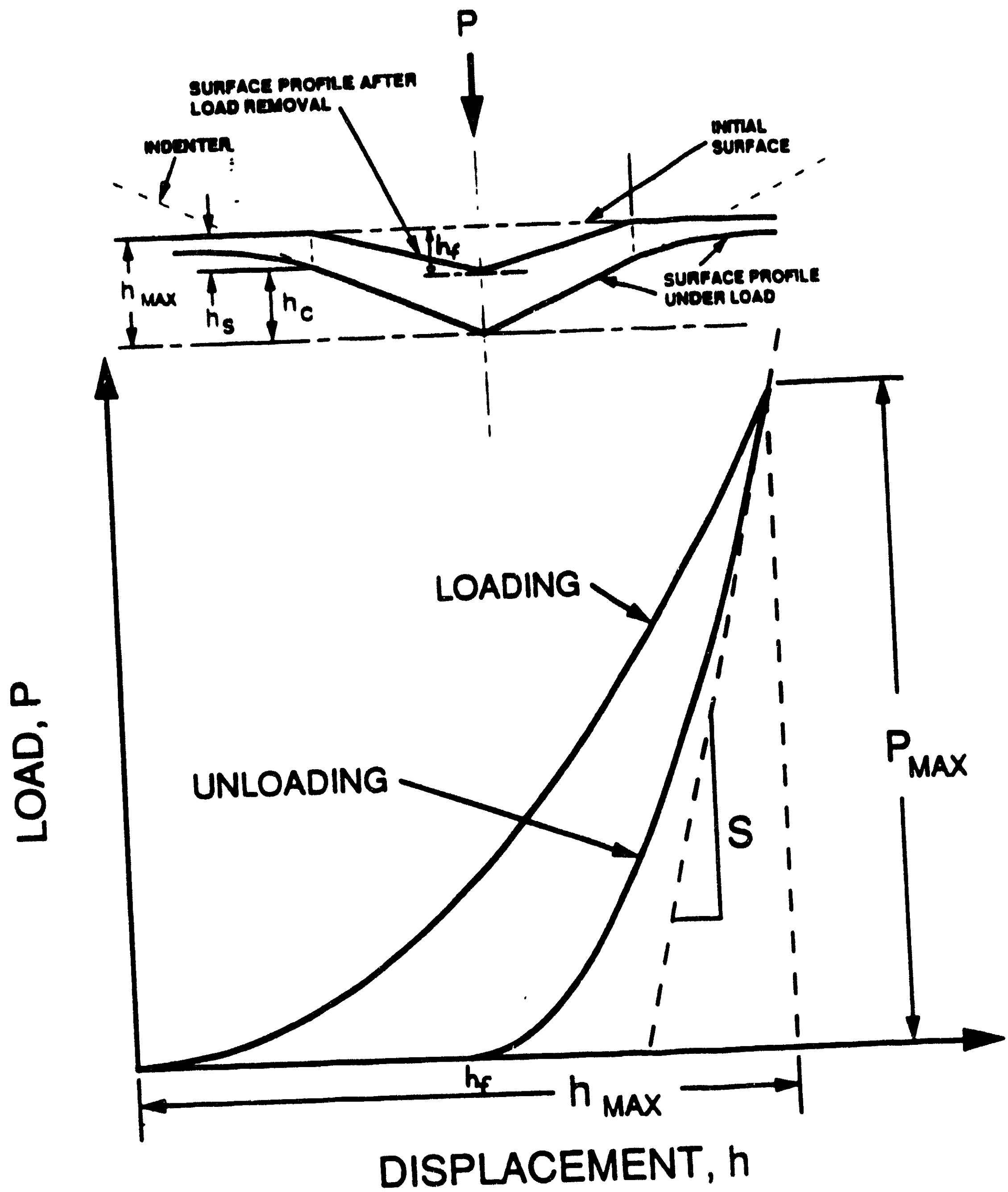
Motivation

- No good data exists for Bi-2223
- Existing data for Bi-2212 show wide variation
  - strong dependence on sample type
  - single crystal data primarily on Pb-free samples
  - Additional Effects
    - Effect of Oxygen Stoichiometry
    - Effect of Pb
- No direct measurements on PIT materials

NANOINDENTER IS CAPABLE OF CONTINUOUSLY MEASURING LOAD AND DISPLACEMENT DURING INDENTATION TESTING



- **Force Resolution = 0.5 μN**
- **Displacement Resolution = 0.16 nm**
- **Resolution of motorized xy stage ~ 1 μm**



P
SURFACE PROFILE AFTER
LOAD REMOVAL
INDENTER
INITIAL
SURFACE
h_f
h_{MAX}
h_s
h_c
SURFACE PROFILE
UNDER LOAD
LOADING
LOAD, P
UNLOADING
S
P_{MAX}
h_f
h_{MAX}
DISPLACEMENT, h

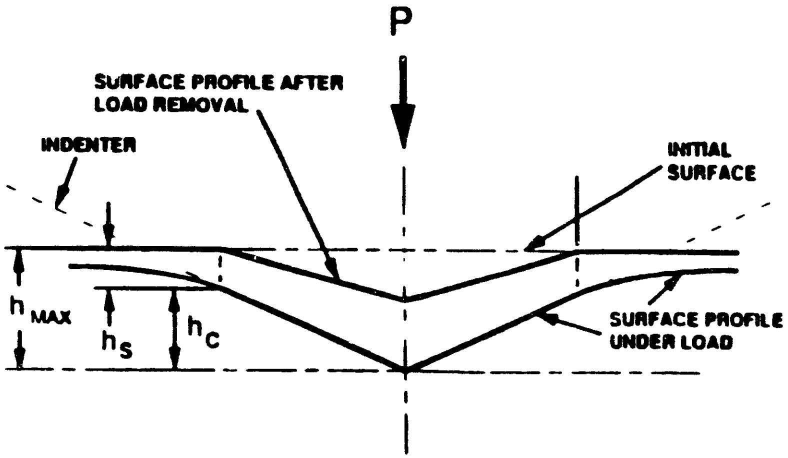
Extraction of the Hardness and Elastic Modulus from the unloading curve

Elastic Properties

The unloading process can be modelled by considering the contact of the indenter with an elastic half space

$S = dP/dh = \beta E_r\sqrt{A}$; $E_r = [(1-\upsilon^2)/E + (1-\upsilon_o^2)/E_o]^{-1}$

S = slope of unloading curve at point of max. loading
β = constant dependent on the shape of indenter



Total displacement of the indenter

$h_{max} = h_s + h_c$; $h_s = \varepsilon P_{max}/S$;
ε = constant dependent on the geometry of indenter
ε = 1.0 for flat punch, 0.75 for parabola of revolution

Hardness

Defined as the mean pressure the material can support under load

$H = P_{max}/A$; A = **projected area of contact under load**

MECHANICAL PROPERTIES OF MELT-PROCESSED123 AND TRAPPED 211 INCLUSIONS DETERMINED USING A NANO-INDENTOR

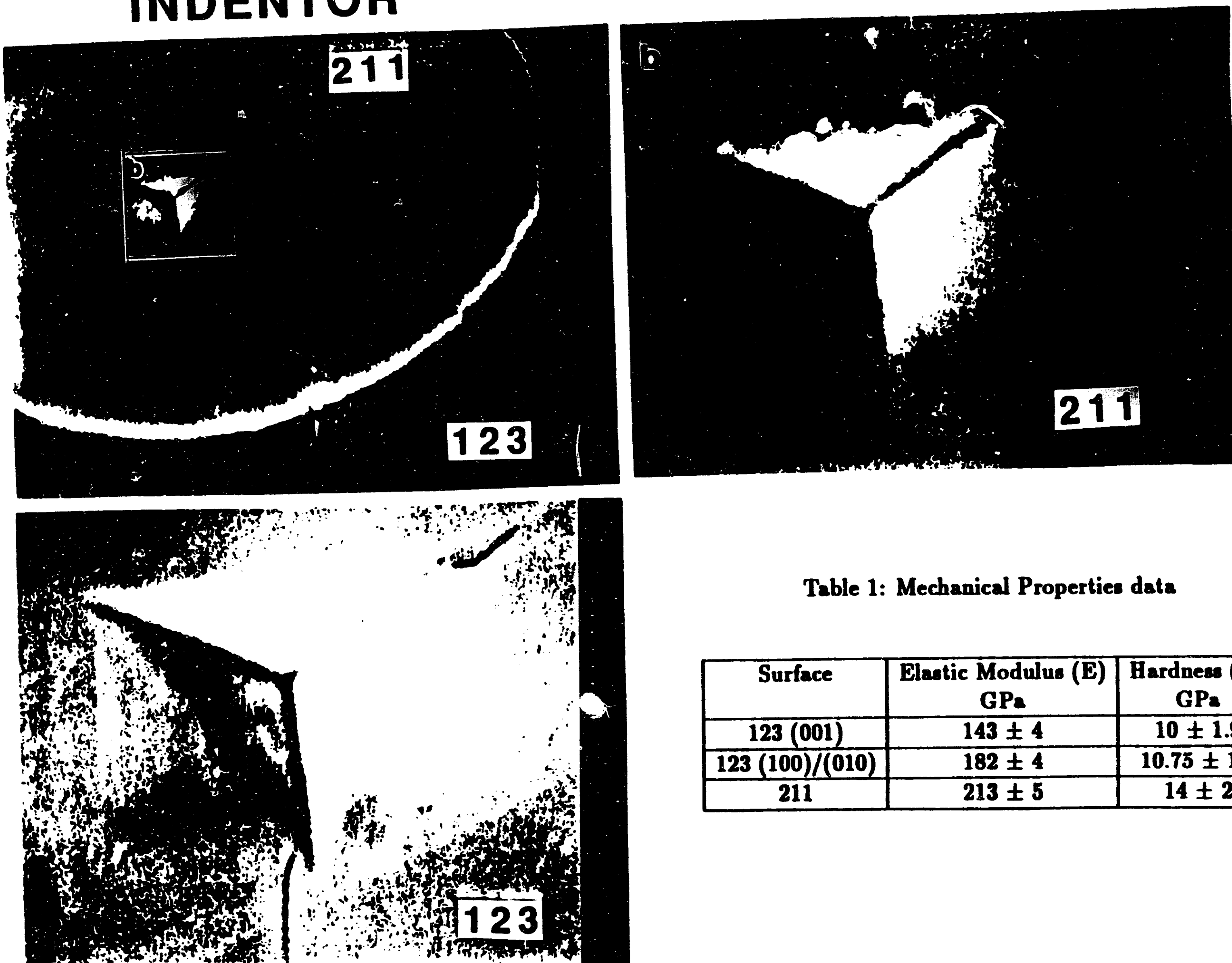


Table 1: Mechanical Properties data

Surface	Elastic Modulus (E) GPa	Hardness (H) GPa
123 (001)	143 ± 4	10 ± 1.9
123 (100)/(010)	182 ± 4	10.75 ± 1.7
211	213 ± 5	14 ± 2

MECHANICAL PROPERTIES OF BSCCO PIT SAMPLES

Material	Elastic Modulus (GPa)	Hardness (GPa)
2212 (100) or (010)	93.8 ± 3.5	2.3 ± 1.3
2212 (001)	49.8 ± 11.6	2.7 ± 1.2
2212 (as rolled)	64.9 ± 4.5	2.4 ± 0.4
2223 (100) or (010)	90.2 ± 9.5	1.9 ± 0.5
2223 (001)	54.4 ± 1.8	1.5 ± 0.7
Second Phase	59.6 ± 6.5	2.4 ± 0.4

Material	Elastic Anisotropy (100)/(001)	Hardness Anisotropy (100)/(001)
123	1.3	0.9
2223	1.7	1.1
2212	1.9	0.9

- **The elastic modulus of Bi-2212 and 2223 is highly anisotropic. The higher compressibility along the c-direction is due to the layered structure.**
- **Compared to 123 the BSCCO phases are much softer and less stiff.**

Summary

- The Nanoindenter or the Mechanical Properties Microprobe is ideally suited for direct measurements of elastic moduli and hardness of high-T_c superconductors
- 123, Bi-2212 and Bi-2223 exhibit highly anisotropic properties
- Compared to 123, Bi-2212 and Bi-2223 are much softer and much less stiff

SECTION VI

TECHNOLOGY FOR OVERCOMING BARRIERS: WEAK LINKS AND FLUX PINNING

High Temperature Superconducting Wire Development Workshop

February 16-17, 1994

Session II

Technology for Overcoming Barriers: Weak Links and Flux Pinning

A. Proposal to Develop Standardization of Measurement Procedures and Interpretation for Critical Currents

Preliminary draft available here and at tomorrow's session

Please provide comments and feedback on draft

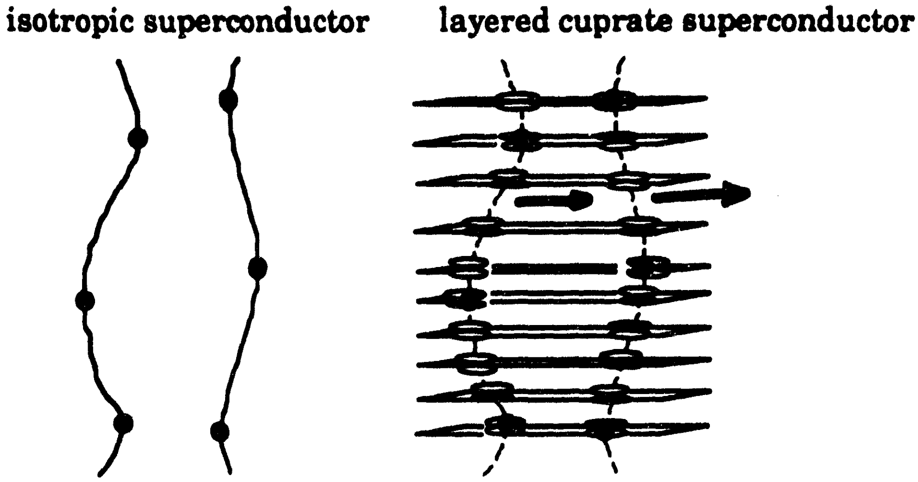
B. Issues for Session II

Flux Pinning, within well-coupled, non-weak-linked regions

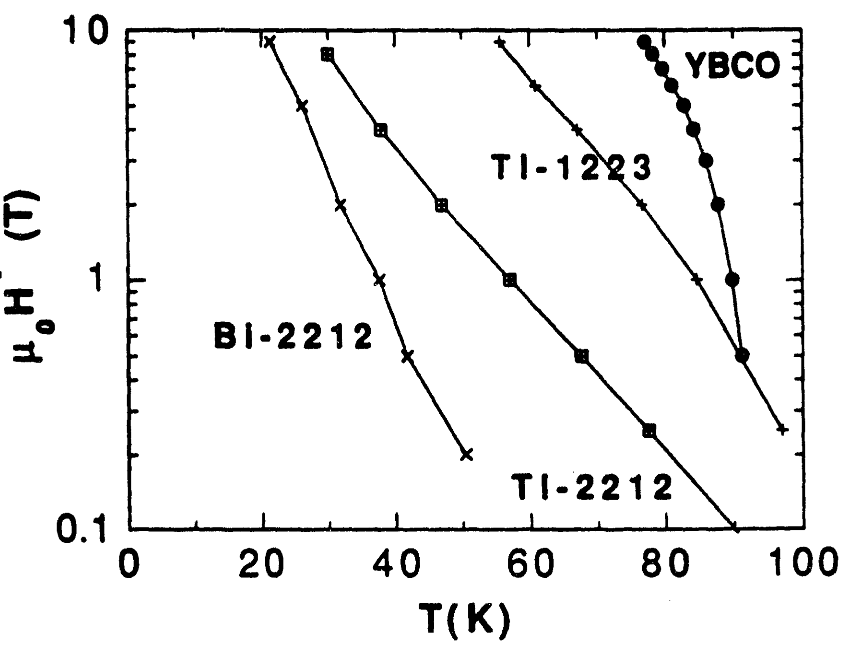
Irreversibility behavior at high fields and temperatures

Weak links, e.g., grain boundaries

Effective pinning is reduced if interlayer coupling is weak



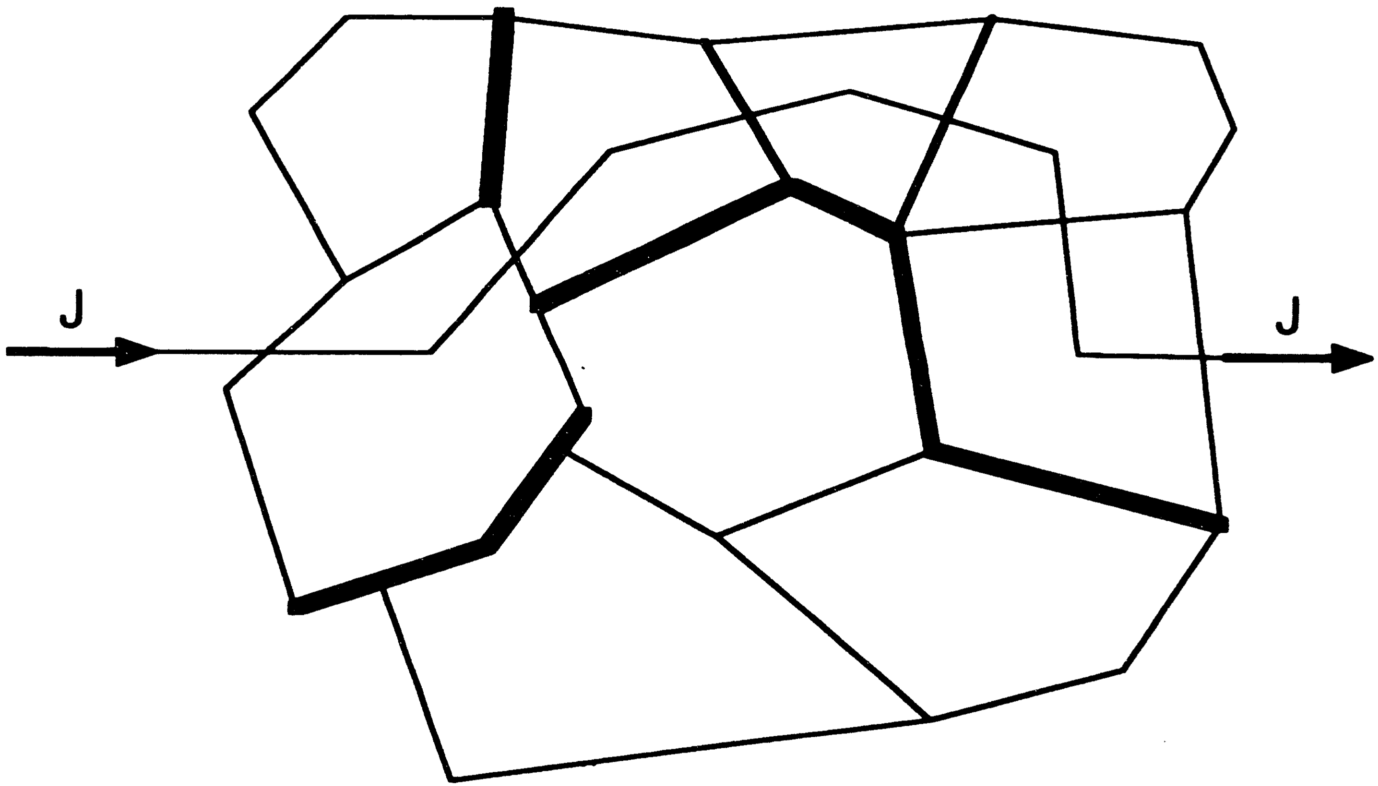
Our model thus explains the characteristic fields for thermally-activiated flux motion in a variety of layered HTS cuprates



Tl-1223	- MOCVD film from T. Marks, Northwestern Univ.
Tl-2212	- epitaxial film from STI, Inc.
YBCO	- epitaxial film from Westinghouse
Bi-2212	- single crystal from D.L. Shi, ANL, DOE-BES

Technology for Overcoming Barriers: Weak Links and Flux Pinning

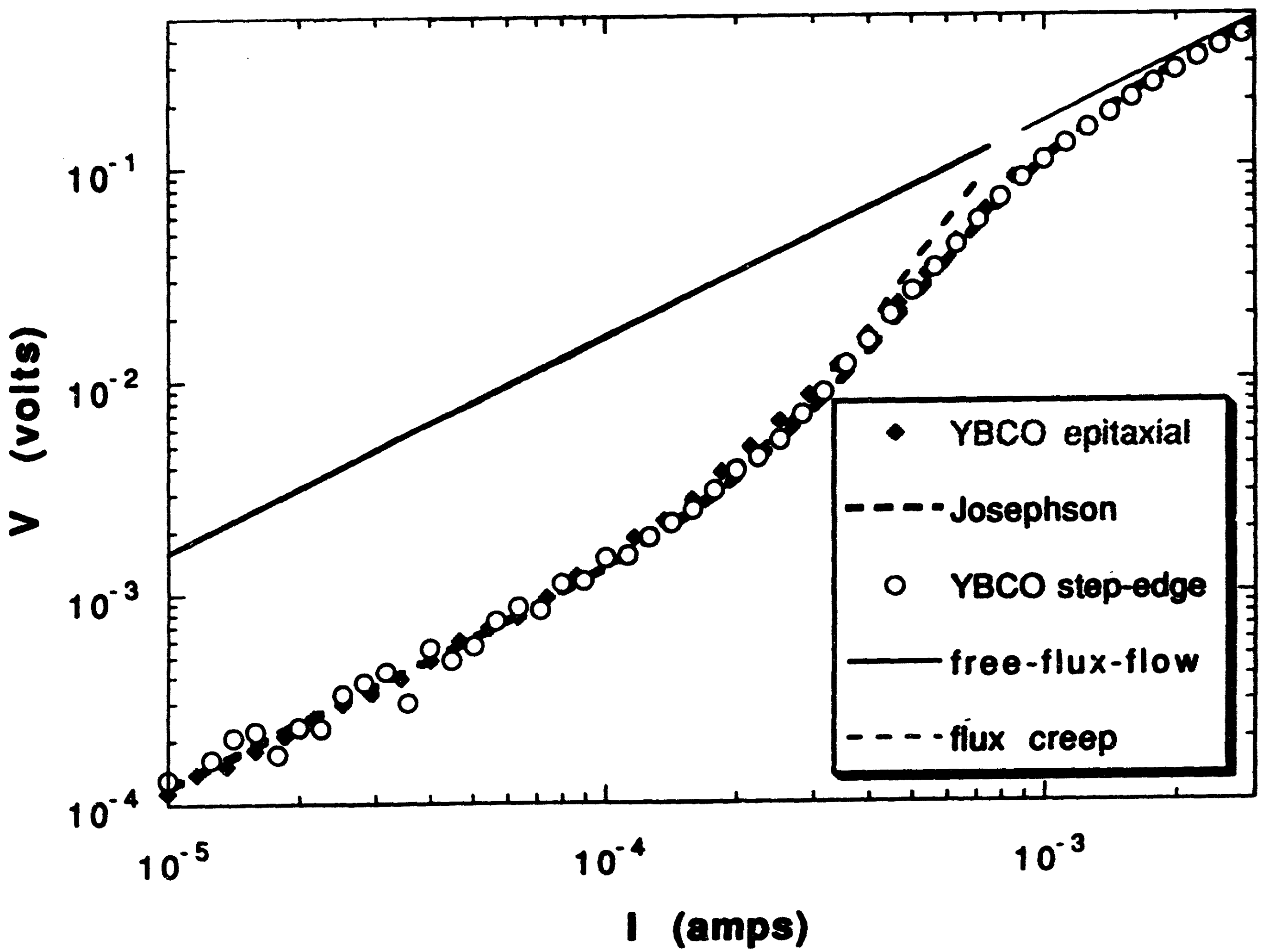
Polycrystalline samples have series and parallel grain boundaries

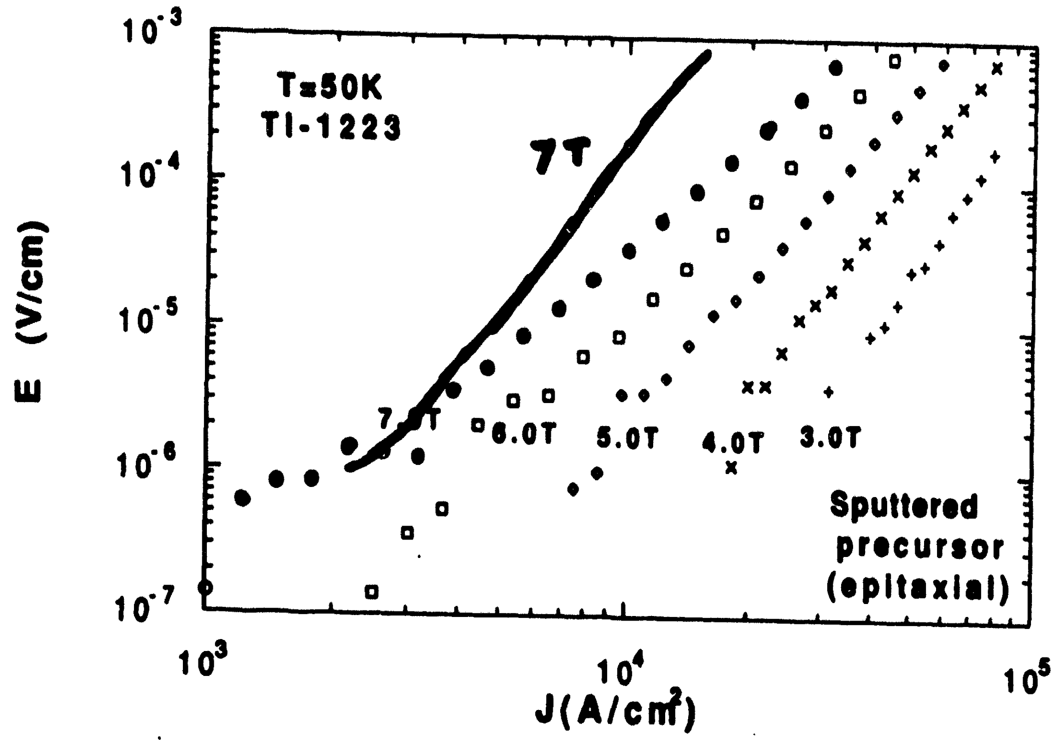


As the field increases, the strongest paths predominate the current flow

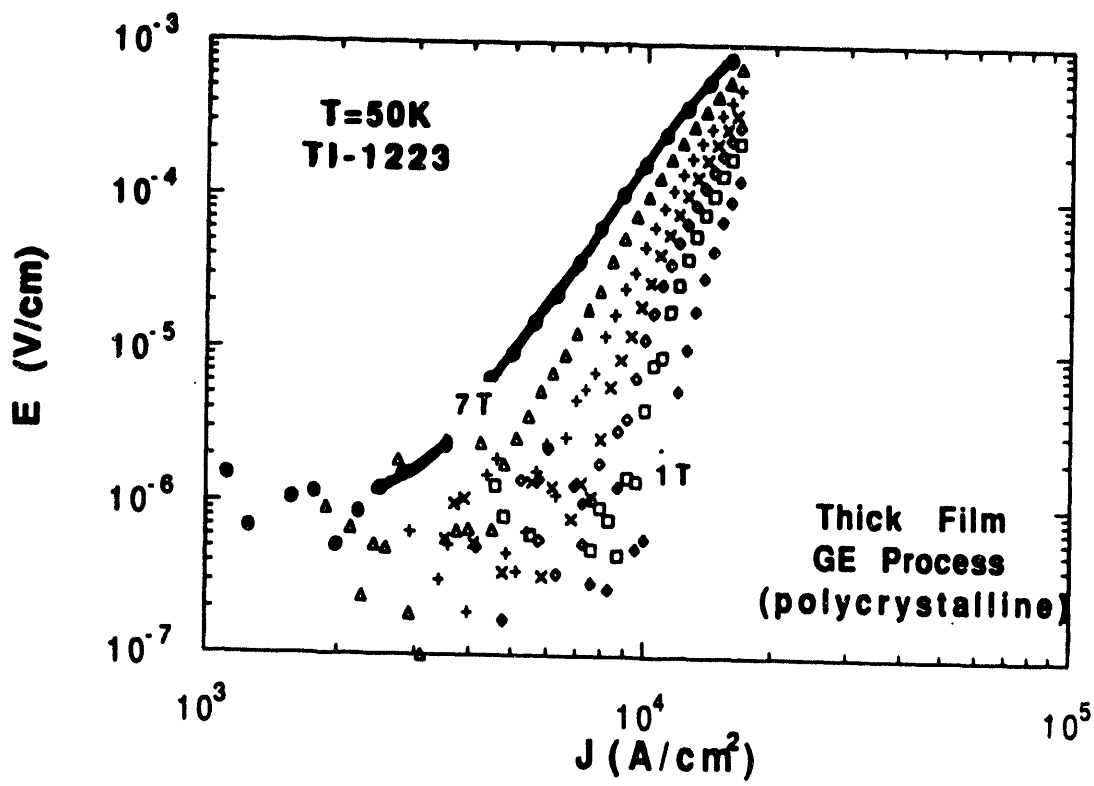
However, they may still have weak, but not very weak, links

Current-Voltage Characteristics for Josephson Junctions and Anderson-Kim Flux Creep





T=50K
Tl-1223
7T
7.0T
6.0T
5.0T
4.0T
3.0T
Sputtered
precursor
(epitaxial)
E (V/cm)
J(A/cm²)



T=50K
Tl-1223
7T
1T
Thick Film
GE Process
(polycrystalline)
E (V/cm)
J (A/cm²)

WHERE IS THE CRITICAL CURRENT CARRIED IN 2223-BSCCO AND WHAT LIMITS IT?

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ABSTRACT

Recent investigations at Wisconsin into the factors controlling the J_c of BSCCO-2223 tapes are reviewed. Great local variations of the active current path exist, causing percolative current flow and greatly limiting the overall critical current. Some of the reasons for this variation are discussed. We conclude that increasing the active cross-section is the most promising way to raise the overall J_c of BSCCO tapes.

1. Introduction

Ag-sheathed $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (BSCCO-2223) superconducting tapes[1-6] made by the powder-in-tube process show great promise as conductors for magnetic field use. However, extensive study of their deformation, heat treatment, phase relationships and microstructure has not yet yielded a proper understanding of how to reproduce the best properties consistently. High phase purity and strong texture are widely agreed to be crucial for high J_c, yet relatively little is understood about the mechanism(s) by which the 2223 phase forms, the texture develops and the complex role that silver plays. We here summarize recent work from our programs[7-14] which concern the formation, properties and connectivity of the 2223 phase. An important conclusion is that the local J_c can vary by at least a factor of six from region to region within a tape and that J_c(0T, 77K) values exceeding the highest previously reported[1-3] can exist within even moderate quality tapes[8]. Improving the connectivity of the BSCCO filament(s) is believed to be the most direct way of making further improvements in the overall J_c of BSCCO-2223 tapes.

2. Competitive Reactions Between BSCCO-2212 and Second Phases

A study of the reactions that occur when powder is reacted within Ag illustrates the complexities of the system[9]. Many phases are present in starting powders and multiple parallel reactions can generate undesired non-superconducting phases, interfering with the desired 2212 to 2223 reaction, which has a significantly larger reaction energy (~ 1.5 MJ/mol[15,16]) than that measured for the undesired reactions (0.27-0.51 MJ/mol)[9]. The 2:1 AEC (alkaline earth cuprate) has the lowest formation energy (~370kJ/mol) and is the rate-limiting reaction in air. Growth of large 2:1 AEC particles inhibits completion of the 2212 to 2223 reaction by denying the growing 2223 phase essential Ca and Cu, besides greatly perturbing the alignment of the 2223 grains that do form. Uncontrolled reaction

1. Now at Superconductivity Research Laboratory (SRL-ISTEC), Tokyo Japan
2. Now at Quantum Design, San Diego CA, USA

to AEC is very common, particularly in the center of filaments. We must expect that such central regions are inefficient current paths.

3. Preferential Formation of 2223 at the Ag Interface

Preferential reaction to the 2223 phase occurs near the Ag interface, at temperatures about 20°C below that at which 2223 forms in the interior of the BSCCO core[7,9]. This 2223 reaction layer aligns itself such that its basal planes are parallel to the Ag, thus appearing to use the Ag as a template. The preferential formation of the 2223 phase at the interface is most reasonably explained by the depression of the melting point observed when Ag is present[15,17]. This is consistent with the model of liquid-assisted-transformation proposed by Morgan et al.[18]. However, there cannot be much liquid formed, because the preferential reaction zone is confined to the vicinity of the Ag-oxide interface, particularly for reactions in air. Because the growing 2223 phase front tends to align itself to the Ag, any sausaging or irregularity of the Ag tends to propagate to the superconductor, misaligning the grain-to-grain connections and interfering with potentially good "railway switches" [5,7].

4. Structure of the Ag-BSCCO Interface

For both 2212 and 2223 tapes, the interface between the Ag and the BSCCO is well bonded, free of non-superconducting phases and appears abrupt in HRTEM images[7,11,19]. In most cases, the Bi-O double layers abut the Ag. Fig. 1 shows a typical example for a 2223 tape. The (001) BSCCO planes lie parallel to the Ag, regardless of the Ag crystal orientation. Small misalignments are accommodated by half unit cell steps of the BSCCO. 2212 composites have their own peculiarity: whether processed by melting or by sintering below the melting point, there is always a residual half cell of 2201 at the Ag interface (see figure 2)[19]. By contrast, no 2201 or 2212 layers of any thickness were observed at the Ag/BSCCO interface in 2223 tapes[11].

5. Measurement of the J_c of Microslices cut from within Filaments

We developed techniques for cutting microslices from within filaments[8], so as to study the positional variability of J_c. In one example experiment, we cut five slices ~0.5 mm long with widths from ~80-130 μm from a tape with an overall J_{ct}(0T, 77K) of 14,000 A/cm^2 (Fig. 3). The central slice (3) and the intermediate position slices (2 and 4) had J_{ct}(0T, 77K) values characteristic of the whole tape. These three slices had well-rounded V-I characteristics, typical of a stable, reversible transition to the flux flow state. By contrast, the two outside slices (1 and 5) had abrupt transitions at much higher J_c values of 32,000 and 38,000 A/cm^2. These transitions were unstable (and probably underestimate the true J_c), no doubt due to contact and/or lead heating. The edge slices also had lower resistivities and field sensitivity than the central ones; one origin of these differences is clearly microstructural, as is seen in Fig. 4. The edge slice, close to the Ag, (Fig. 4a) has

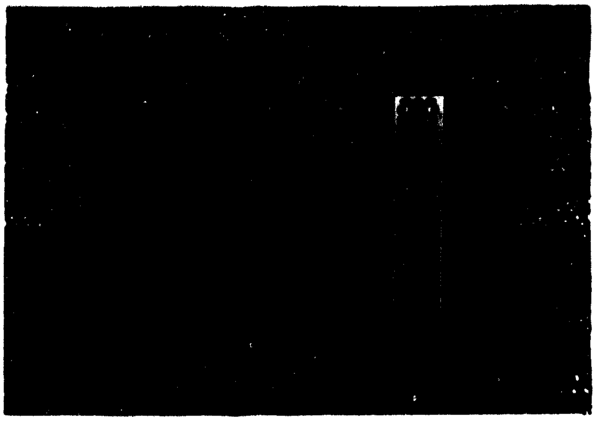

Fig. 1. HRTEM image of a Ag/BSCCO-2223 interface

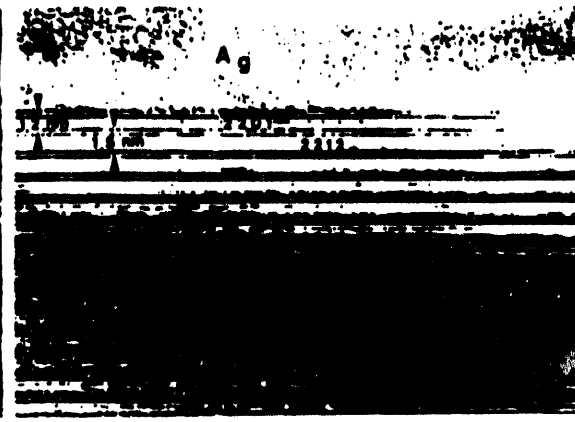

Fig 2. HRTEM image of a Ag/BSCCO-2212 interface

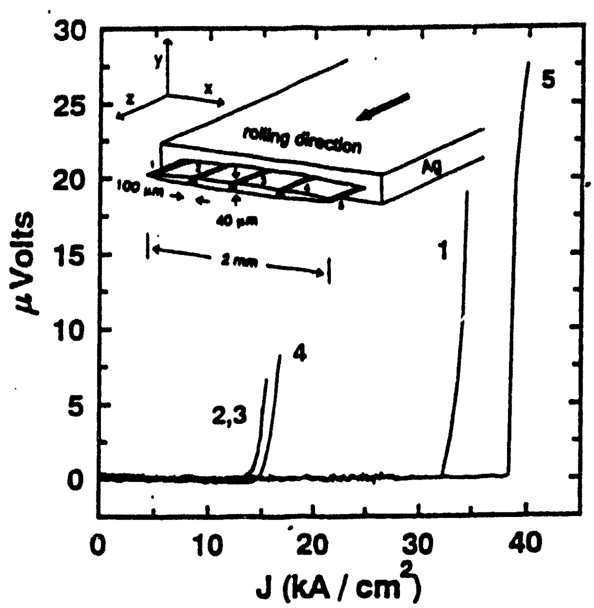

Fig. 3 V-I traces and positions for different microslices of a 2223 tape

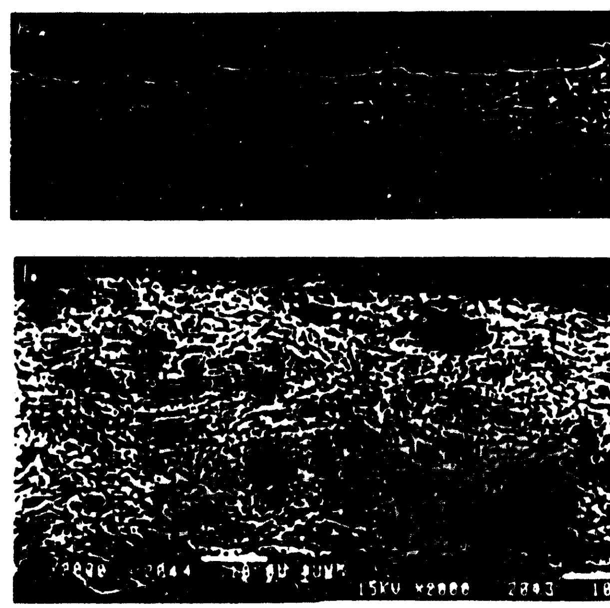

Fig. 4 SEM images of (a) slice 1 and (b) slice 3 of the 2223 tape described in Fig. 3

well-aligned grains, scarcely perturbed by second phase particles. Such a microstructure appears quasi-ideal. The central slice (Fig. 4b) is obviously multiphase and less well aligned, especially towards the tape center where the Ag is distant. Other tapes have different positional dependences of J_c, however. The highest value of J_c(0T, 77K) that we have measured is 76,000 A/cm^2; this was from a center slice, like slice 3 in Fig. 3, cut from a tape having an overall J_c of 12,000 A/cm^2. Other tapes exhibit strong evidence of cracking or weak block-to-block bonding and have microslice J_c values less than the overall. Thus multiple behaviors are seen; such variability means that multiple sources of current limitation exist, reducing the active cross-section to a fraction of the total and making the overall current path percolative. Extensive cracking has been observed in tapes having J_c > 20,000 A/cm². Since a deformation step is a crucial part of the optimization of all 2223 tapes, cracks cannot be avoided but must be healed in the subsequent heat treatment if they are not to disrupt current flow over large distances. Explicit tests for the avoidance of cracks could have a large influence on raising J_c values.

6. Residual 2212 Layers at the [001] Twist Boundaries and Their Influence on J_c

Field-dependent AC or DC susceptibility measurements were correlated with transport J_c and microstructure[10,22] for some 20 Ag-clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (2223) tapes having J_c (0T, 77K) values ranging from 0-20,000 A/cm². Fields of 0.1 - 10 mT induce

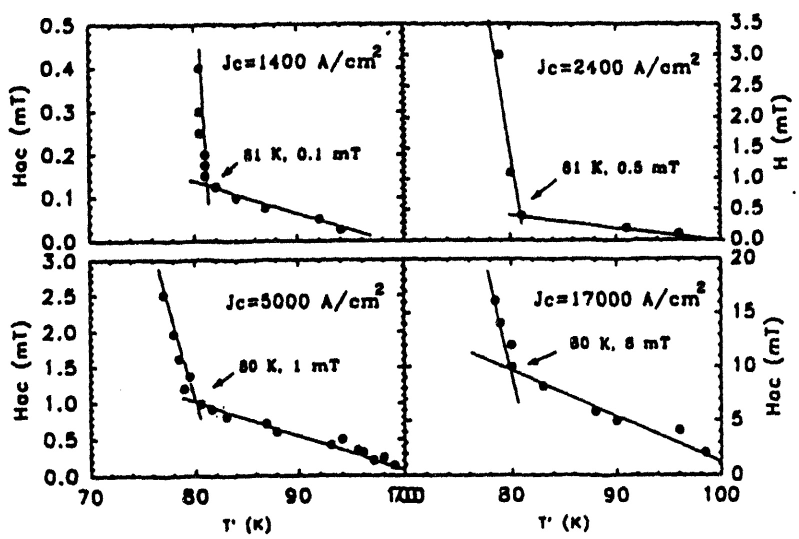

Fig.5 Field dependence of T' for various tapes with different J_c(0T,77K) values

a lower transition, T'(H), in the real component of the susceptibility. T'(H) exhibits a kink at 80-81 K, being relatively insensitive to H below 80 K and very sensitive above 80 K, indicating electromagnetically granular behavior (Fig. 5) at higher temperatures. HRTEM[10,22] reveals a direct correlation between the frequency of 2212 intergrowths at [001] twist boundaries (Fig. 6) and the field required to produce the kink in T'(H). A strong correlation between T'(H) and J_{ct}(0T, 77K) is direct evidence that c-axis transport across these (001) twist boundaries occurs[23]. However, this current should be suppressed by weak fields and, indeed, it is commonly observed that there is an anomalous drop of ~50% in J_c(77 K) in mT fields[5]. Presumably only the strongly linked grain-to-grain connections[5] without intergrowths remain active in higher fields.

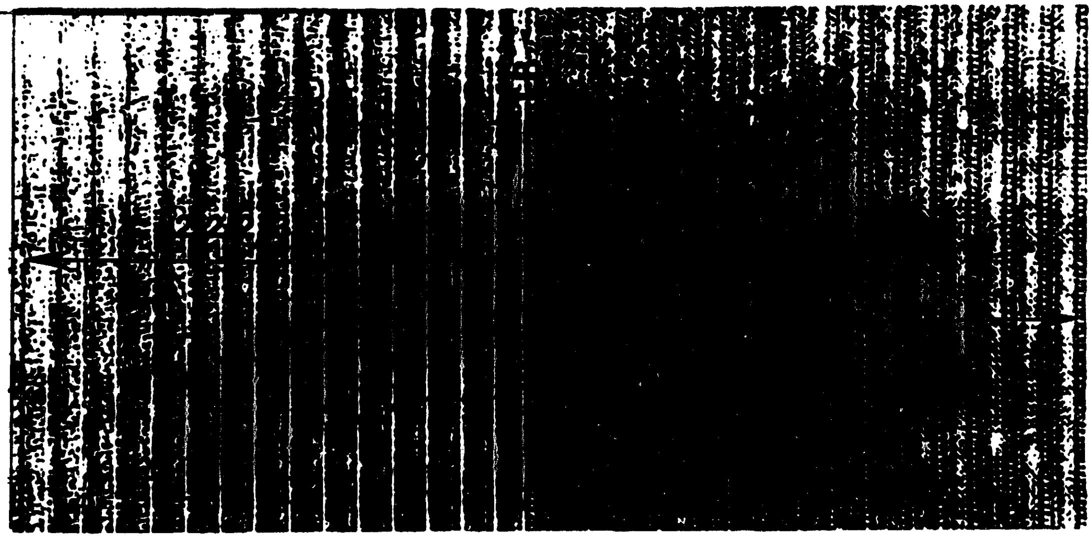

Fig. 6 HRTEM image showing 2212 intergrowths at an [001] twist boundary in a tape having J_c = 17,000 A/cm^2

7. Summary Comments

As the above brief summary indicates, there are many possible barriers to current flow in a given BSCCO tape. A fundamental requirement is to convert the starting mixed phase powder to a well connected, largely 2223 phase. Because the reaction process is poorly understood, the 2223 conversion is never uniform or complete. Thin filaments encourage complete reaction and 2212 intergrowth removal; unfortunately they also encourage sausaging[14,26]. Some long distance connectivity exists in all tapes[24]. The microslice experiments strongly suggest that good connections are favored near the Ag. Even when all the above factors are controlled, the current may be limited by cracks, which can be particularly deleterious because cracks are large area 2D interfaces. Since a new record J_c of 76,000 A/cm^2 was measured in a slice of a tape having an overall J_c six times less, it seems that the active cross-section of 2223 tapes is small. Raising the intragrain flux pinning will affect only that fraction of the tape which is well connected[25]. This fraction is unclear: probably it is only a few per cent. Thus, for now at least, it seems that the most productive way to increase J_c is to raise the active cross-section.

8. Acknowledgments

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PHYSICA C

Position-sensitive measurements of the local critical current density in Ag sheathed high-temperature superconductor $(Bi, Pb)_2Sr_2Ca_2Cu_3O_y$ tapes

The importance of local micro- and macro-structure

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Small sections cut from within individual superconducting filaments of Ag sheathed $(Bi, Pb)_2Sr_2Ca_2Cu_3O_y$ (BSCCO-2223) tapes have critical current densities (J_c) which depend very much on the local microstructure and which can be as much as five times higher than the average J_c. Tapes having average J_c values of 12–15 000 A/cm² (77 K, 0 T) had local J_c values up to 76 000 A/cm², a value larger than hitherto reported for any bulk sample. Close to the Ag sheath the conversion to the 2223 phase is more complete and the grains are larger and better aligned and the J_c is then much higher and less field sensitive. Large variations are also found in more uniformly reacted tapes, perhaps due to variations of the local crack density. The microstructure of the highest J_c regions is still far from ideal, thus showing that the limits of this technologically very important system are far from being achieved.

1. Introduction

A vital requirement for the many anticipated uses of high-temperature superconductors (HTS's) in transmission lines, motors and other devices of large-scale electrotechnology is a high critical current density (J_c), at least 10^4 and preferably $>10^5$ A/cm² in the field and temperature range of interest. Ag sheathed tapes of the Bi based HTS compounds having the nominal composition $(Bi, Pb)_2Sr_2Ca_2Cu_3O_y$ (BSCCO-2223) show particular promise as HTS conductors and short, pressed samples having J_c (0 T, 77 K) values of ~50–65 kA/cm² [1,2] have demonstrated the technological feasibility of this system. However, high J_c values have been difficult to attain reproducibly; moreover, samples longer than a few cm must be produced by rolling and the best J_c values then lie around 15 kA/cm² [3,4]. Since many variables control the properties of this very complex materials system, it is not surprising that properties are irreproducible and the system limits are not yet well understood. The present paper advances as understanding of the system by showing that local J_c values exceeding the highest yet reported are present in tapes having only modest average J_c values, thus demonstrating that BSCCO-2223 tapes still have significant untapped technological promise.

2. Experimental procedures

The Ag sheathed mono[illegible]ment tapes were made by the oxide-powder-in-tube (OPIT) process according to a standard fabrication procedure involving sheathing of powders of nominal BSCCO-2223 composition in Ag, their fabrication to tape by extrusion, wire drawing and rolling, followed by a heat treatment, an intermediate pressing and a final heat treatment [1-4]. The tapes have highly aspected fil-

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aments with an approximately elliptical cross-section 40–60 μm thick × 2 mm wide. The goal of the experiment was to obtain information about the positional variability of J_c. To this end techniques for the cutting of microslices from within the BSCCO filaments were developed. Some microslices were prepared by cutting a bare filament along the *yz* plane (fig. 1) with a diamond saw. The rough-cut slice was then thinned with a precision grinder until it was ~80 μm thick in the *x* direction. This method generally yielded only one sample per slice; a defect of this method is that it was not easy to determine the exact placement of the cut with respect to the tape as a whole, nor was it possible to produce slices near the filament edges. A more versatile technique is to completely etch away the Ag and then cut slices ~50–100 μm wide (*x*) by ~1 mm long (*z*) from the bare BSCCO core using a laser. The slices were not easily prepared by either technique and cracking was always a problem. In either case, the sides of the samples were well-defined, permitting their dimensions to be measured with a calibrated light microscope and their microstructure to be examined in the SEM in both secondary electron (SE) and backscatter (BS) mode.

The slices were electrically set in contact with 5

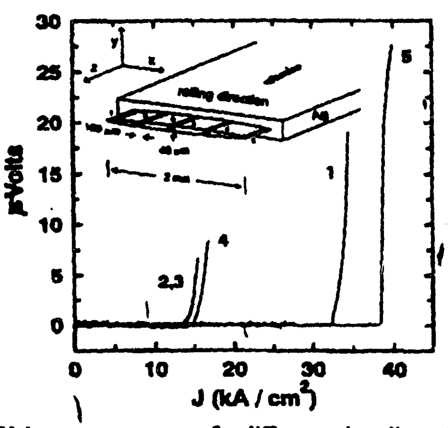

Fig. 1. Voltage–current traces for different microslices of tape A at 77 K and zero applied field are shown. The slices were also measured in a field of 8 mT applied normal to the broad face of the original tape surface; the J_c values were then unchanged (slice 1), 0.45 (3) and 0.8 (4) of the zero field values, respectively. The geometry of the slices cut from tape A and the coordinate axes of the cuts are shown in the inset.

colinear 13 μm diameter Au wires which were glued directly to the BSCCO with Ag filled epoxy. The tap length along the *z*-axis varied from ~70–130 μm. Critical current density measurements were generally made with the sample completely immersed in liquid nitrogen in order to provide the maximum possible cooling for the leads. In spite of this, the very high lead current densities led to considerable self-heating at the contacts and lead breaks were frequent. Thus, some samples were tested in helium gas starting at temperatures of ~100 K where the J_c values were smaller. The critical current was determined at the minimum detectable voltage of ~0.25 μV. For all cases the contact separation (~100 μm) was much longer than the grain size (~2–10 μm) and the transport results are therefore characteristic of polycrystalline, not single-crystalline material.

3. Experimental results

The most systematic view of the positional variation of the J_c was obtained from the laser-cut microslices of tape A, which had a J_c (0 T, 77 K) of 14 000 A/cm², as measured over the whole BSCCO cross-section at a criterion of 1 μV/cm with the Ag sheath still present. Five slices, having widths from ~80–130 μm were cut from this tape. Their zero-field, 77 K *V–I* traces and positions are shown in fig. 1. The central slice (3) and one intermediate position slice (2) had a J_c (0 T, 77 K) value of ~13 000 A/cm², just below the average of the whole cross-section, while the second intermediate slice (4) achieved ~14 000 A/cm², just about the average. These three slices had well-rounded *V–I* characteristics, typical of a stable, reversible transition to the flux-flow state. By contrast, the two outside slices (1 and 5) had abrupt transitions at much higher J_c values of 32 000 and 38 000 A/cm². These transitions were unstable (and probably underestimate the true J_c), no doubt due to contact and/or lead heating. In fact the higher J_c sample lost its leads during its first transition to the normal state, burning out the sample. Three of the microslices were also measured in an applied field of 8 mT. The outer slice 1 exhibited no field dependence whatsoever, while the intermediate position slice (4) and the central slice (3) had their J_c values reduced to 0.8 and 0.45 of their zero-field values.

The very different grain structures of the edge and central regions are shown in the SEM pictures of fig. 2. The edge slice (fig. 2(a)) has a generally well-aligned plate-like grain structure, the BSCCO-2223 grains being ~10 μm long. Such a microstructure appears similar to those reported for the best J_c samples [1,2]. The second phase particles are quite small (~5 μm or less) and widely separated and they do not greatly perturb the local BSCCO grain alignment. On the other hand, there are occasional disruptions to the alignment in the vicinity of interface grain intrusions into the Ag, as is seen at several points in fig. 2(a); thus the long-range grain alignment of the high J_c regions is still far from perfect. The microstructure of the central slice (fig. 2(b)) is obviously less uniform and markedly worse, especially towards the tape center. However, this is not at all untypical of the central regions of many tapes [5]. Even towards the interface, the BSCCO-2223 grains are smaller in size and aspect ratio. Generally they are poorly aligned and often disrupted by large second-phase particles.

Further insight into the position sensitivity of the properties is provided by the normal-state electrical resistivity, $\rho_n(T)$ of each slice (fig. 3). The outer slices 1 and 5 have low resistivities with extrapolated zero temperature values close to 0 μΩ cm, values typically found only in good-quality single crystals and thin films [6,7], where grain boundaries are absent or of low angle, and transport occurs along the Cu–O planes. The adjacent intermediate slices 2 and 4 exhibit a slightly positive resistivity intercept (< 10 μΩ cm), while the central slice (3) has the large intercept of ~200 μΩ cm, suggestive of a significant intergranular resistance or c-axis transport in whatever path the current is taking.

We also made slices using the cut-and-grind method from central sections of two other tapes hav-

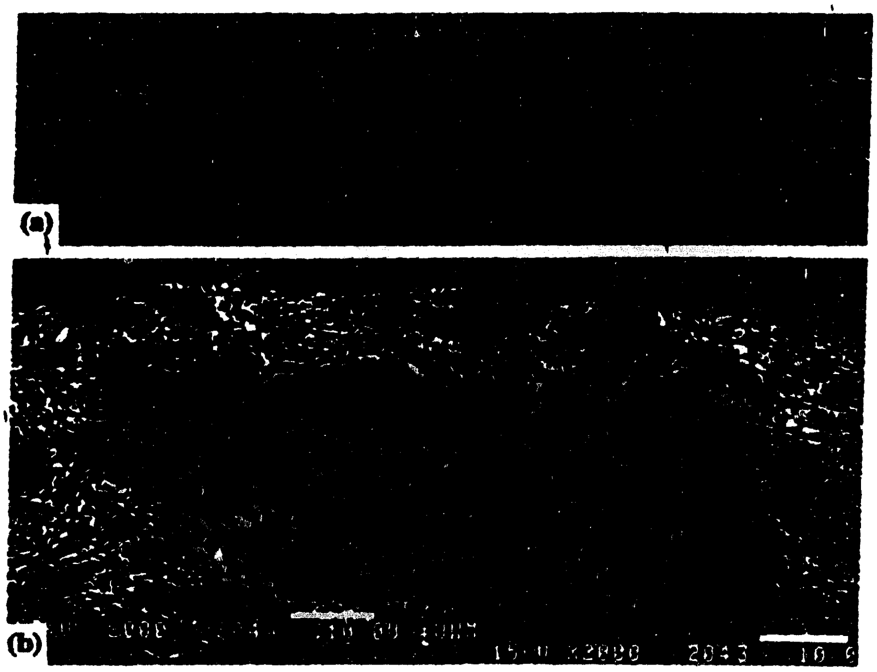

Fig. 2. Scanning electron micrographs of (a) slice 1 and (b) slice 3 of tape A. The slices were polished so that the exposed surface (yz) is normal to the rolling plane and the long direction is parallel to the rolling axis. The vertical direction in the micrographs is approximately the c-axis of the grains, which lies normal to the thin dimension of the tape. Large alkaline-earth cuprates (AEC) are evident in the central slice 3.

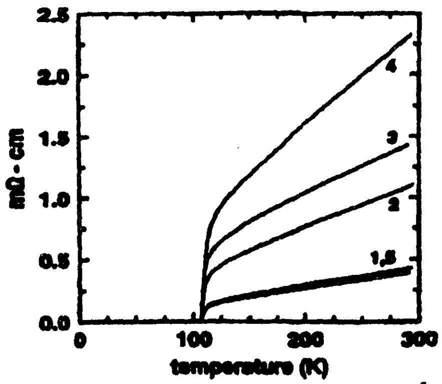

Fig. 3. Resistivity vs. temperature plots for slices from tape A. The high resistivity of slice 4 is believed to be due to a current path that was longer than the measured macroscopic dimension (see ref. [6]), consistent with the presence of cracks in the slice. The zero-temperature intercept of slice 4 is not anomalous; this parameter steadily decreases to ~0 μΩ cm as the slice position moves towards the outside.

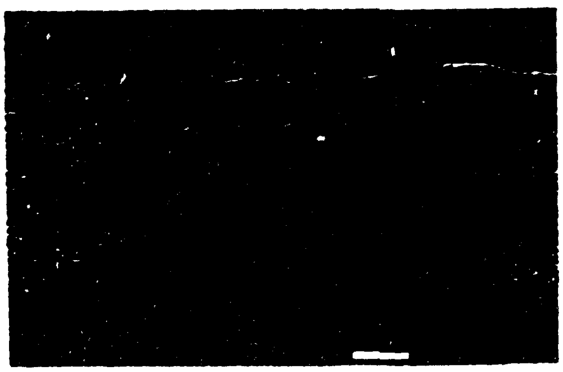

Fig. 4. Scanning electron micrograph of the approximately central section slice cut from tape B. The geometry is the same as that observed in fig. 2 for tape A but the microstructure is evidently much more uniformly reacted. In spite of this, the overall J_c (77 K, 0 T) value was only 12 700 A/cm².

ing relatively uniform through-thickness microstructures, as shown for tape B in fig. 4. Large second-phase particles were absent in these tapes and even their central-region microstructures appear much closer to the fully reacted appearance of the edge region of tape A (fig. 2(a)) than to the poorly reacted central region (fig. 2(b)). Nevertheless, the overall J_c of the 40 μm thick tape B was only 12 700 A/cm²,

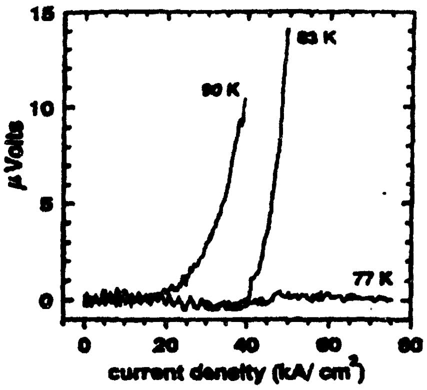

Fig. 5. Voltage–current traces of a midwidth slice cut from tape B as tested in helium gas at 90 and 83 K and in liquid nitrogen at 77 K. The sample destroyed itself on testing at 77 K.

lower than that of tape A. V–I traces of the central section microslice at temperatures from 90 to 77 K are shown in fig. 5. This slice was tested first in gas. At 83 K it already reached the very high J_c value of 40 000 A/cm². At 77 K the J_c reached 76 000 A/cm², a value which was so high that the slice destroyed itself in a sudden quench. A similarly prepared midwidth slice from a 60 μm thick tape with an overall J_c (0 T, 77 K) of 15 000 A/cm² also yielded a high J_c (0 T, 77 K) value, 55 000 A/cm² in this case. In contrast to tape A where the mirostructure provides an obvious reason for the difference in J_c, the SEM views of the microstructure of these two tapes provided no obvious clues as to the great difference between the performance of the microslices and the tapes as a whole. One clue may be that the 15 000 A/cm² tape showed evident spallation of the BSCCO core when the Ag was etched away, thus indicating that cracks may be an important current-limiting factor for such well-reacted tapes.

4. Discussion

What are the implications of these experiments for achieving the full potential of BSCCO-2223 tapes? The most direct lesson is that high local J_c values which are several times the average J_c exist within regions of the tape that are much larger than the grain size (or colony size: see refs. [8] and [9]). It is therefore clear that J_c (77 K, 0 T) values up to at least 76 000 A/cm^2 need not be limited by poor flux pinning or grain-to-grain contact. The experiments thus emphasize the importance of identifying the dominant current-limiting mechanism, which may vary markedly from tape to tape, as indicated here. In principle, there can be many sources of J_c limitation in BSCCO tapes [10,11]: some are microscopic in origin, for example, weak intra-grain flux pinning [11] or poor inter-grain connectivity [8,9,12]. Such microscopic features often receive more attention than the macroscopic parameters of variations in filament cross-section (sausaging) [13,14], filament cracking and non-uniform conversion to the 2223 phase. In the present case, there is explicit evidence that proximity to silver, because of the enhanced local transformation to the 2223 phase [5,15–17], is an important variable and is at least partial support for the role of local cracking in controlling the J_c. The key point is that macroscopic-scale defects must be minimized before improvements in the intra-grain flux pinning or inter-grain connectivity can play their full role. These observations are all consistent with the idea that the active supercurrent-carrying cross-section of BSCCO-2223 tapes is only a small fraction of the total [9,12–14]. Since any rational optimization plan for BSCCO-2223 tapes should seek out their dominant current-limiting mechanisms, experiments such as the present one have an important role to play in the furthe. development of this important material system.

In summary, we have presented a new technique by which the microstructure and superconducting properties of local segments of BSCCO-2223 tapes can be determined. The experiments demonstrate that there are very large local variations of the J_c even in well made tapes. A record value of J_c (77 K, 0 T) of 76 000 A/cm^2 was measured for a central slice of a tape having an overall J_c value which was more than five times lower. Thus it has again been confirmed that microstructure and macrostructure control are key requirements of the technology of making useful conductors from high-temperature superconductors.

Acknowledgements

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The Influence of Phase Development on Critical Currents in Powder-in-Tube Wires

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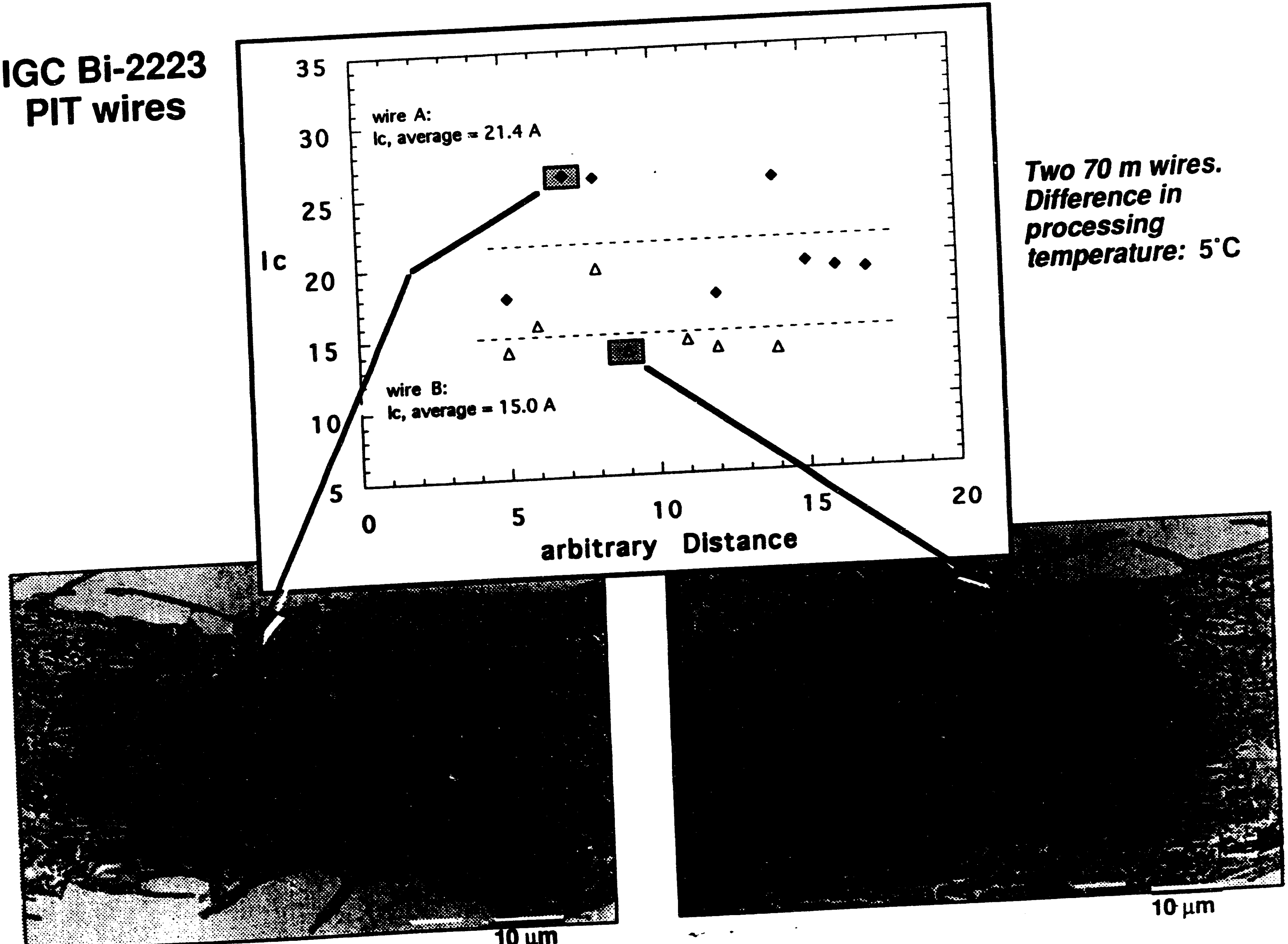
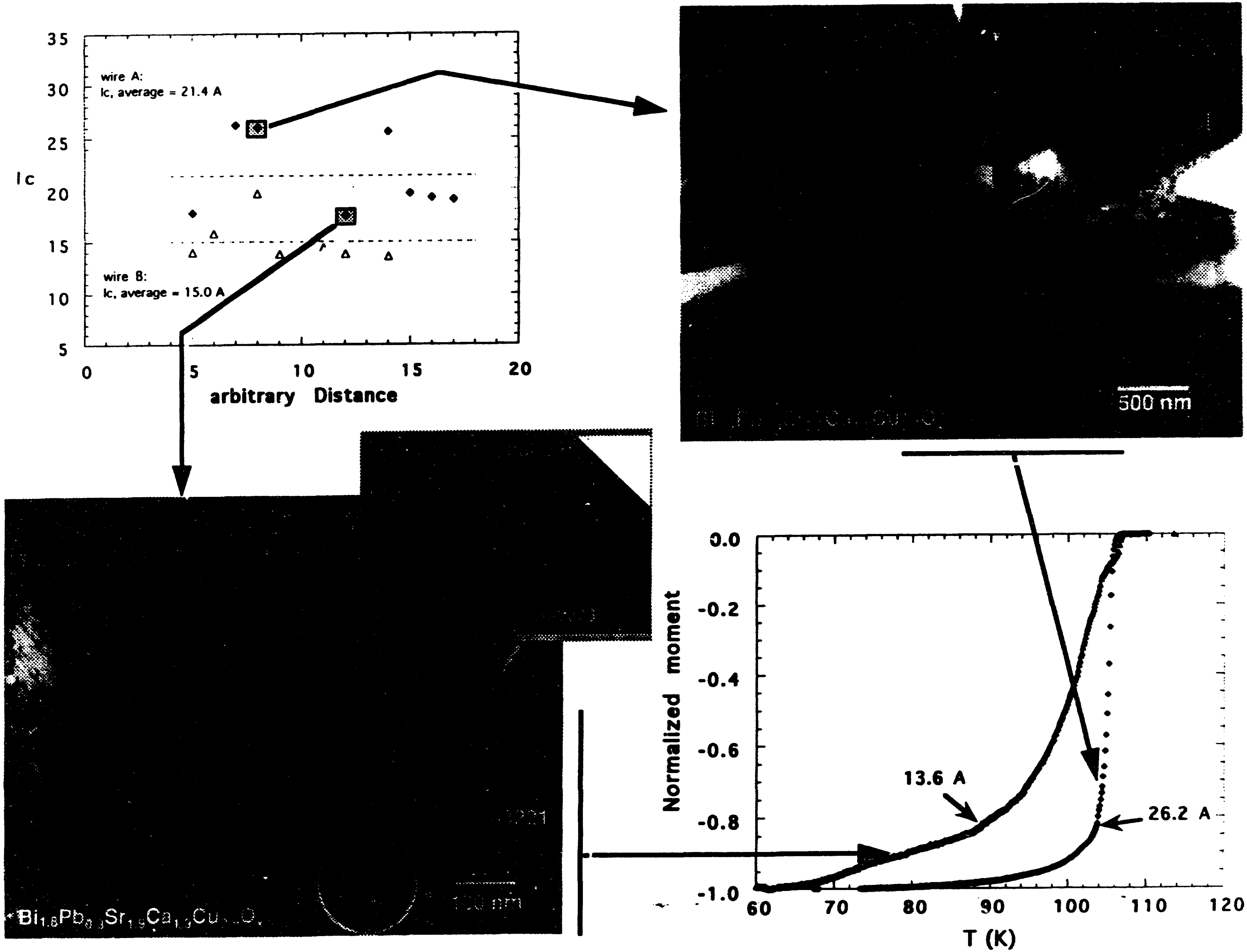
Work supported by the U.S. Department of Energy, Divisions of Basic Energy Sciences-Materials Sciences and Energy Efficiency and Renewable Energy, under Contract W-31-109-Eng-38.

IGC Bi-2223 PIT wires



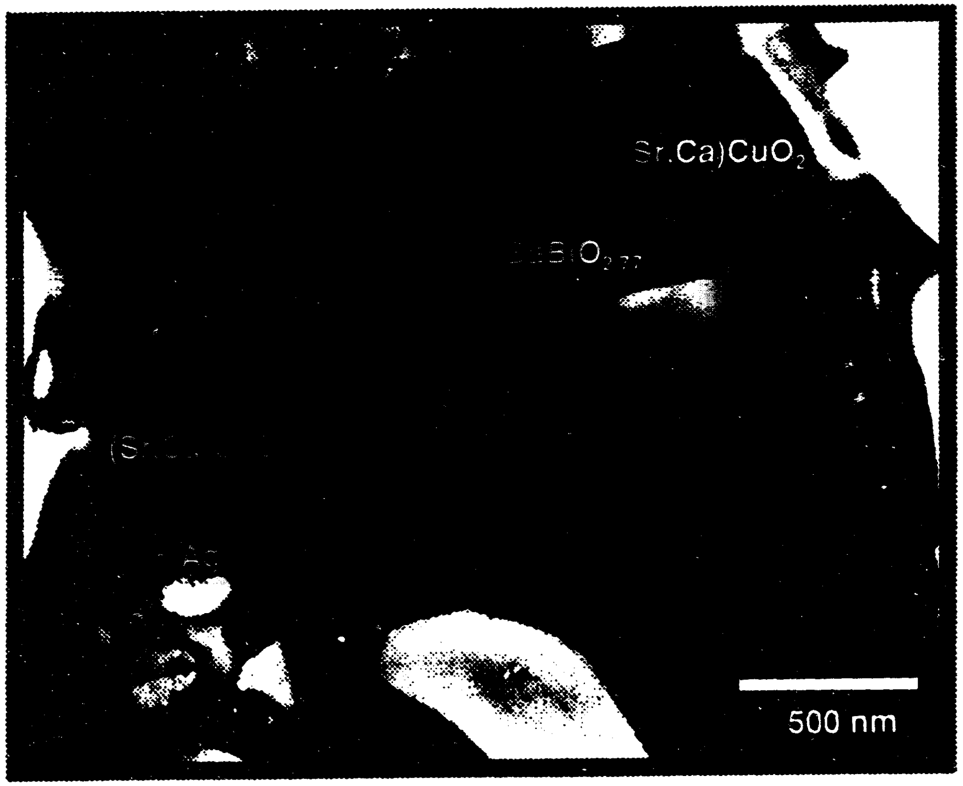
SEM images

Two 70 m wires. Difference in processing temperature: 5°C

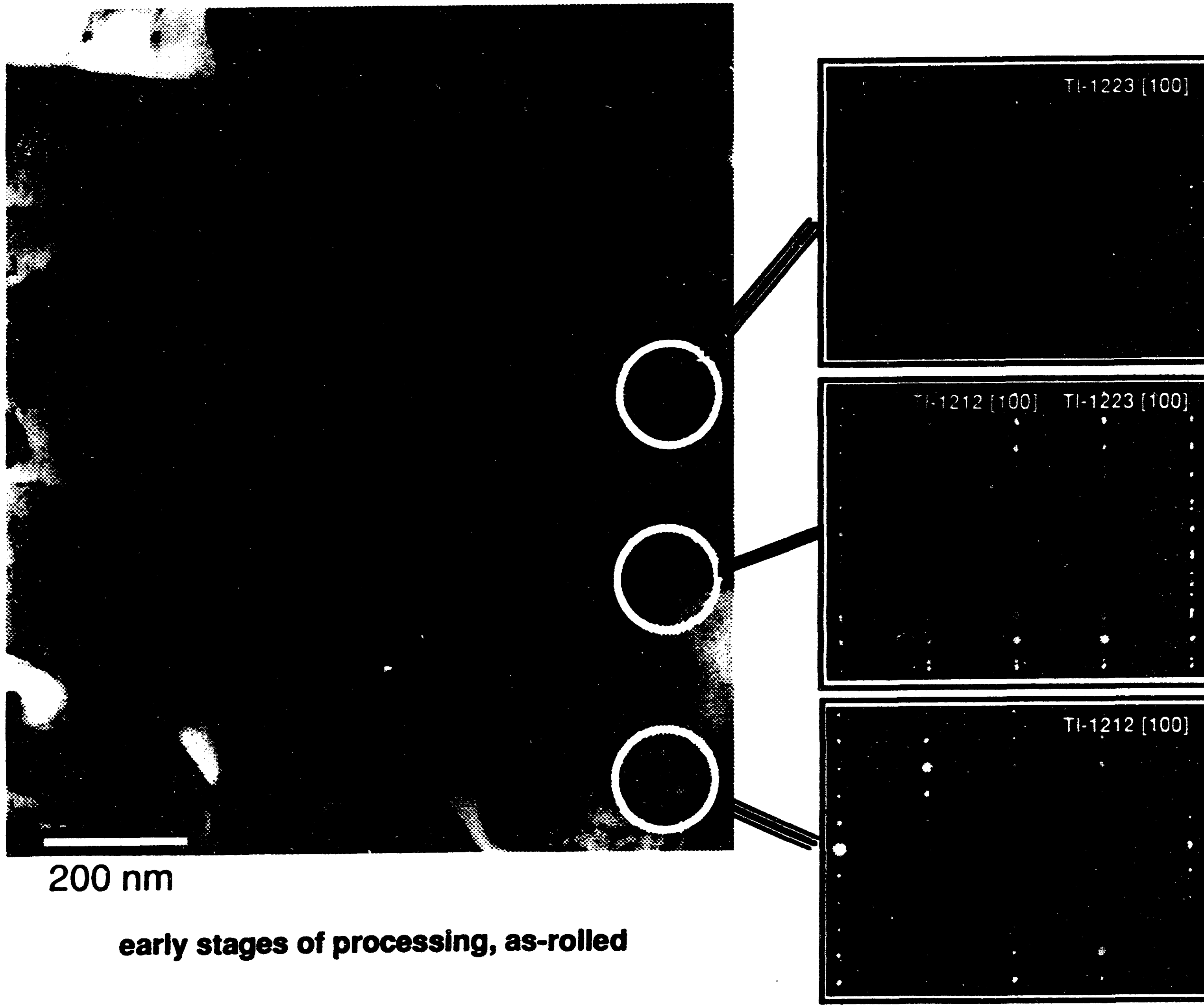


wire A:
Ic, average = 21.4 A
wire B:
Ic, average = 15.0 A
Ic
35
30
25
20
15
10
5
0
5
10
15
20
arbitrary Distance
500 nm
100 nm
Normalized moment
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
60
70
80
90
100
110
120
T (K)
13.6 A
26.2 A

SUNY Tl-1223 tapes

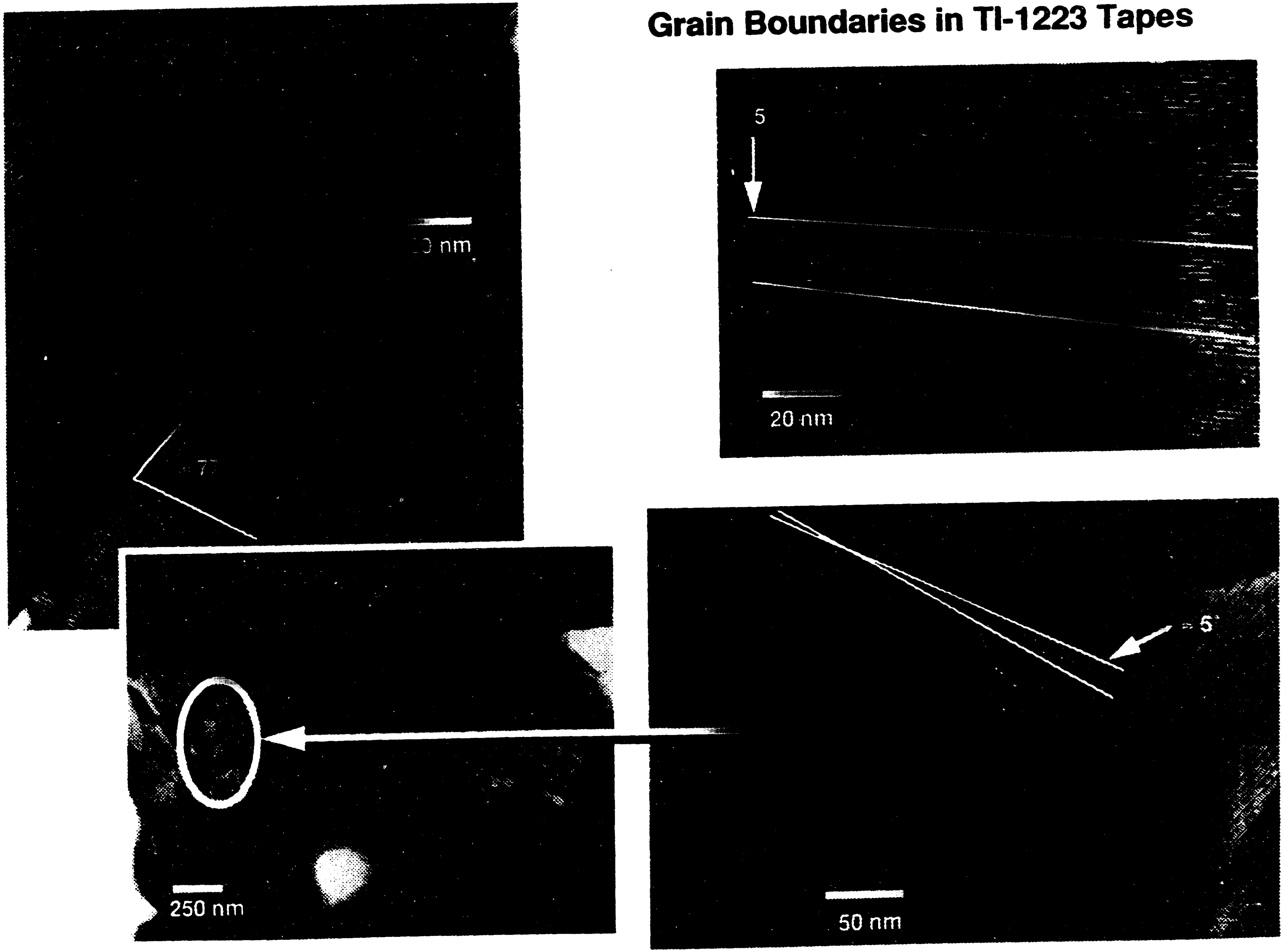


SUNY-Buffalo Tl-1223 PIT

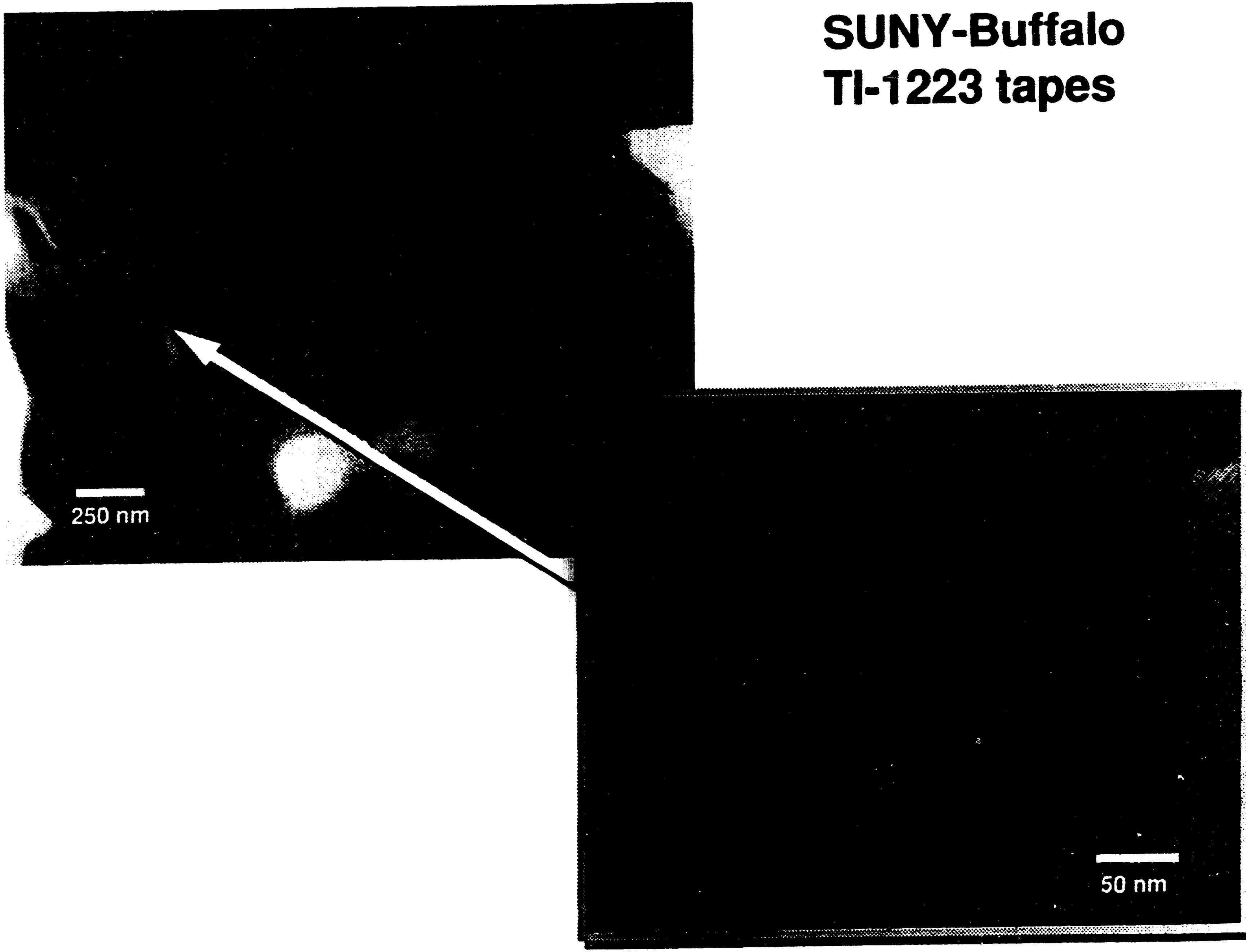


early stages of processing, as-rolled

Grain Boundaries in Tl-1223 Tapes

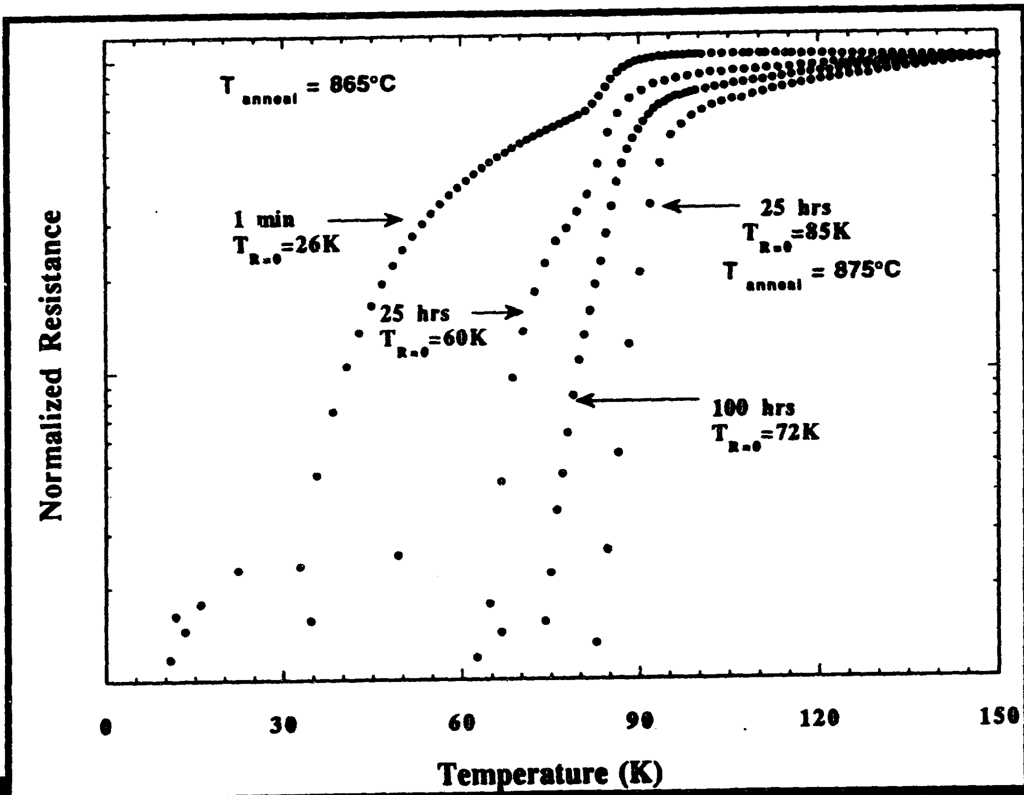


SUNY-Buffalo
Tl-1223 tapes

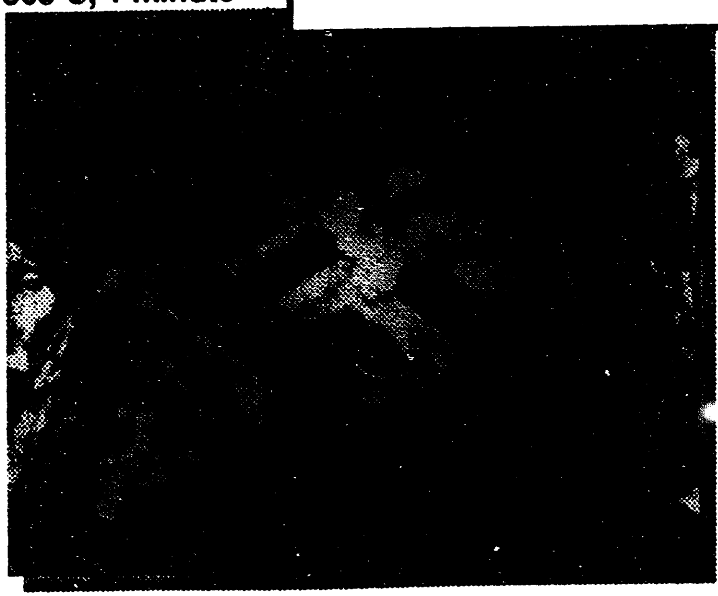


BSCCO 2212

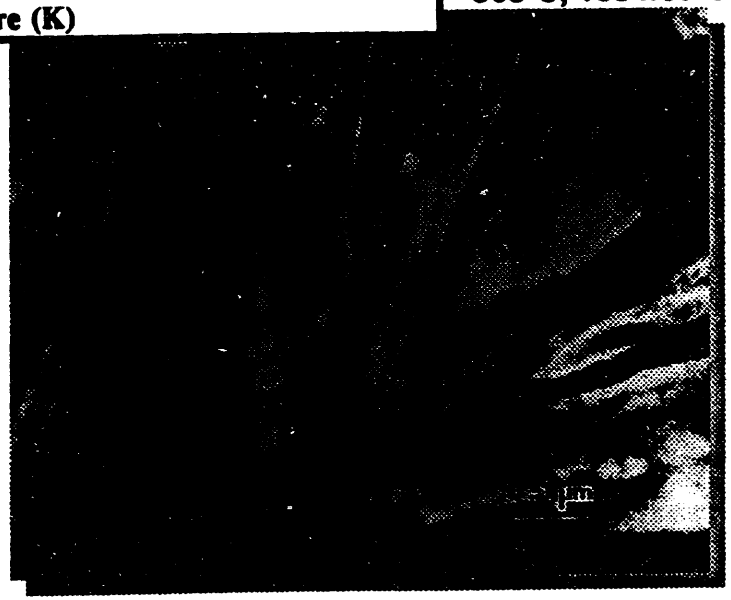
splat quenched glass,
crystallized by h.t.



865°C, 1 minute

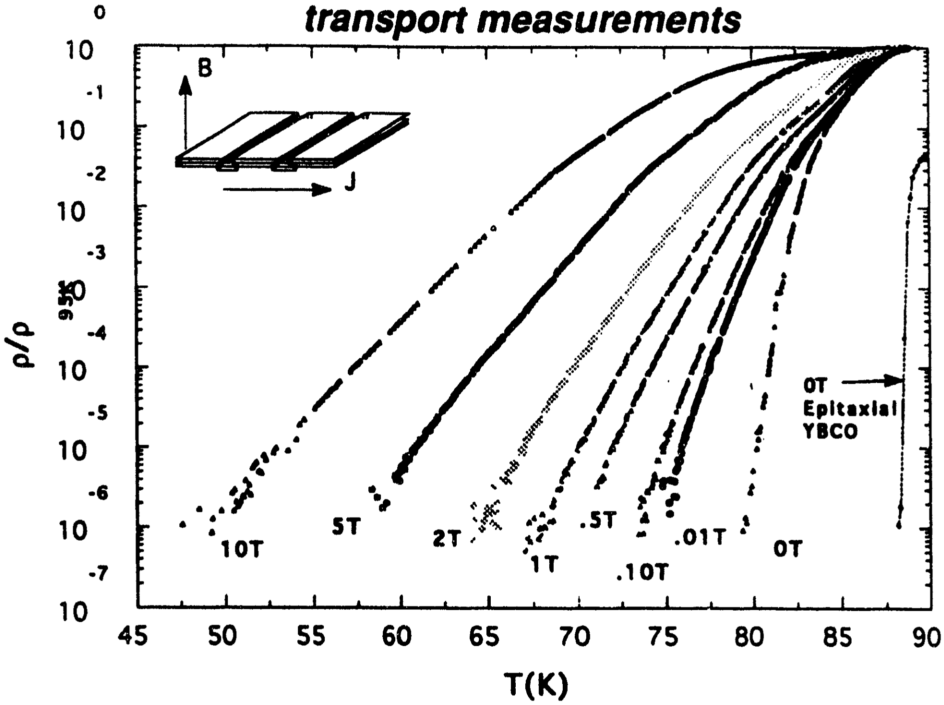


865°C, 100 hours

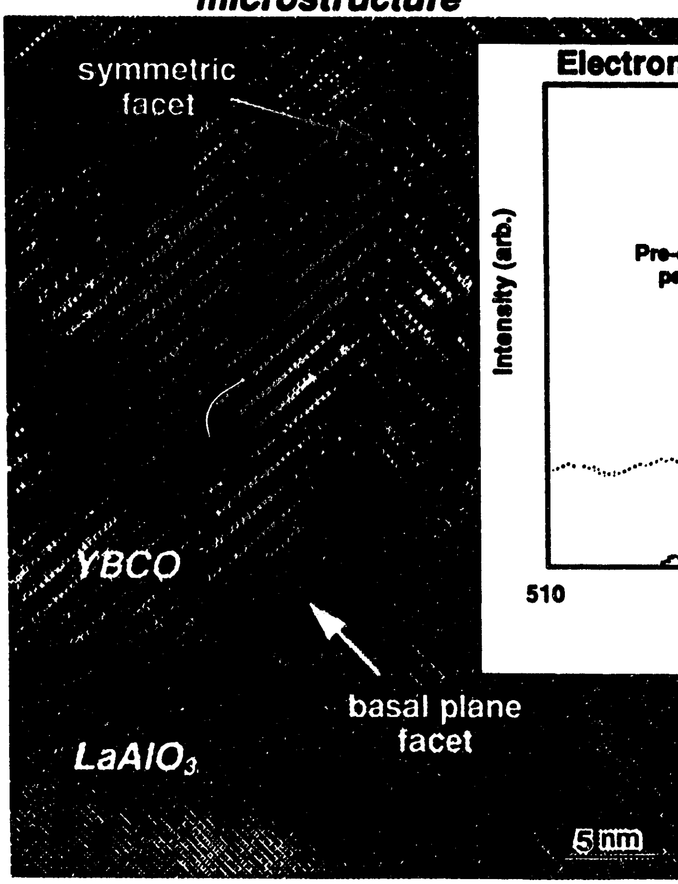


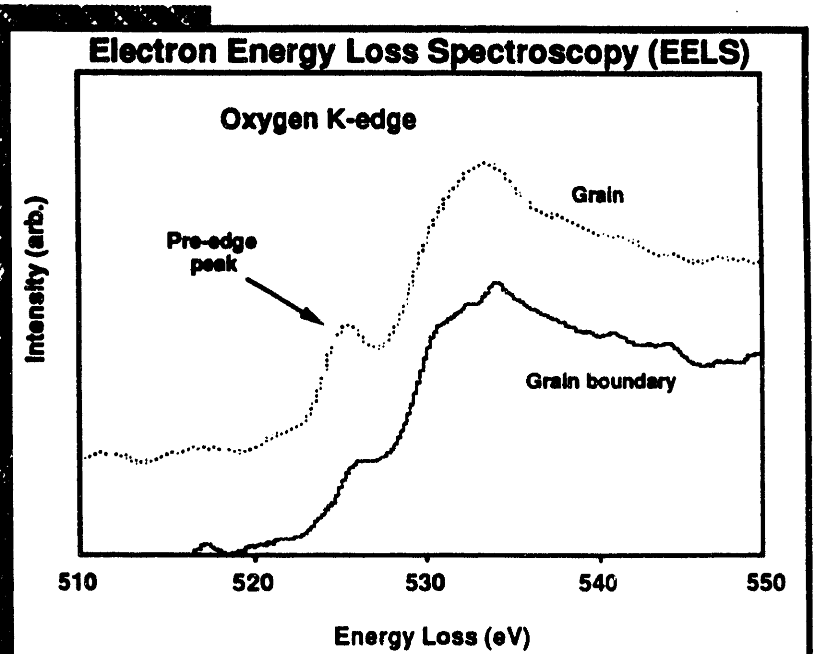
Step-edge grain boundaries (TRW)
[100] tilt boundary

transport measurements



microstructure





electronic structure

Summary

The scale and complexities of HTS synthesis and PIT processing can make meaningful interpretation difficult -

- studies of more easily characterized systems may allow the connection between microscopic features and macroscopic behavior to be established.

A complete understanding of phase evolution can be exploited to:

- optimize quality of HTS grains
- develop texture
- promote good inter-grain coupling

High Jc Tl(1223) Conductors

J. Eric Tkaczyk
General Electric Research and Development

presented at the High Temperature Superconducting Wire Development Workshop
February 16, 1994

Outline

- **Perspective:** Refrigerated MRI
- Tl(1223) characteristics
- Conductor Requirements/Status

Acknowledgments

partial supported by:

US Department of Energy

Pilot Center Agreements

- Oak Ridge National Labs
  - Contract #87x-se934v underDE-AC05-84OR21400
- Argonne National Labs.
  - Agreement #22242401 under W-31-109-ENG-3

SPI:

- DE-FC02-93CH10589

CRADA

- National Renewable Energy Labs.

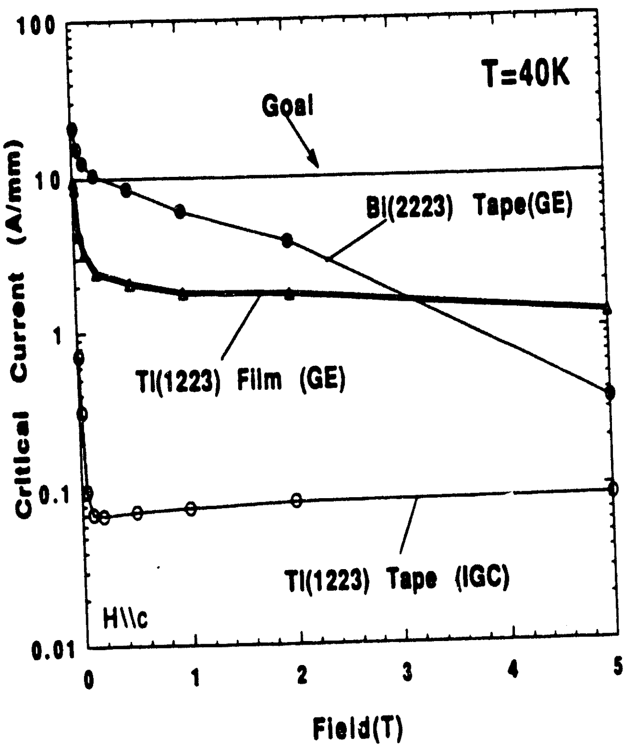
Informal Collaboration

- Sandia National Labs

Refrigerated Applications

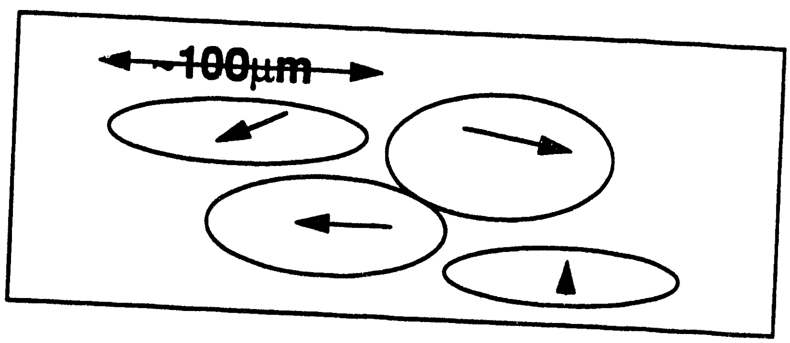
• NbTi	4.2K
• Nb3Sn	10K
• BSSCO	20K
• TBCCO	40K

Tl-HTS Tapes Comparison at 40K



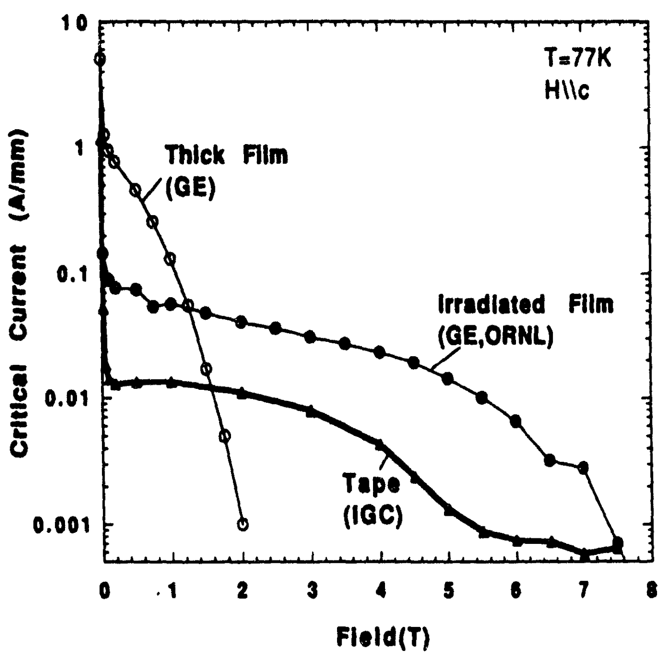
Transport mechanism

- Colonies

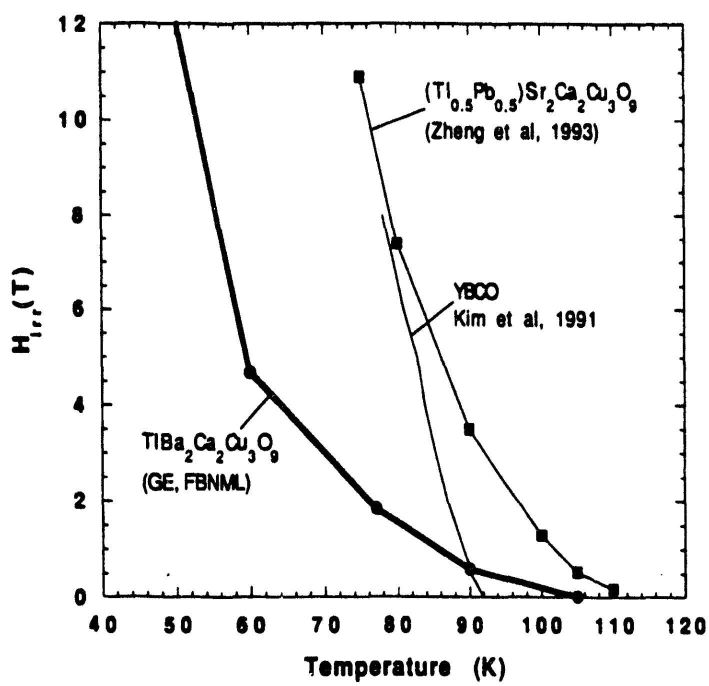


- Brick Wall

77K Operation?



Doped vs Undoped



Requirements for TI-HTS Tapes

Goal	Status
• Current (40K, 2T) 10A/mm	2A/mm 3μm x 100KA/cm²
• Metallic Substrate non-reactive expansion match surface treatment cost	Ag Ni or Fe,Cr,Al
•Manufacturable •long lengths •handling •cost	Continuous vs Batch Open vs Closed (Working Group)

Issues

- Focus: this year
  - Process Optimization
  - Thicker Films
  - Metallic Substrates
  - Scale-up Capability
- Material Issues
  - film growth
    - kinetics/liquid phase
    - texture mechanism
  - chemical optimization
    - doped systems
    - annealing
- Property Issues
  - transport mechanism
  - Tc/Jc optimization
  - pinning

CURRENT FLOW ANISOTROPY IN BSCCO TAPES AND HIGH-J_c BIAXIALLY TEXTURED YBCO FILMS

M.P. MALEY   LANL

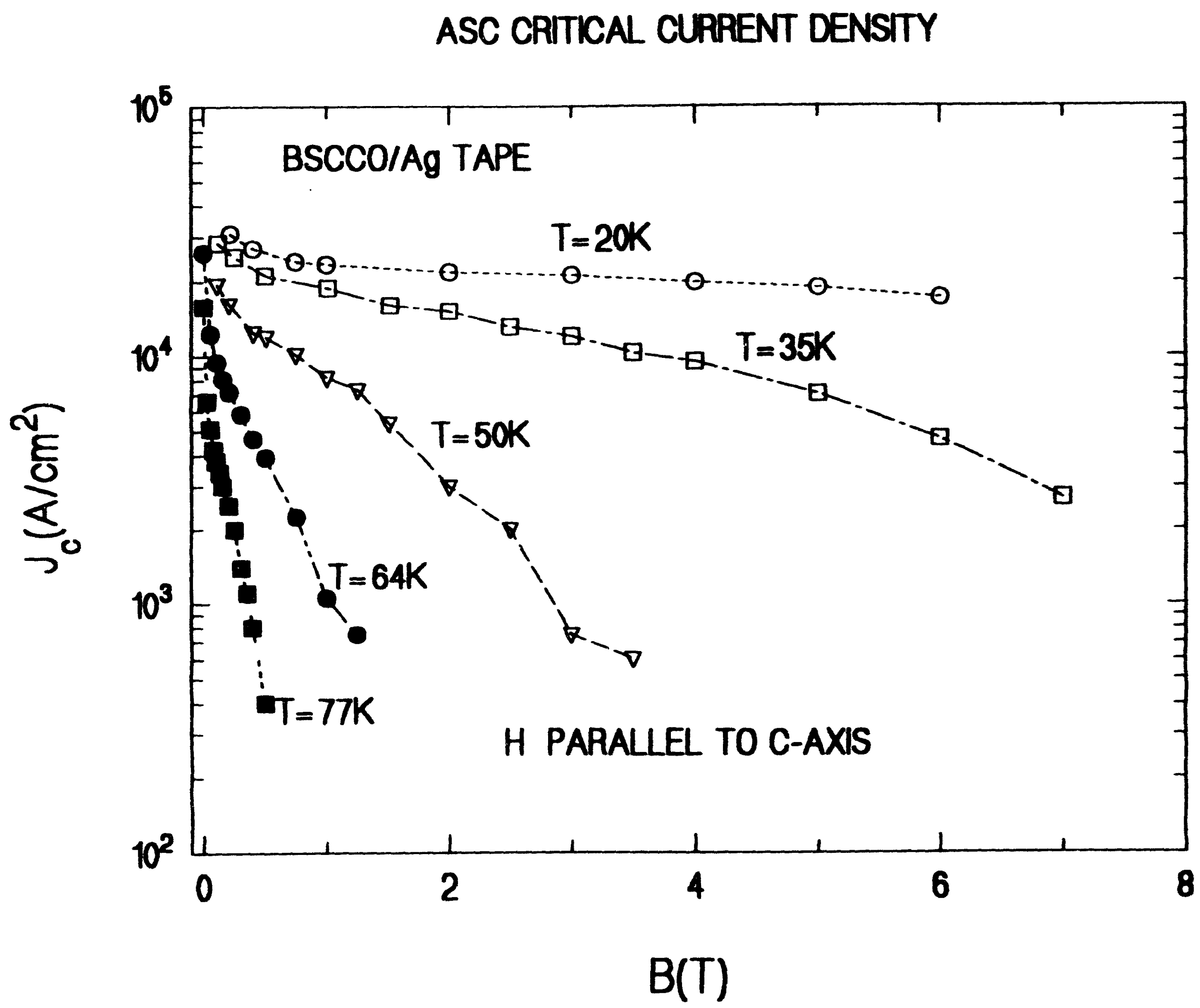
OUTLINE

1. Review of Critical Current Characteristics of BSCCO Tapes, $J_c(B,T,\theta)$-- Comparison with BSCCO Thin Films

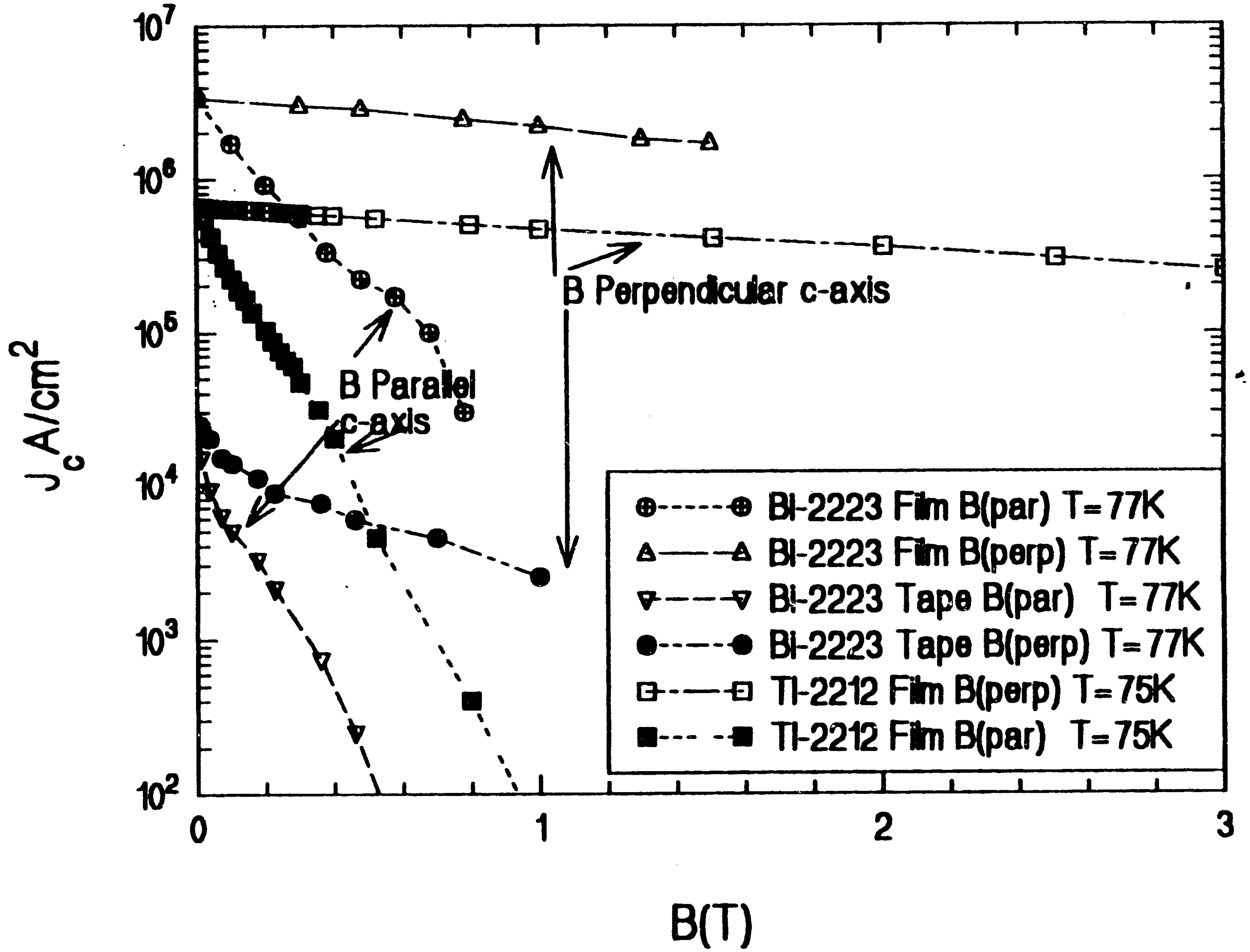
2. Model for J_c Characteristics-- Weak Links Versus Flux Pinning Limited by Extreme Anisotropy

3. Results of Direct Measurements of Transport Anisotropy for Current Flows Parallel and Perpendicular to the Plane of BSCCO Tape Conductors.

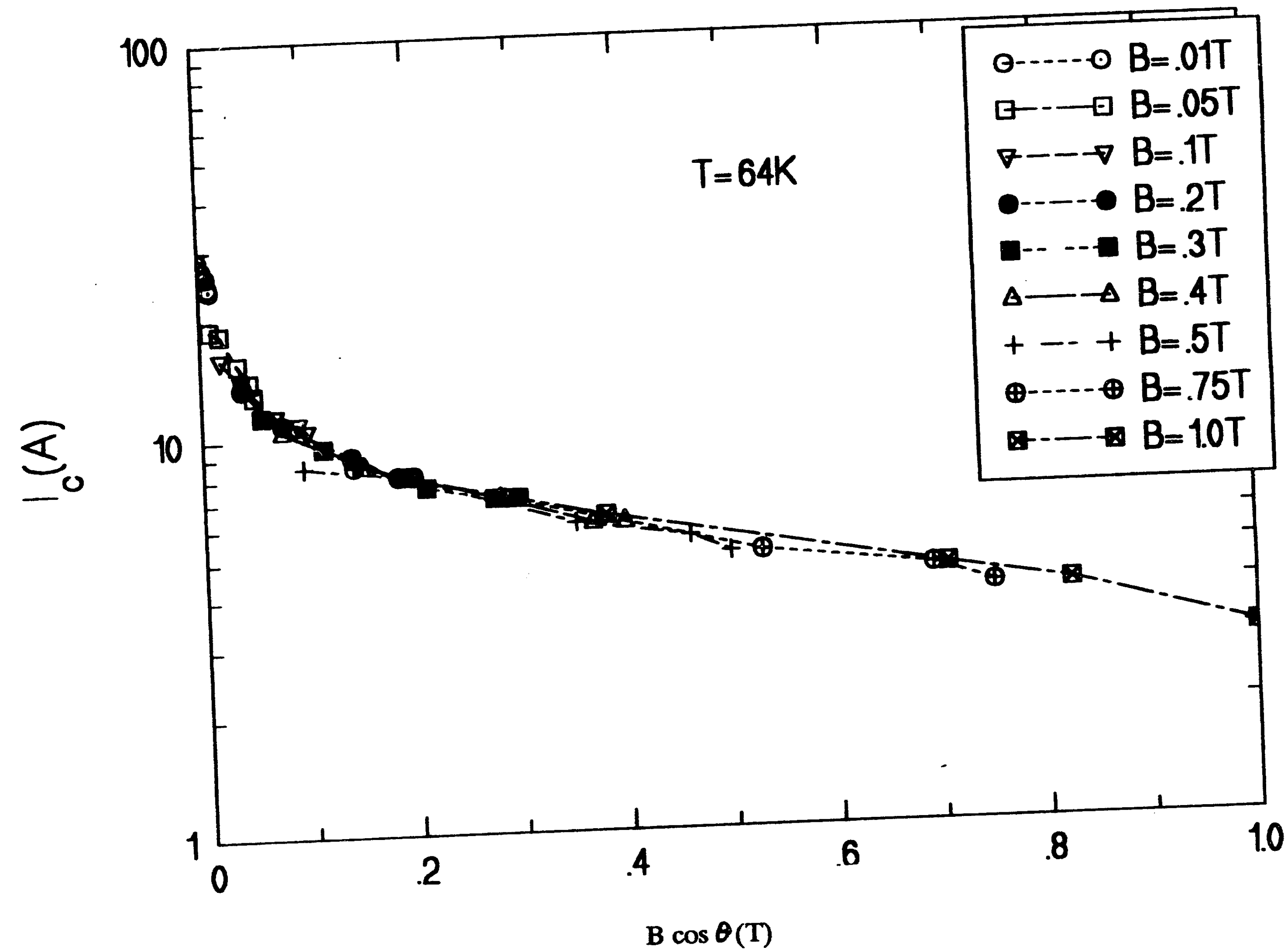
4. Development of High-J_c, High Current YBCO Conductors on Practical, Polycrystalline Substrates by Ion-Beam Assisted Deposition(IBAD)



ASC CRITICAL CURRENT DENSITY
BSCCO/Ag TAPE
T=20K
T=35K
T=50K
T=64K
T=77K
H PARALLEL TO C-AXIS
$J_c (A/cm^2)$
10^5
10^4
10^3
10^2
0
2
4
6
8
B(T)



10^7
10^6
10^5
10^4
10^3
10^2
J_c A/cm^2
0
1
2
3
B(T)
B Perpendicular c-axis
B Parallel c-axis
Bi-2223 Film B(par) T=77K
Bi-2223 Film B(perp) T=77K
Bi-2223 Tape B(par) T=77K
Bi-2223 Tape B(perp) T=77K
Tl-2212 Film B(perp) T=75K
Tl-2212 Film B(par) T=75K



100
10
1
I_c(A)
0
.2
.4
.6
.8
1.0
B cos θ (T)
T=64K
B=.01T
B=.05T
B=.1T
B=.2T
B=.3T
B=.4T
B=.5T
B=.75T
B=1.0T

Yamasaki et al.
Bi-2223
Thin Film

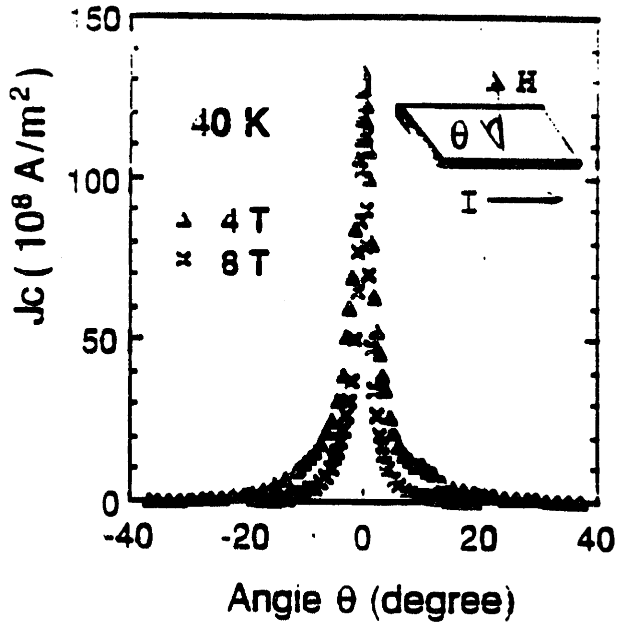


Fig. 3(a) $J_C(H, \theta)$ measured at 40 K as a function of the angle between applied field and the *a-b* plane.

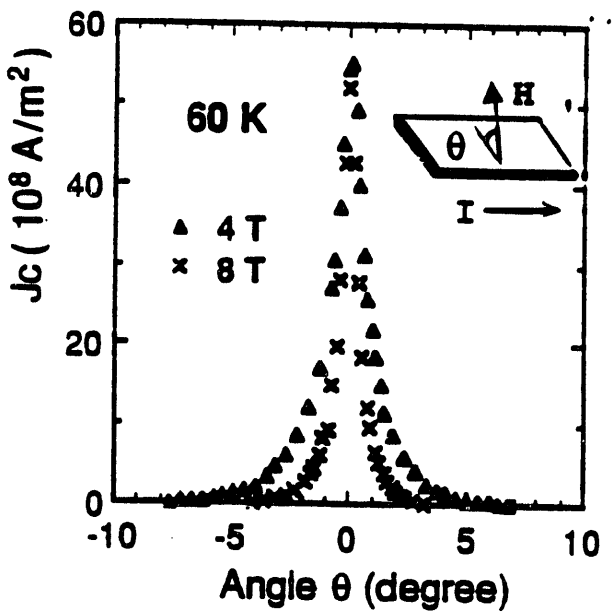
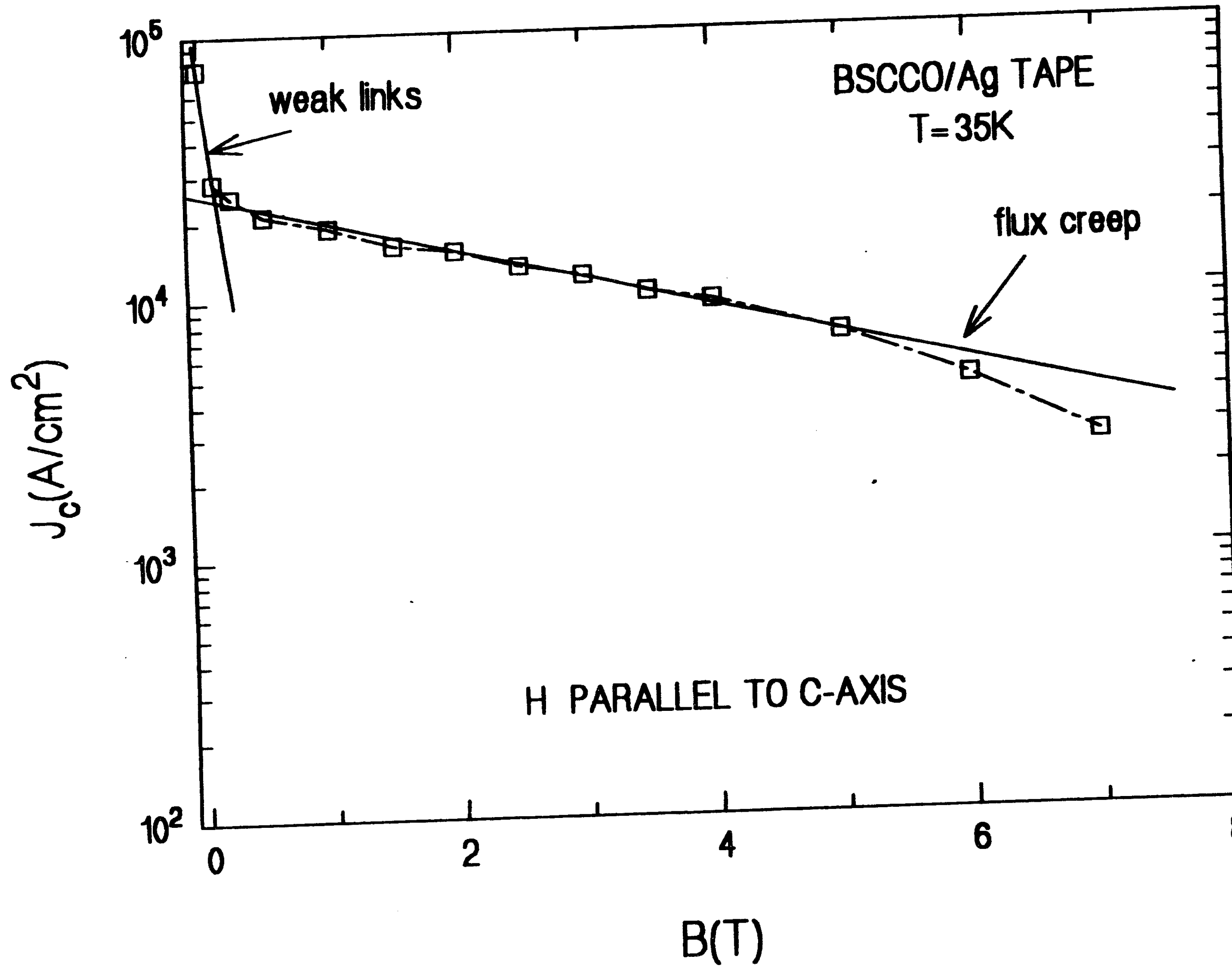
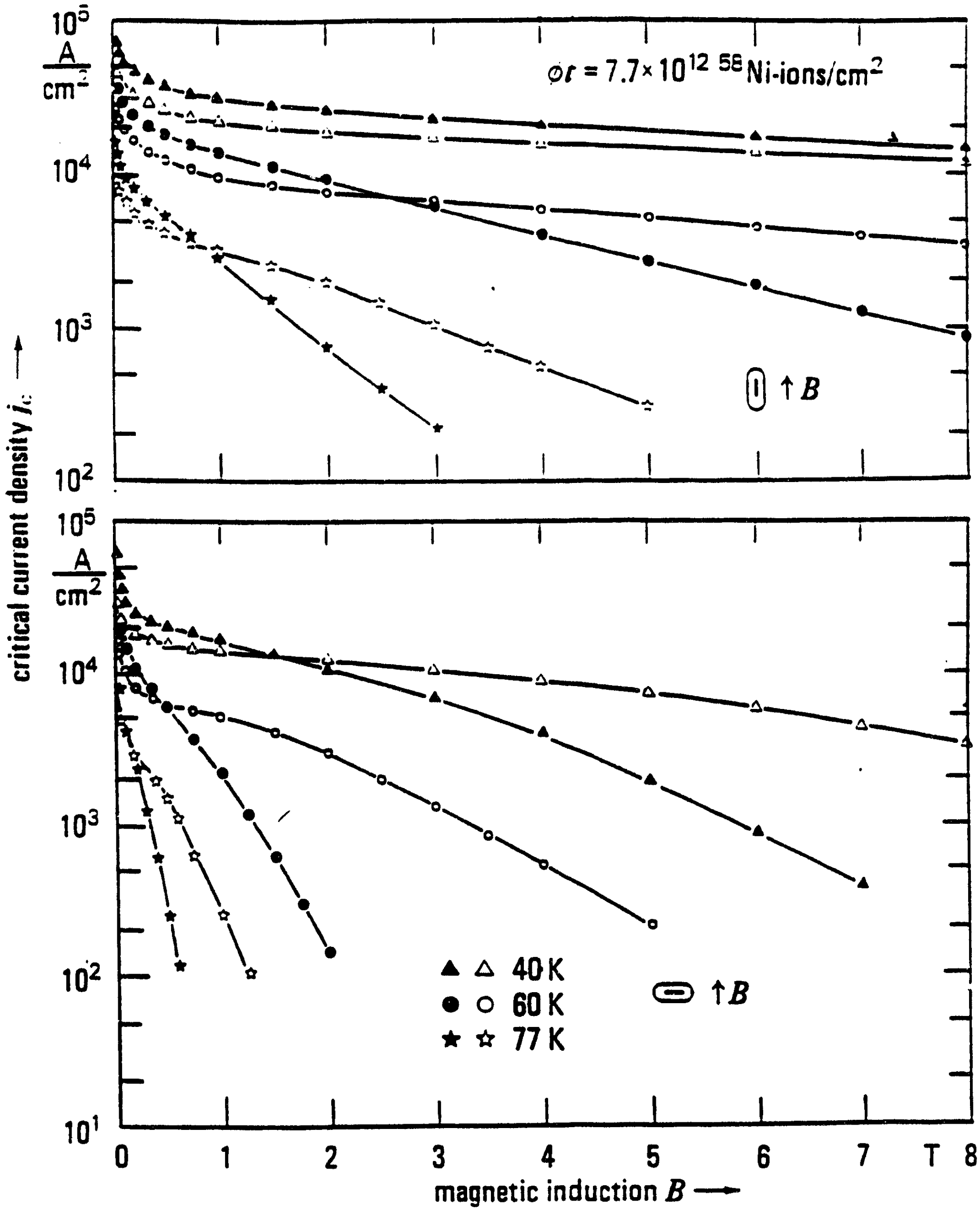


Fig. 3(b) $J_C(H, \theta)$ measured at 60 K as a function of the angle between applied field and the *a-b* plane.



weak links
BSCCO/Ag TAPE
T=35K
flux creep
H PARALLEL TO C-AXIS
$J_c(A/cm^2)$
B(T)
10^5
10^4
10^3
10^2
0
2
4
6
8

Bi-2223 Tape Siemens
Neumuller et al.
Effect of Columnar Defects



Conclusions

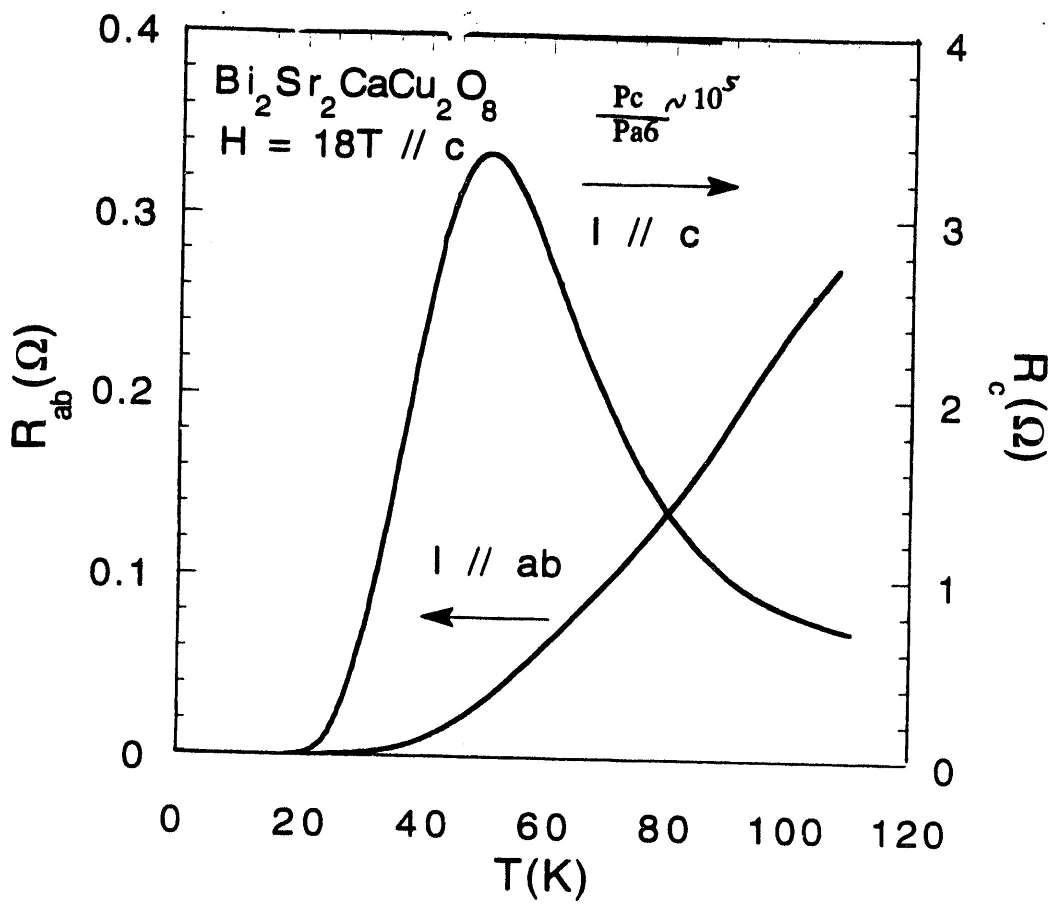
1. The depression from thin film J_c-values indicates that tapes still have weak links that effectively restrict current flow to 1-10% of the total cross-section of the tape.

2. After an initial drop in small fields, $J_c(B,T,\theta)$ reflects the behavior of intragranular pinning in the remaining strongly connected pathways.

3. Improved texturing alone will result in a more field independent $J_c(B)$ for the B parallel to tape plane orientation, but will not affect $J_{c\perp}(B,T)$.

4. Further reduction of weak links, will multiply the entire $J_c(B,T,\theta)$ by a constant factor.

Single Crystal J. H. Cho et al., LANL



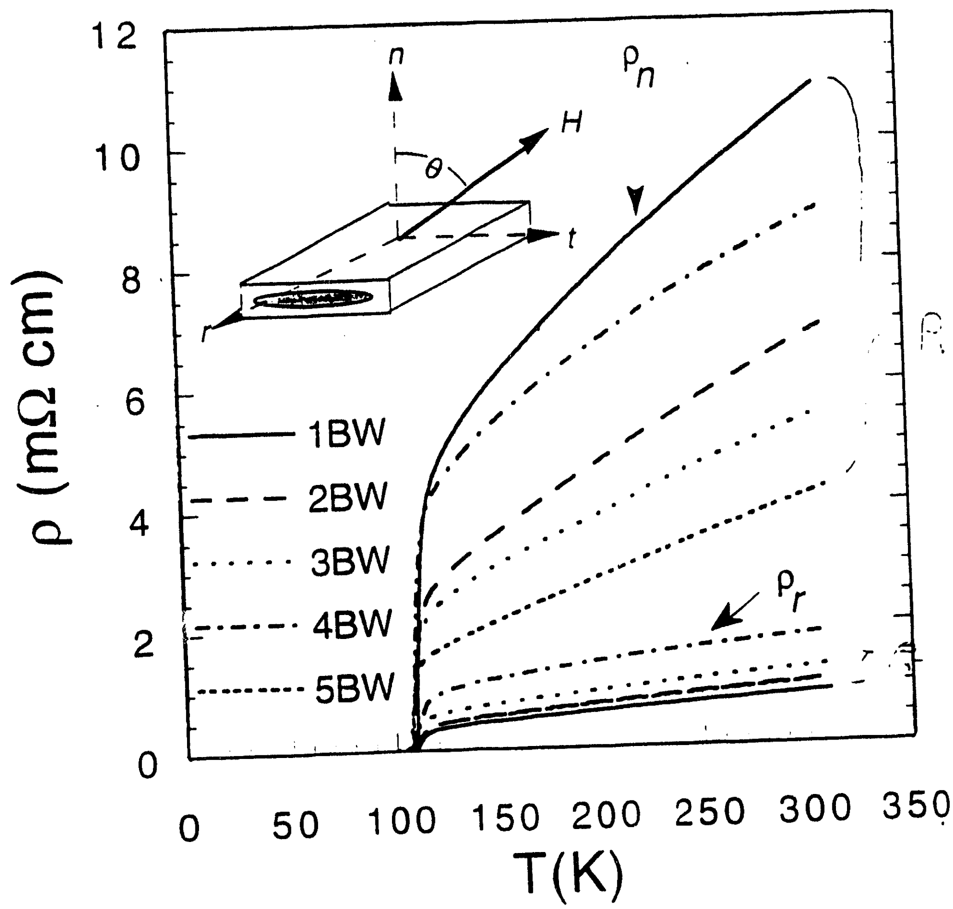


Fig. 1. Resistivity ρ_n for the current direction parallel to the tape normal and resistivity ρ_r for the current along the rolling plane for five different tapes. The critical currents at 75 K in self field for tapes 1BW, 2BW, 3BW, 4BW, and 5BW are ~31 A, ~27 A, ~17 A, ~15 A, and ~23 A, respectively. The inset defines the directions r, n, and t, used in the experiment.

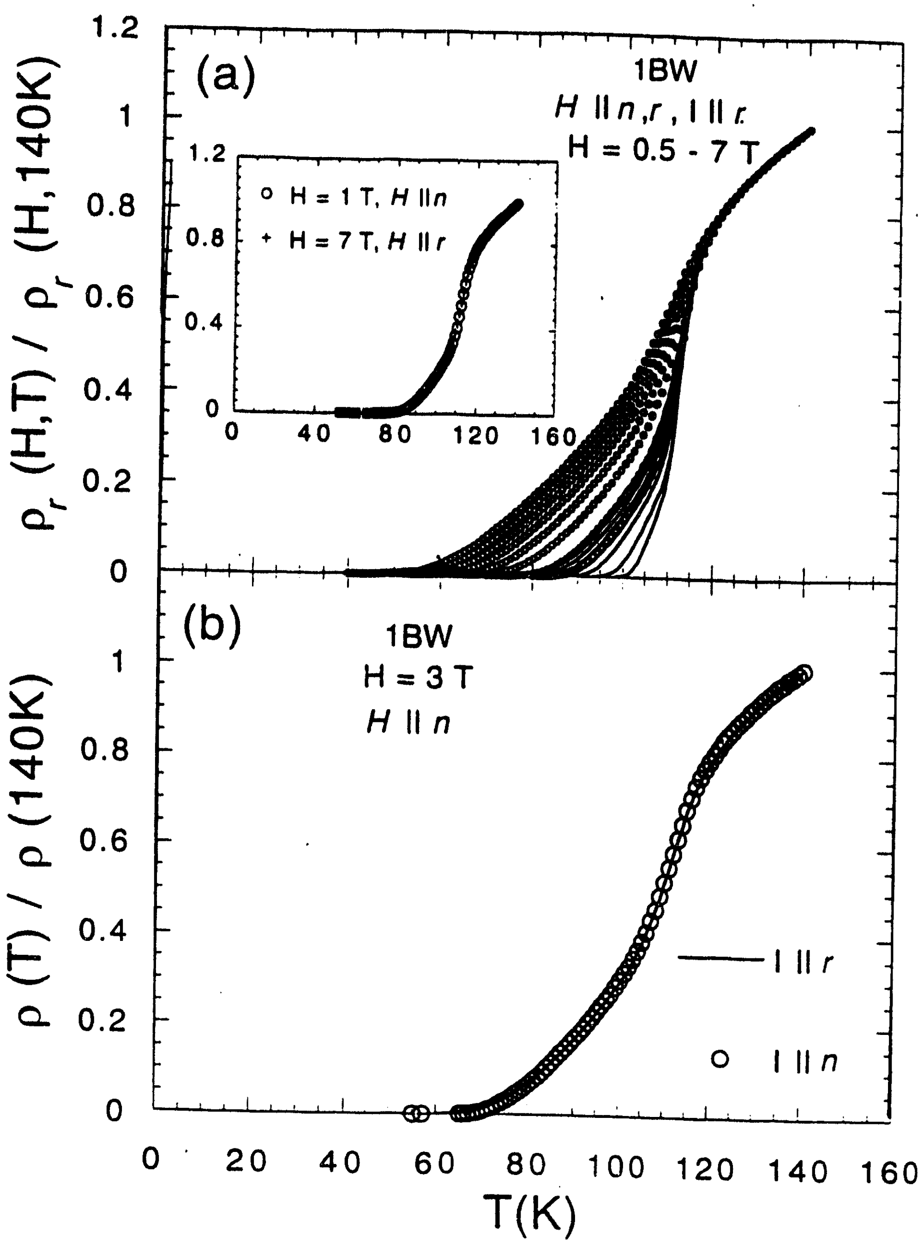


Fig. 2. (a) Magnetic field dependence of the normalized resistivity vs. temperature. Symbols represent ρ for $H \parallel n$ and lines for $H \parallel r$, respectively. From the left to the right, the magnetic fields are 7, 6, 5, 4, 3, 2, 1, and 0.5 T for each set. The inset (axes same as the main figure) shows the scaling of ρ for one value of $H \parallel r$. (b) Normalized resistivity vs. temperature for $H \parallel n$ at 3 T for $I \parallel n$ and $I \parallel r$.

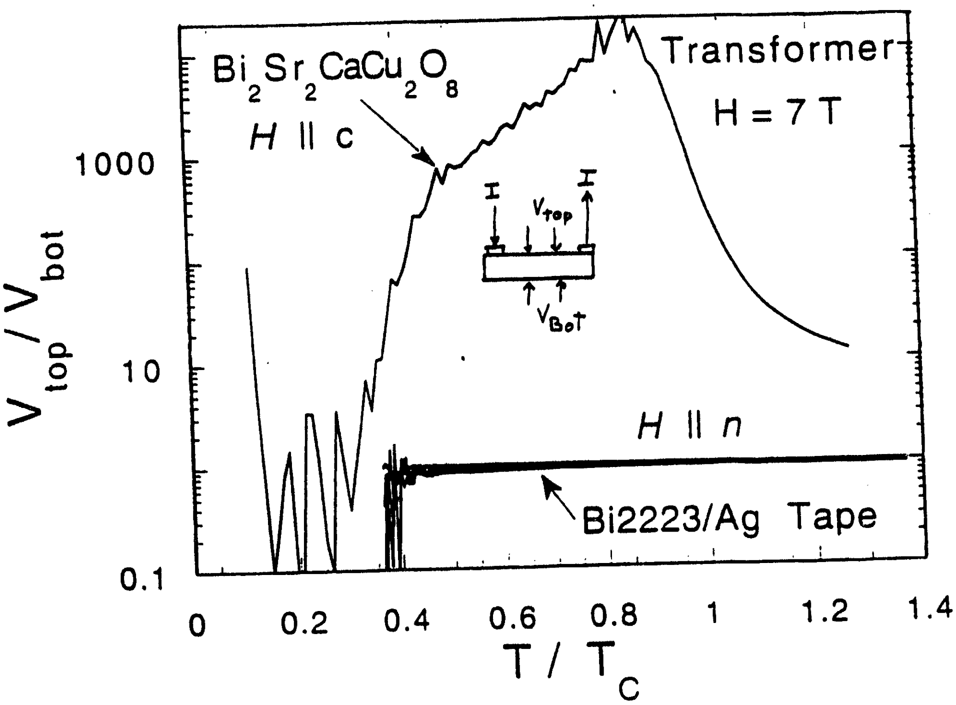


Fig. 4. Comparison of the resistivity anisotropy using the transformer configuration (current contacts on the top surface of the sample, voltage contacts on both the top and the bottom) at $H = 7$ T and $H \parallel c$ for a 10 μm thick Bi-2212 single crystal and $H \parallel n$ for a 50 μm thick Bi-2223/Ag tape.

SUMMARY

- High-J_c BSCCO Tapes Show Extreme Reduction of Resistivity Anisotropy Compared with Bi-2212 Single Crystals.

- Resistance Versus Temperature and Magnetic Field Data for Current Flow Along the Tape Normal are Identical to That Along the Tape Plane When Multiplied by a Scaling Factor.

- "Dc Transformer" Configuration Measurements Show that Current Distributes Nearly Uniformly Through the Tape Cross Section When Introduced From One Side.

- Results are Consistent With Current Flow Predominantly Along a-b Planes Through a Network of Strongly Coupled Low-Angle Grain Boundaries Even for Transport Across the Tape Normal.

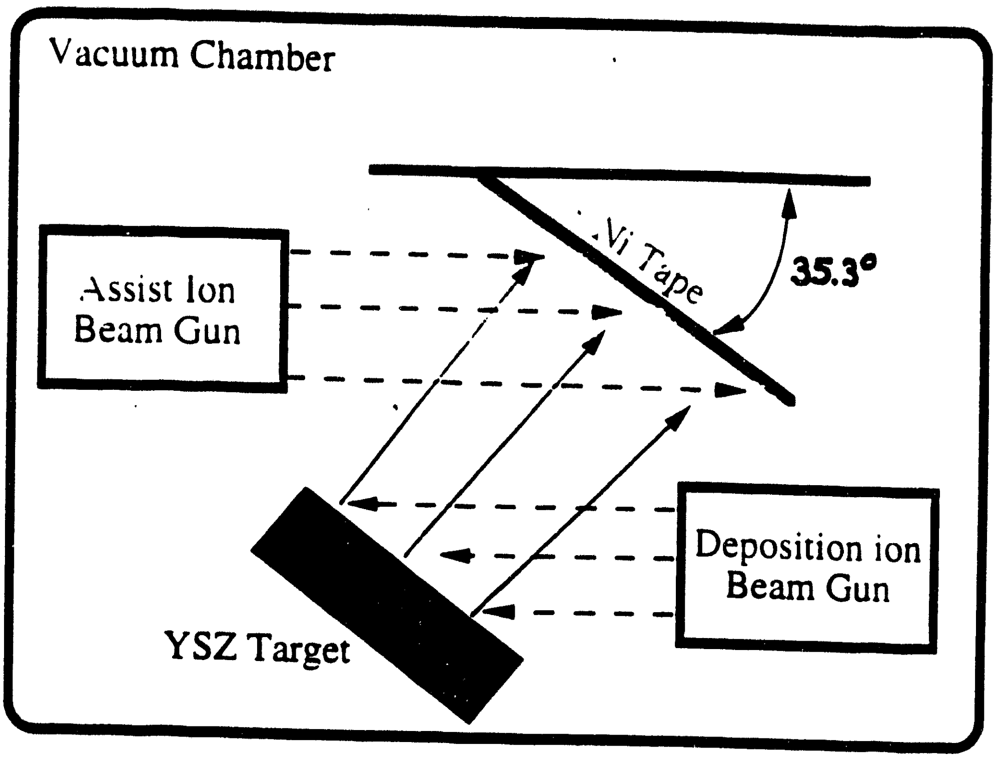
ISSUES CONCERNING YBCO CONDUCTORS

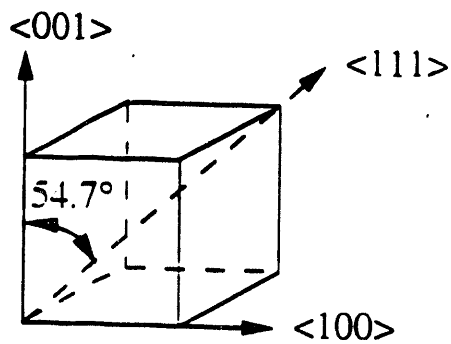
- YBCO Shows Superior Ability to Pin Flux and Sustain High Current Densities at High Temperatures and High Magnetic Fields.

- But Bulk conductors Made by Processing Compatible With Production of Long Continuous Conductors All Show Extreme Weak-Link Limitations.

- Ion Beam Assisted Deposition(IBAD) Reduces High Angle Grain Boundaries on Material Deposited on Practical Polycrystalline Tape Substrates--May Make High Current YBCO Conductors Practicable

Ion Assisted Deposition

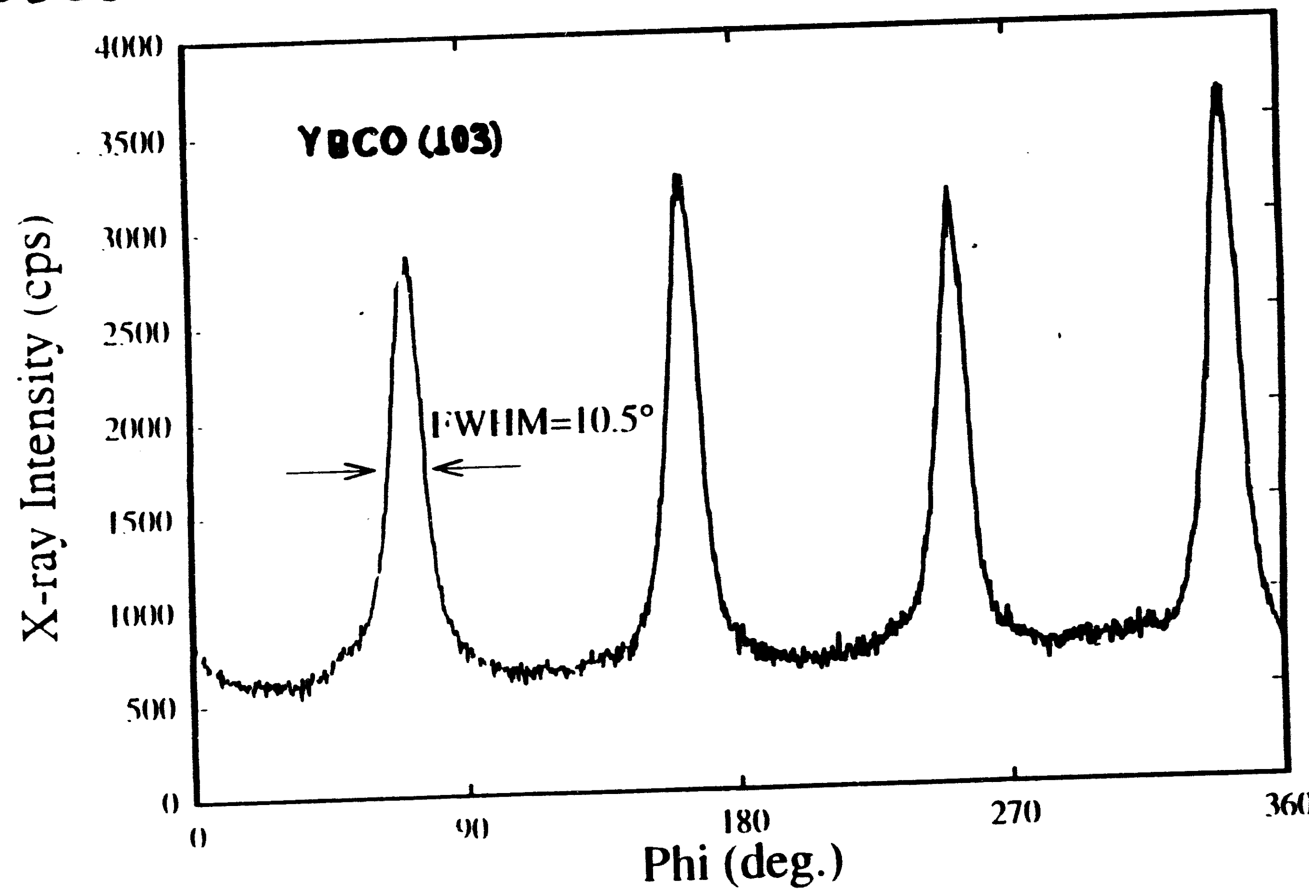




YSZ Unit Lattice

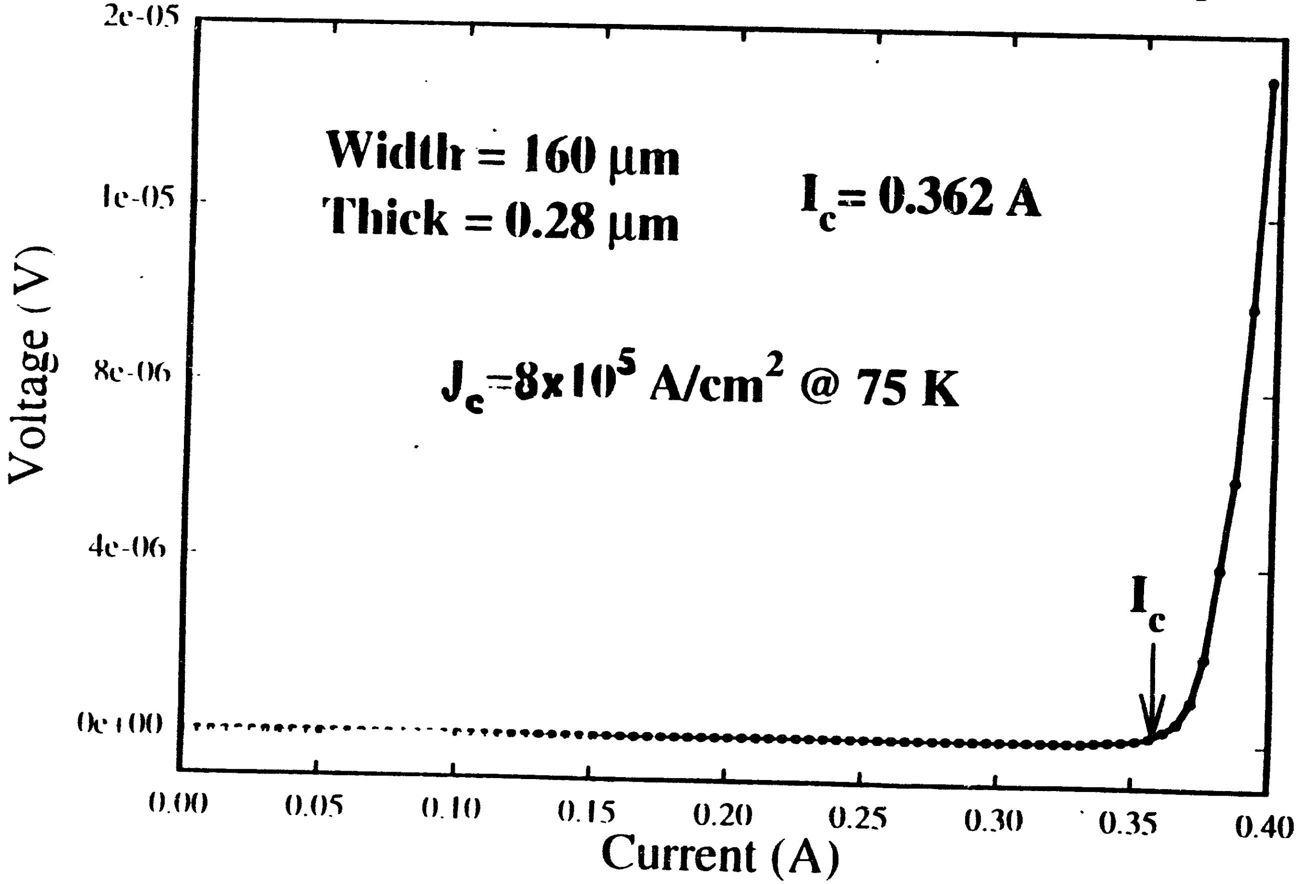
Los Alamos

YBCO on Ni Sheet with Textured Buffer Layers

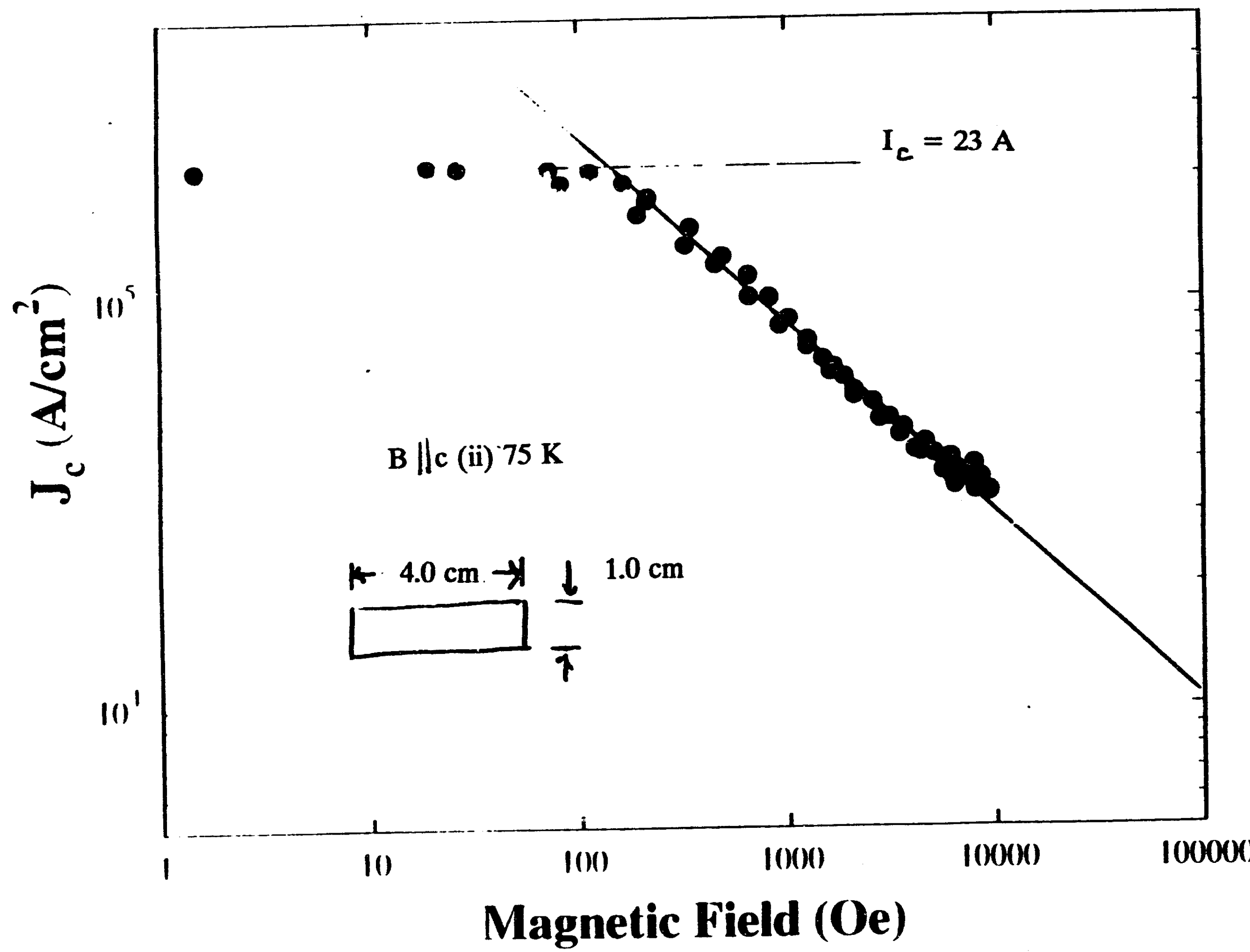


3 of 6

YBCO on Ni Sheet with Textured Buffer Layers



1.4 μm YBCO on Ni with textural YSZ



Bi-axial Texture in YBCO-124 Multifilamentary Composite Conductors

Larry Masur

American Superconductor Corporation

American
Superconductor
CORPORATION

Collaborators

American Superconductor

Eric Podtburg, Chris Craven, Alex Otto

Oak Ridge National Lab

Z.L. Wang and Don Kroeger

Los Alamos National Lab

Yates Coulter and [illegible]rty Maley

American Superconductor CORPORATION

Outline

- ► Objectives
- ► Approach
- ► Texture Characterization:
  Microstructure
  Properties
- ► Opportunities for Development

American Superconductor CORPORATION

Objectives

- Demonstrate texture of non-BSCCO systems in a composite wire environment
  - use thermal-mechanical processing
- Determine influence of texture on weak-link behavior
- Determine microstructure-property relationships

American Superconductor CORPORATION

Approach

- Use metallic precursor process
  - easy access to small filament sizes (<1μm)
- Use $(Ca_{.1}Y_{.9})Ba_2Cu_4O_8$ as demonstration system
  - stable oxygen stoichiometry
  - expectation of more platey grain morphology than YBCO-123, therefore more texturable by thermal-mechanical processing.

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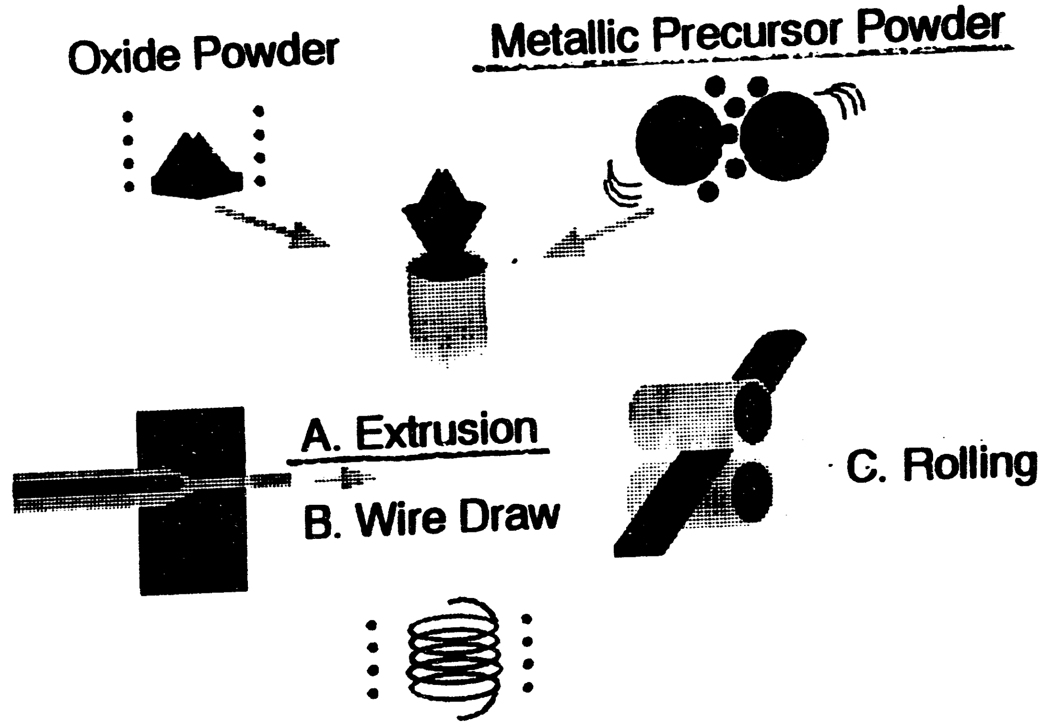
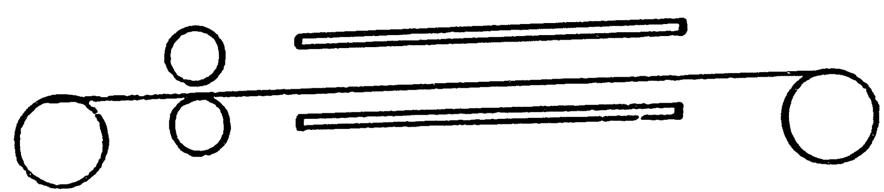
ASC Wire Forming Processes

1. Powder Preparation
2. Billet Packing & Sealing
3. Deformation & Processing
4. Oxidation - Heat Treat

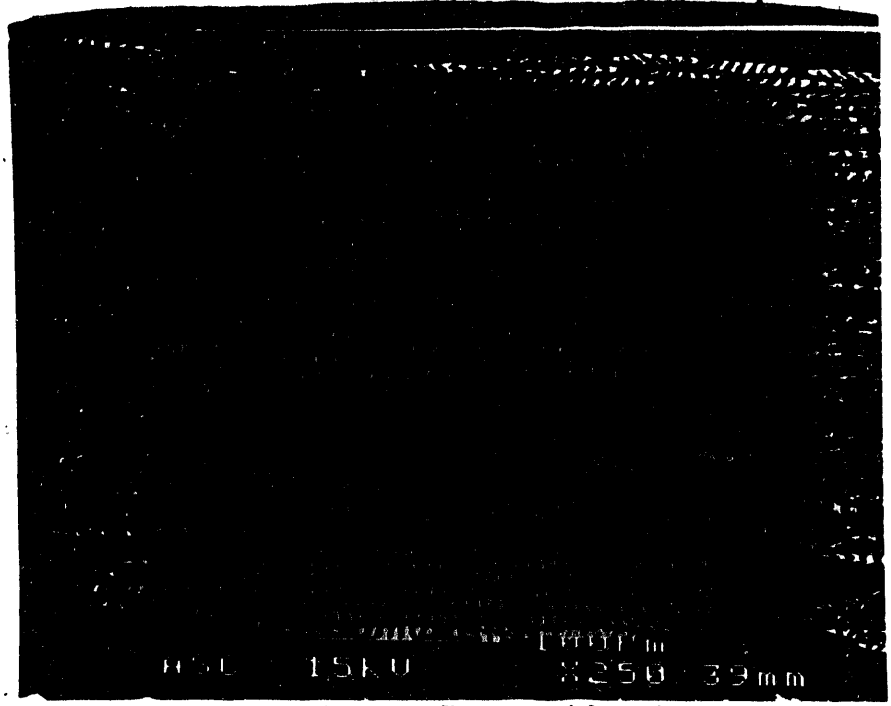


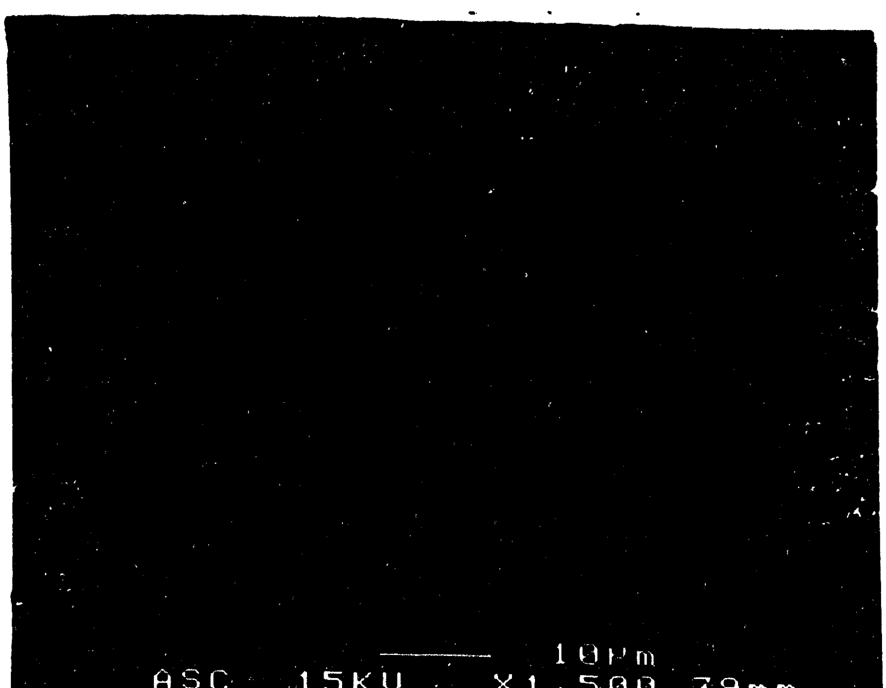
American Superconductor CORPORATION

THERMAL-MECHANICAL PROCESSING



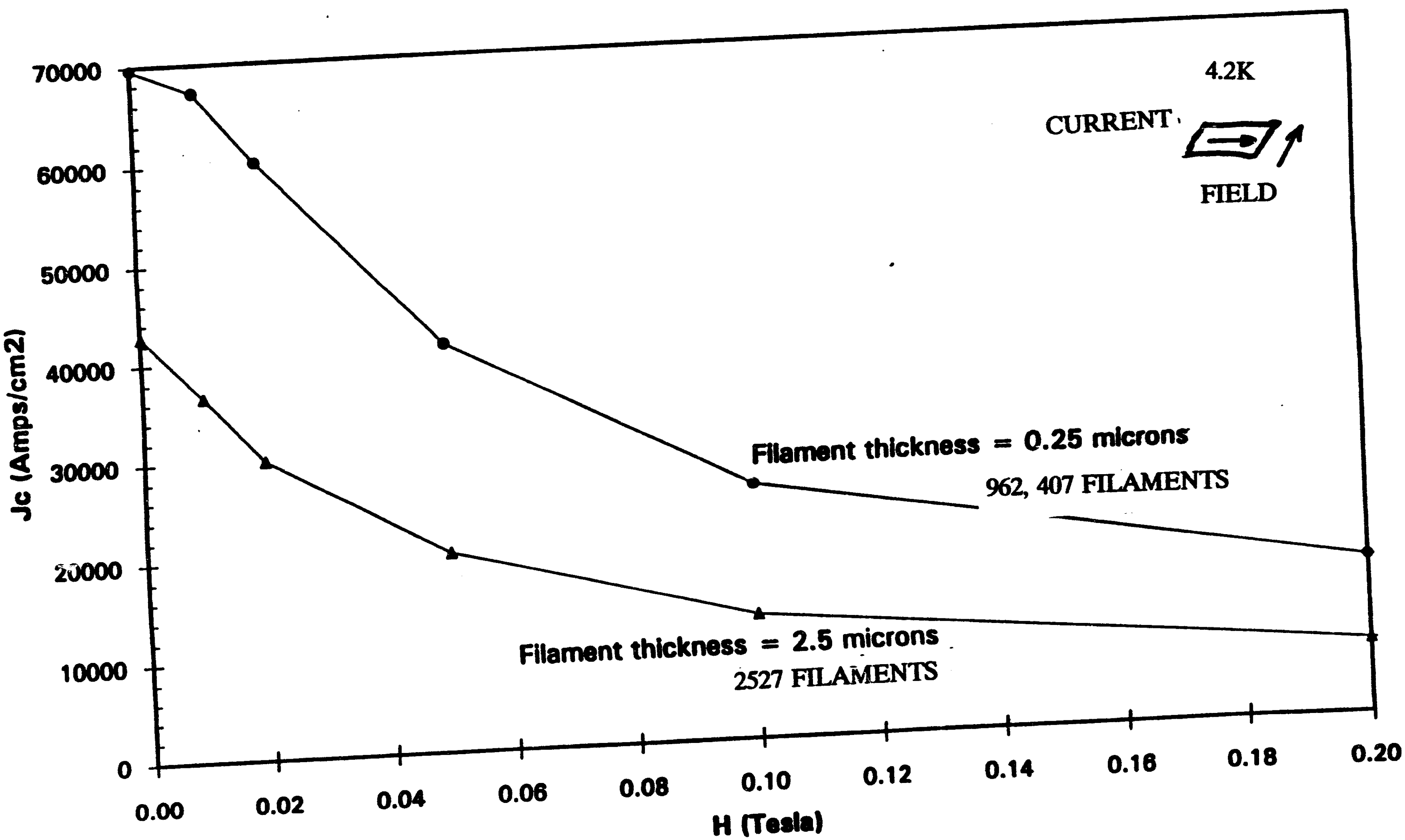
Multifilamentary $Y_1Ba_2Cu_4O_8$ Tape
962,407 filaments
filament thickness = 0.25μm

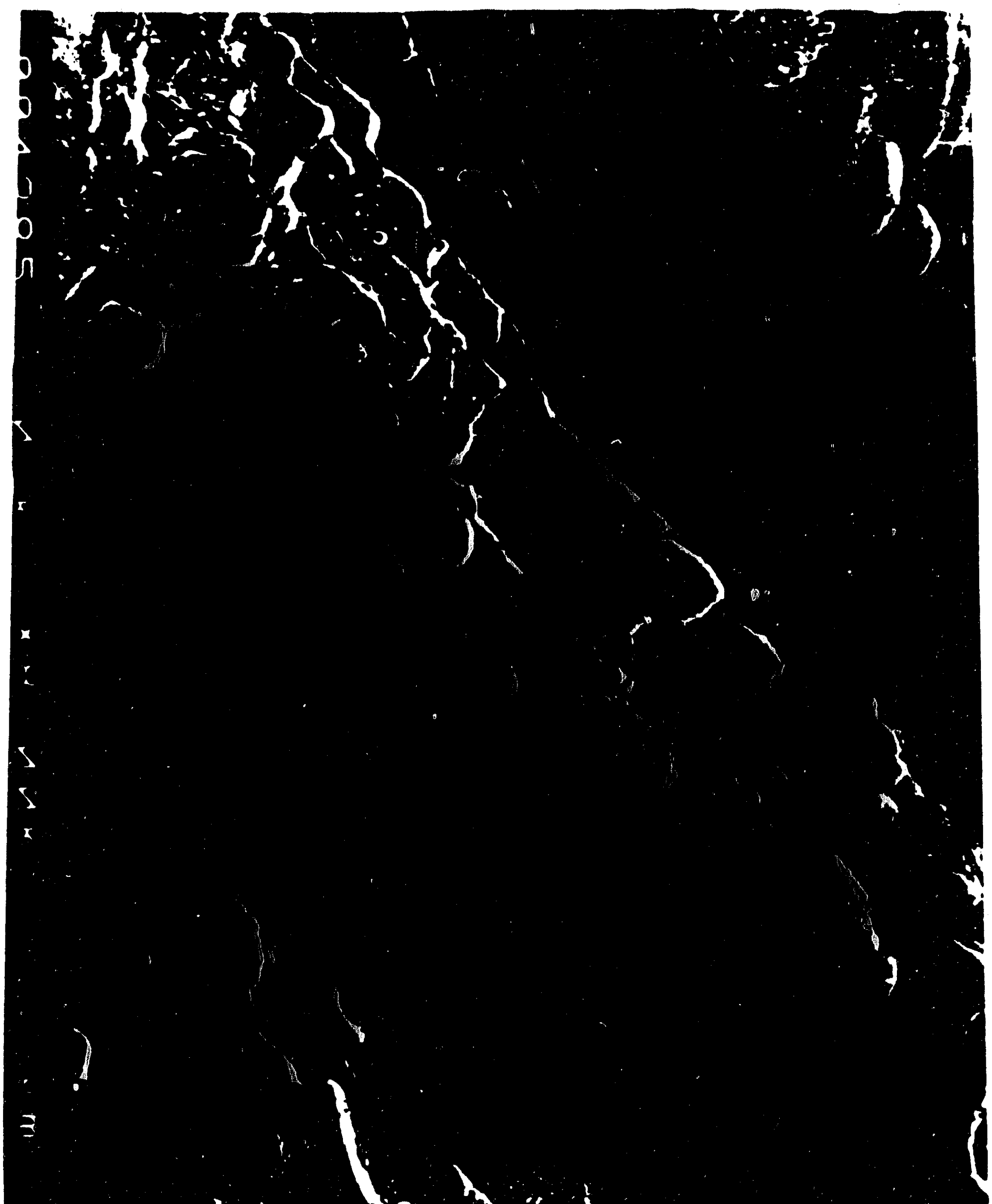




YBCO-124

Influence of Filament Size on Jc Performance





EVIDENCE OF IN-PLANE TEXTURE

TEM VIEWED ALONG [001]

∠10°
MISALIGNMENT

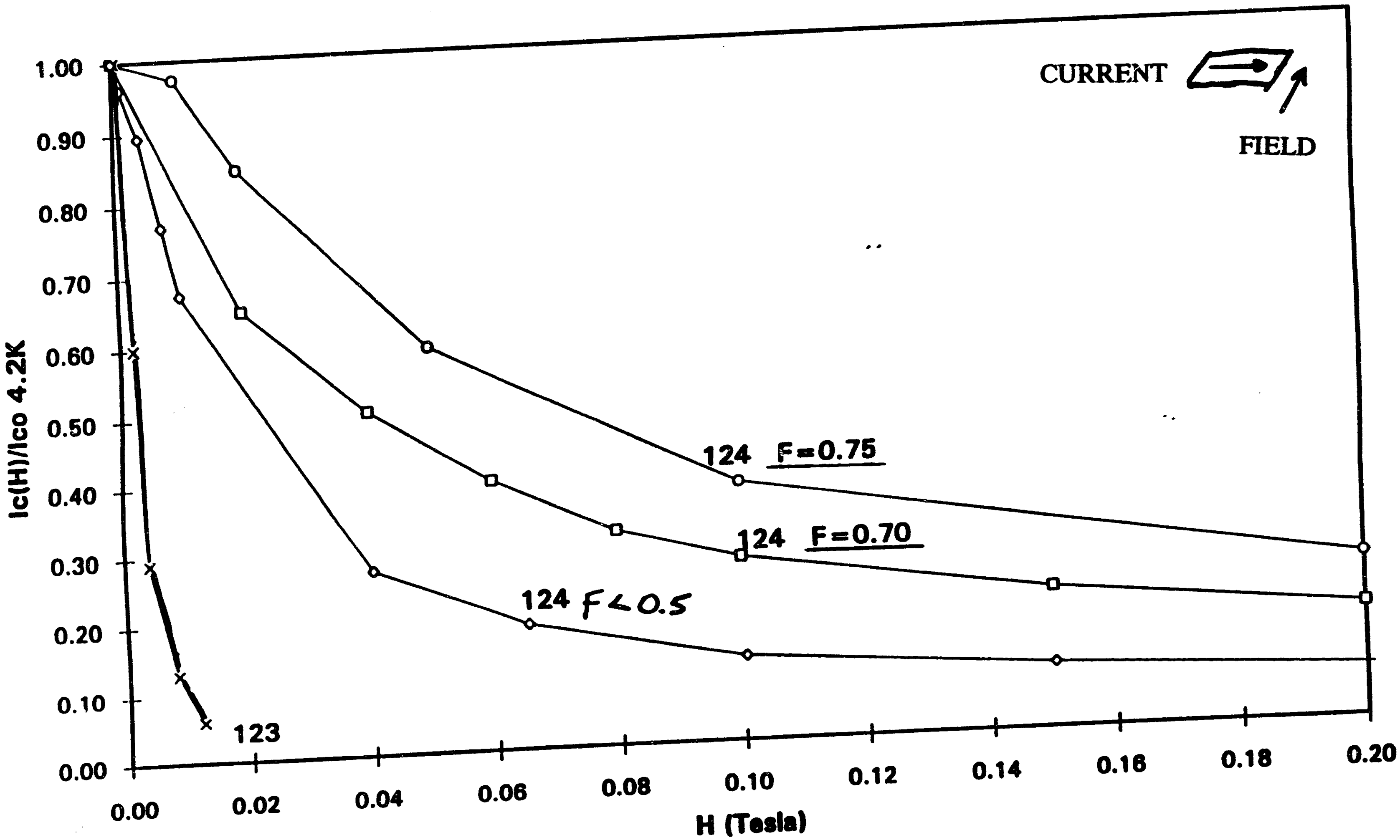
ASC/ORNL COLLAB.

Summary of TEM Observations of 962,407 filament $(Ca_{.1}Y_{.9})Ba_2Cu_4O_8$ Composite Wires

1. Grain size varies from 0.1 to 1μm
2. Strong [001] texture is observed in plane view; c-axis misalignment < 5°
3. All grain boundaries are clean and structurally intact
4. Strong a-b texture is observed in plane view; ab-axis misalignment < 10°
5. ab-axes aligned parallel to filament axis.

American Superconductor CORPORATION

In Fi· . Performance Of Y-124



Conclusions

- Bi-axial texture has been demonstrated in a composite wire environment.
- Weak-link behavior of Y-124 silver-sheathed composite tapes improves with texture

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CORPORATION

Opportunities for Development

Deformation processing of ultra-fine filament composites may enable alternatives to BSCCO for composite conductors.

Critical issues are:

- Current limiting mechanisms
- Role of filament size
- Application of these processing techniques to other composite conductor systems

American Superconductor CORPORATION

SECTION VII

MANUFACTURING ISSUES FOR LONG LENGTHS

DOE HTS WORKSHOP, Feb. 16-17, 1994
St. Petersburg Florida

DEVELOPMENT OF ROUND MULTIFILAMENT BSCCO-2212 WIRE

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IGC Advanced Superconductors
Waterbury, CT 06704

P. HALDAR

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Battelle
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E. HELLSTROM

University of Wisconsin
Madison, WI

Supported by DOE SBIR Program, Phase II work.
Contract # DE-FG02-92ER 81461

OUTLINE

* Fabrication of 2212 Multifilament Wire.

* Show optical cross-sections of the conductors before and after final heat treatment.

* I-V Traces of the wire.

* Critical current density characteristics as a function of temperature, magnetic field and filament size.

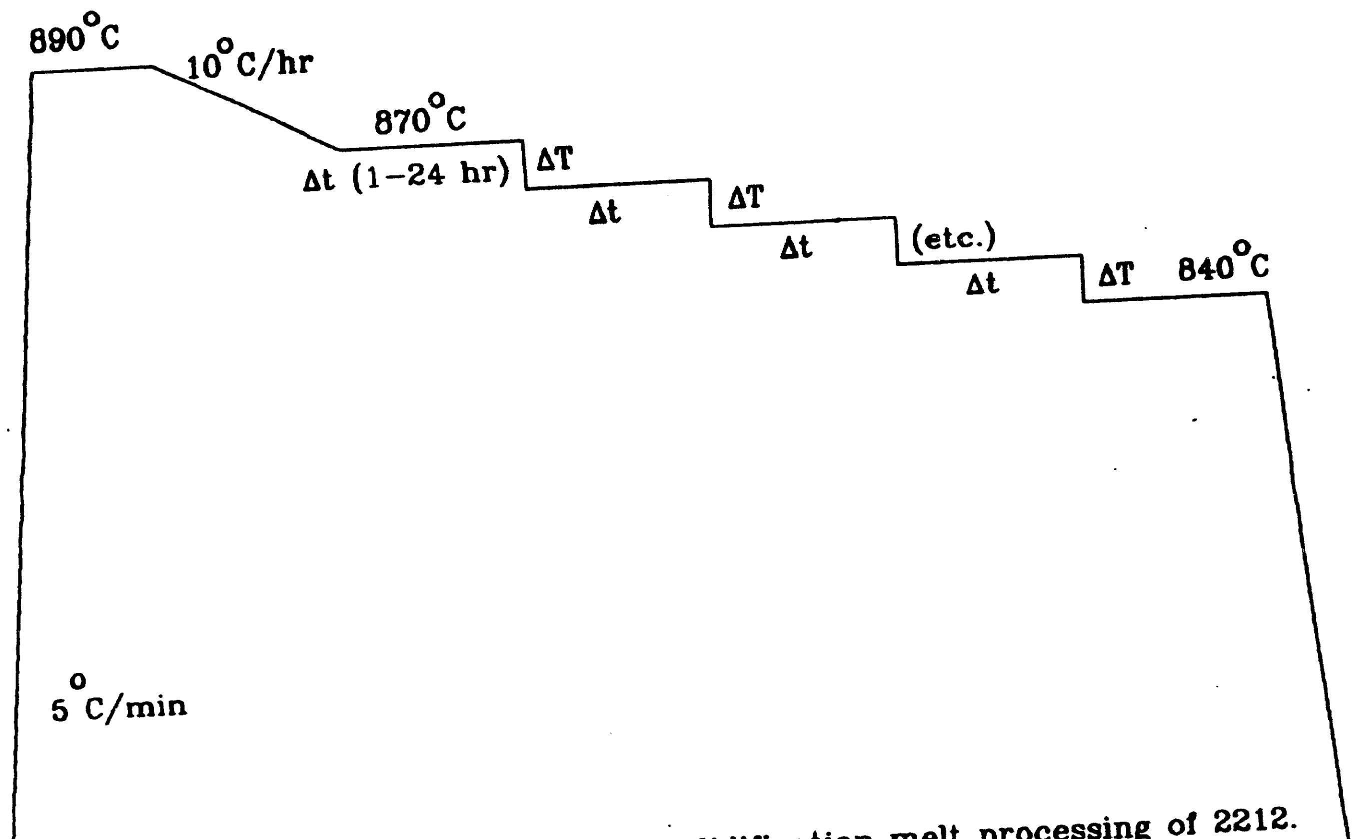
* Stress versus time of composite wire for Ag and Ag-Alumina matrix.

* Concluding remarks.

CONDUCTOR DEVELOPMENT PROGRAM TECHNICAL GOALS:

* Long Length.
* 500 Amp/mm^2, > 15 Tesla.
* High Strength.
* Round Multifilament.

BSCCO (2212) Heat Treat Schedule



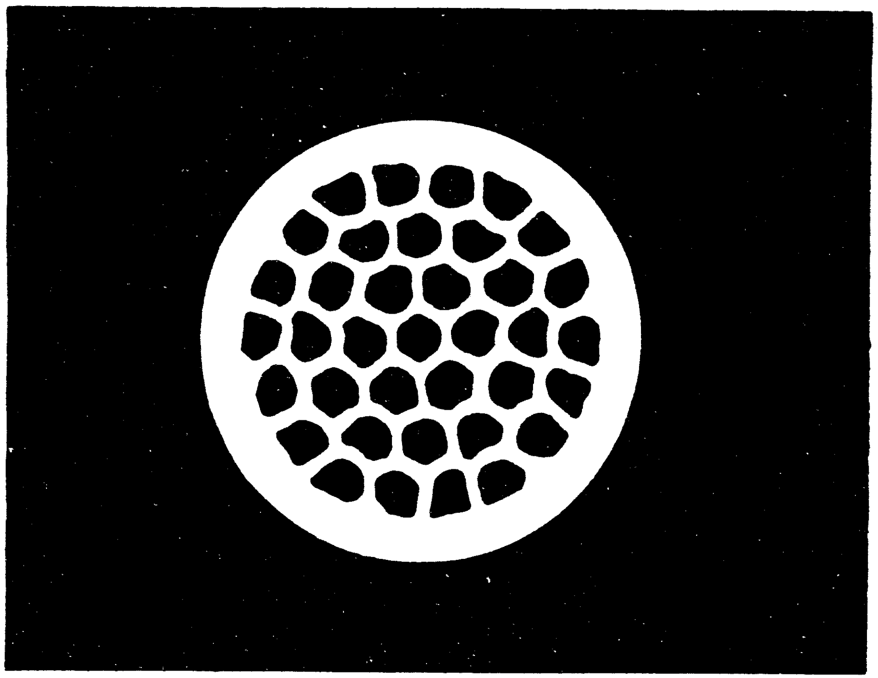
Schematic diagram for step–solidification melt processing of 2212. The temperature at which the steps begin and end, and their length, size, and number have yet to be optimized.

Courtesy Eric Hellstrom.

IGC ADVANCED SUPERCONDUCTORS

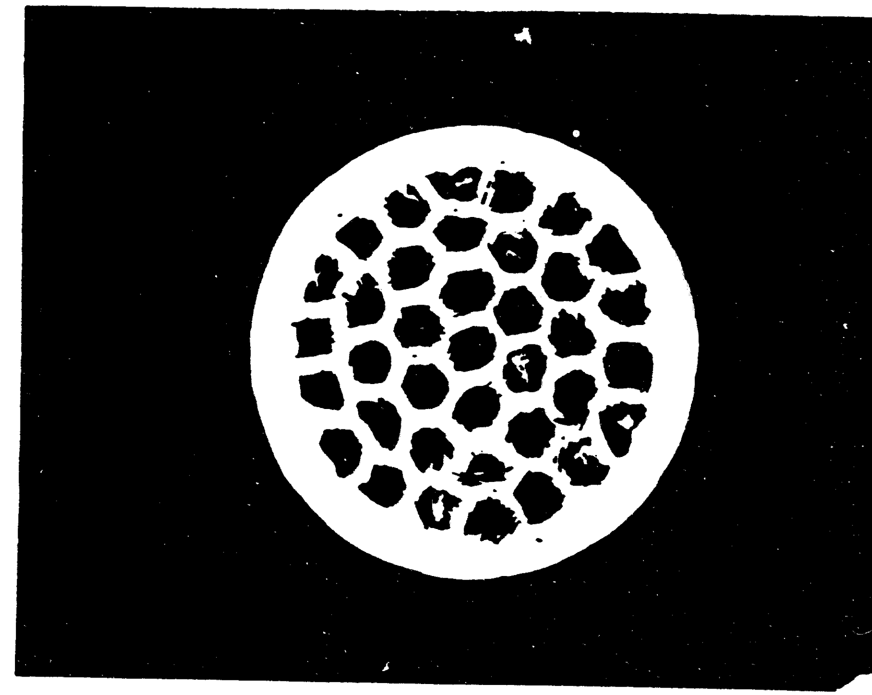
Multifilament 2212 BSCCO

Before Heat Treating



37 filaments (100μm) (50x)
0.043"ϕ

After Heat Treating

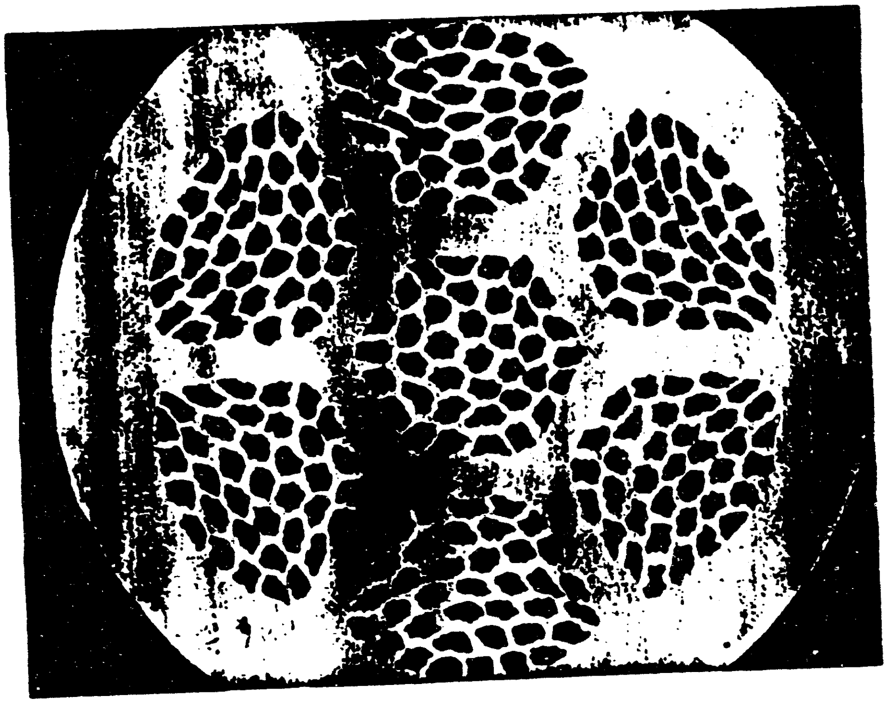


37 filaments (100μm) (50x)
0.0437"ϕ J_c = 13,300 A/cm^2

DOE Workshop   16 Feb. 1994   IGC Advanced Superconductors

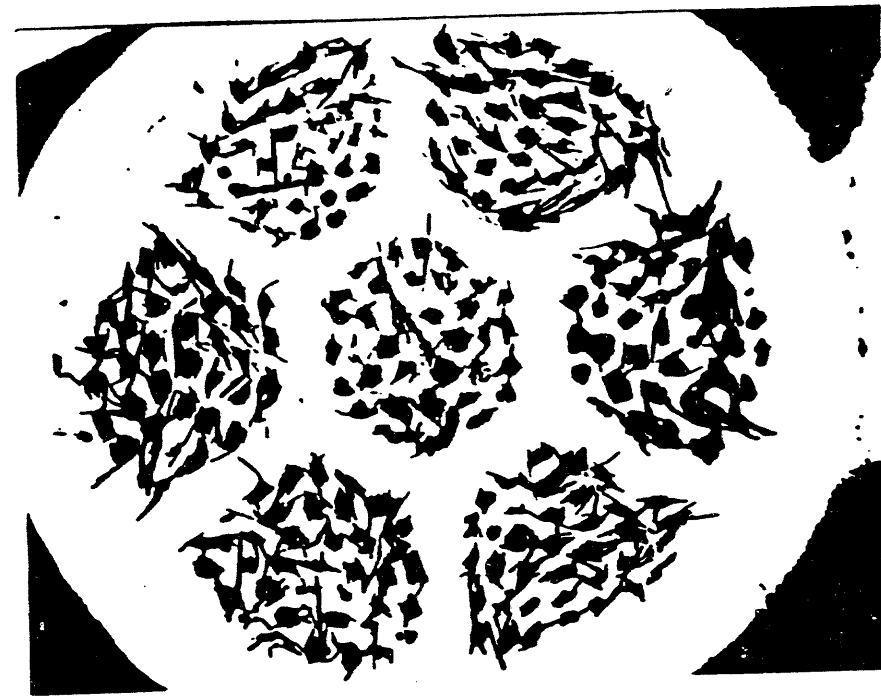
Multifilament 2212 BSCCO

Before Heat Treating



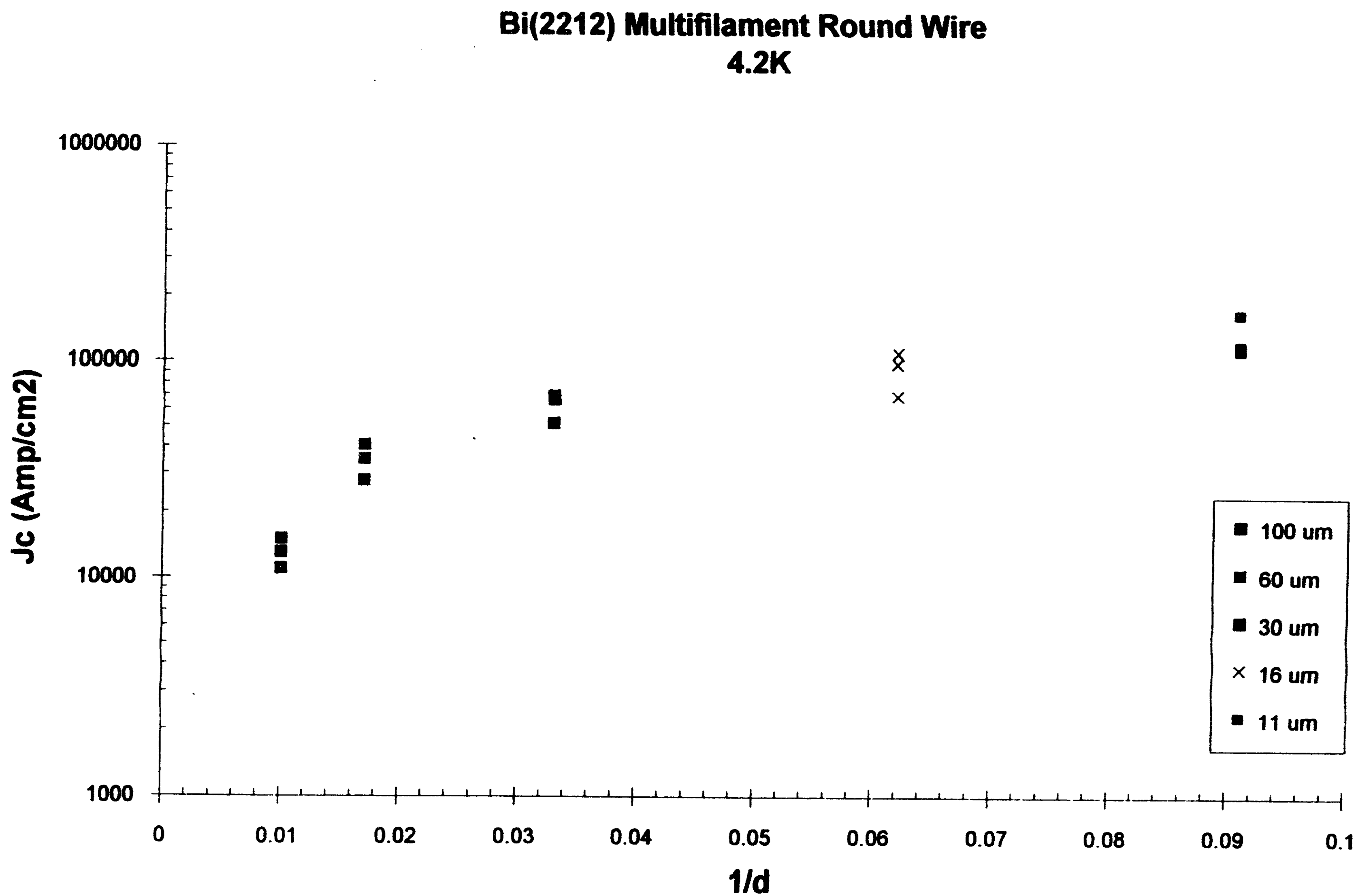
259 filaments (16μm) (200x)
0.020"ϕ

After Heat Treating

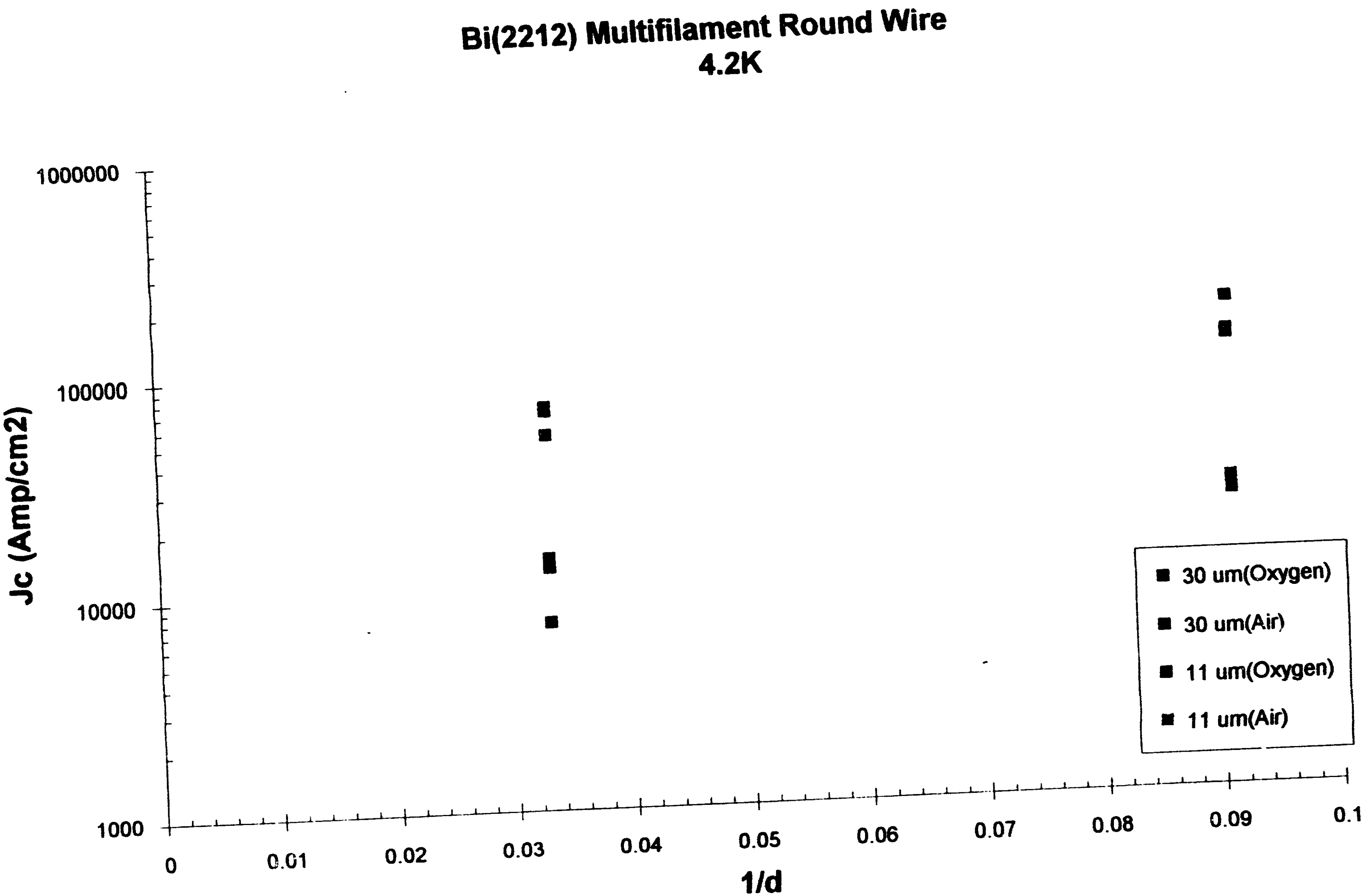


259 filaments (16μm) (200x)
0.0204"ϕ Jc = 118,000 A/cm2

DOE Workshop 16 Feb. 1994 IGC Advanced Superconductors

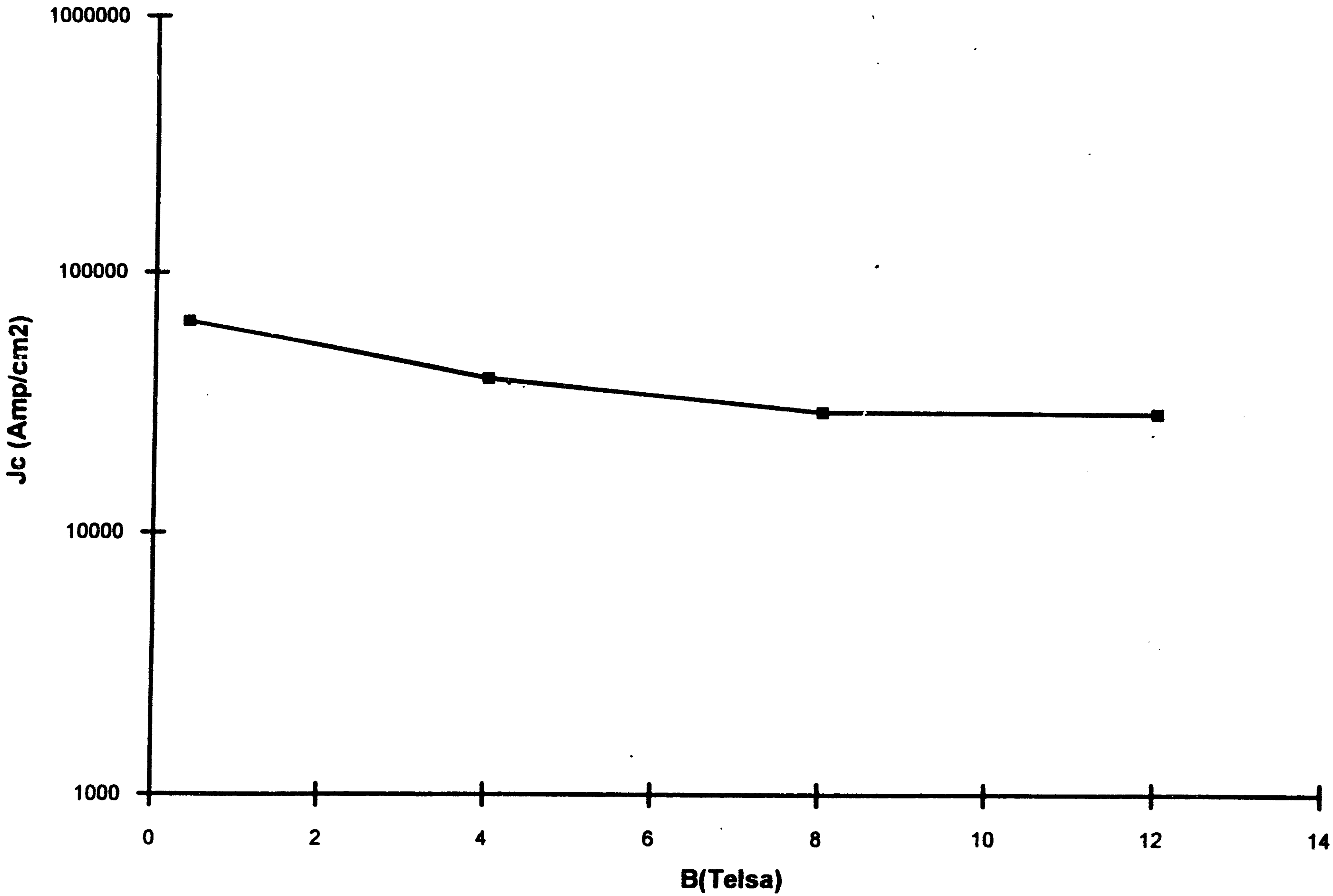


IGC ADVANCED SUPERCONDUCTORS

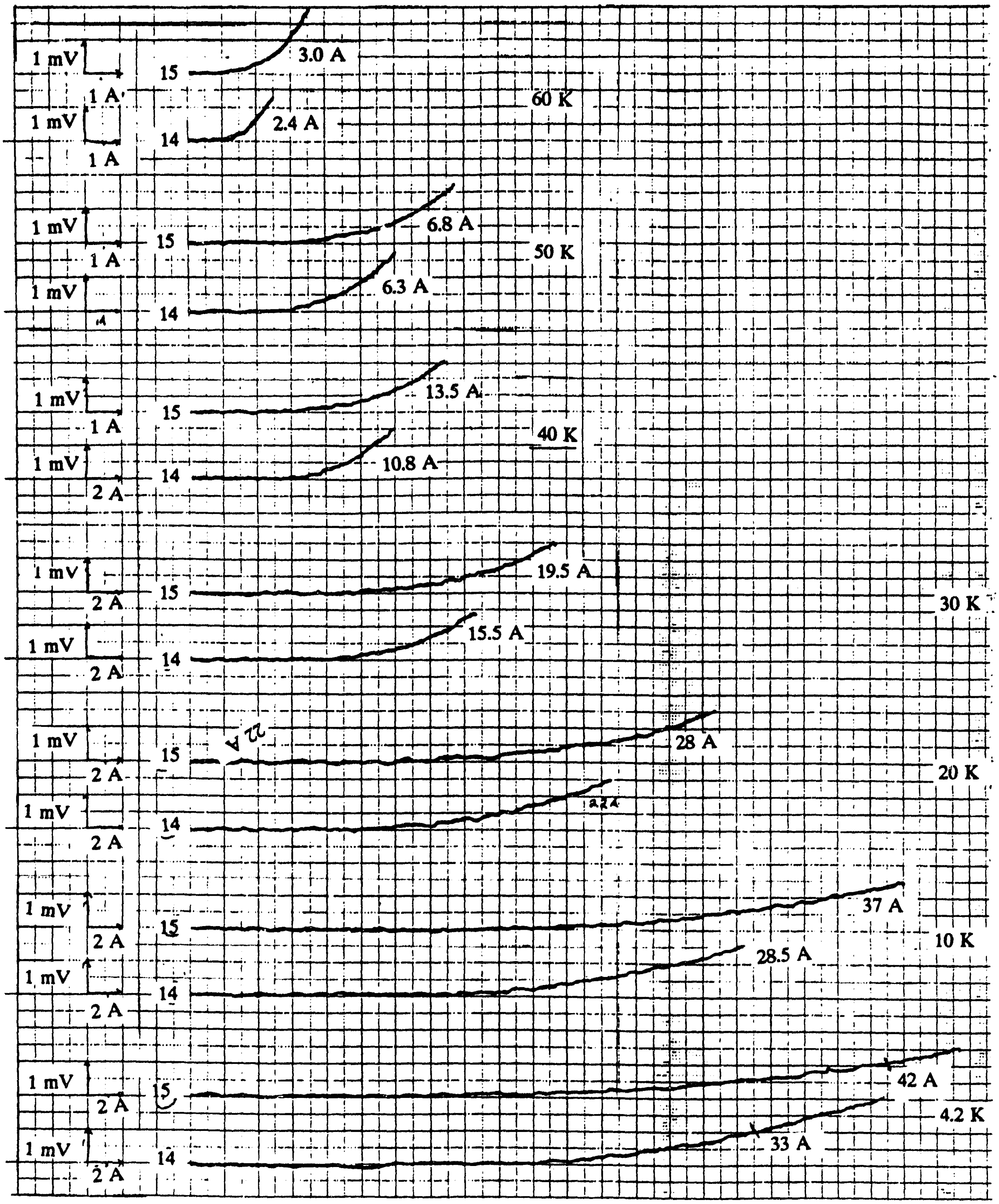


Bi(2212) Multifilament Round Wire
4.2K
Jc (Amp/cm2)
1000000
100000
10000
1000
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
1/d
30 um(Oxygen)
30 um(Air)
11 um(Oxygen)
11 um(Air)

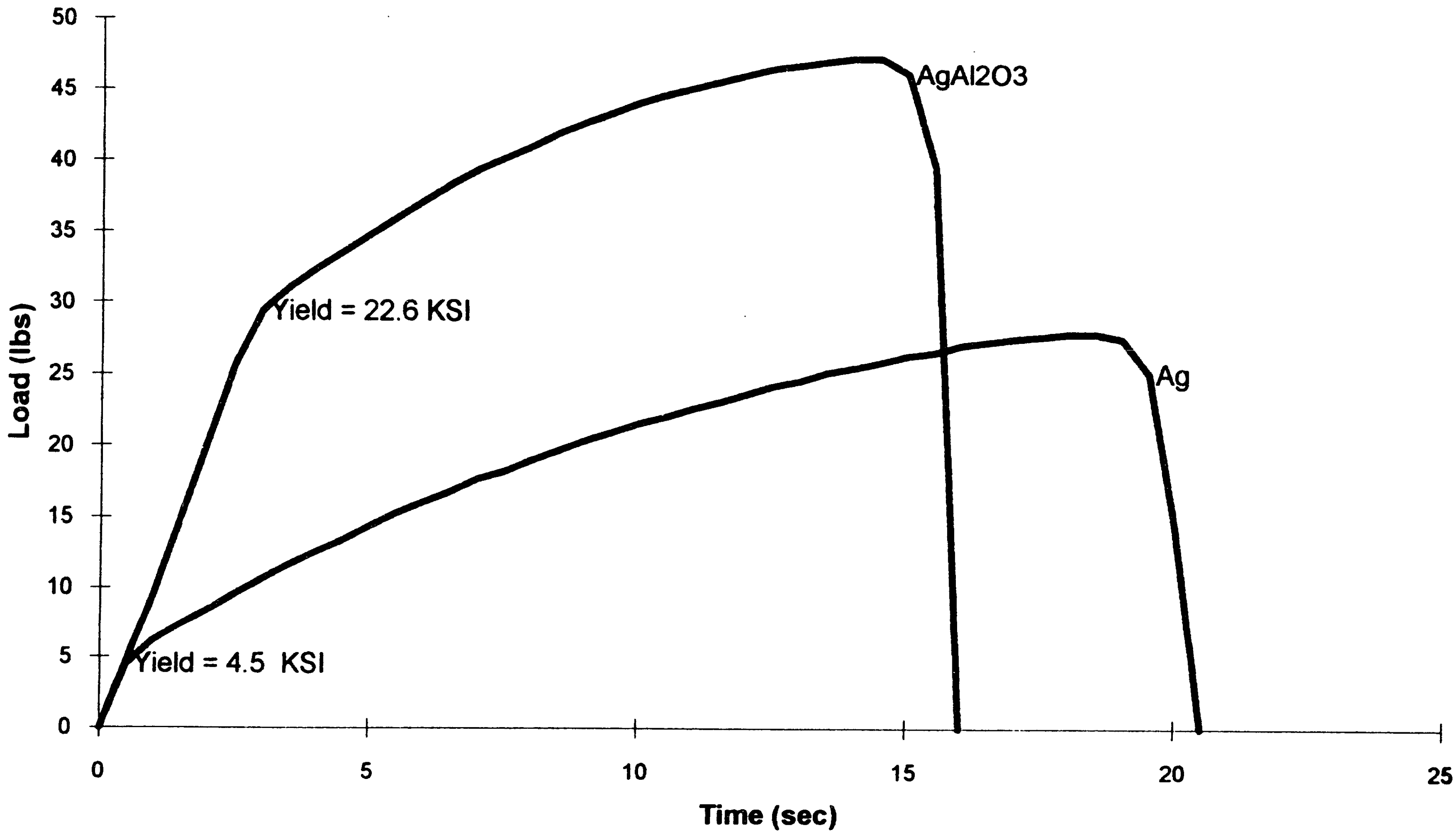
BSCCO 2212
Multifilament Round Wire **4.2K**



IGC ADVANCED SUPERCONDUCTORS



IGC ADVANCED SUPERCONDUCTORS


50
45
40
35
30
25
20
15
10
5
0
Load (lbs)
0
5
10
15
20
25
Time (sec)
AgAl2O3
Ag
Yield = 22.6 KSI
Yield = 4.5 KSI

CONCLUDING REMARKS

Fabricated BSCCO 2212 with 259 filaments round wire, J_c = 165,000 A/cm^2.

J_c with decreasing filament size goes up.

Results from oxygen anneal higher than with air anneals.

Yield strength of BSCCO/Ag-Al_3O, 3 to 4 times higher than in BSCCO/Ag.

Fabricated over 700 meter length of BSCCO 2212 multifilament wire.

PROCESS CONTROL ISSUES FOR FABRICATION OF LONG BSCCO-2212 CONDUCTORS

K.R. Marken, W. Dai and S. Hong

OXFORD

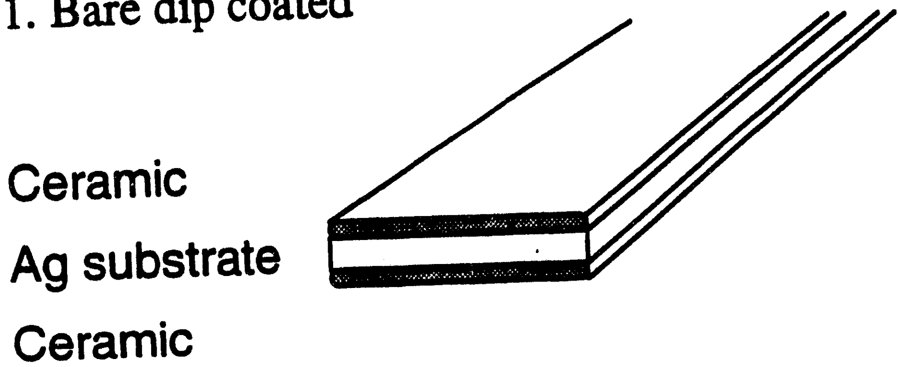
Oxford Instruments Inc
Superconducting Technology
Carteret, New Jersey

High Temperature
Superconducting Wire Development Workshop
St. Petersburg, Florida
February 16-17, 1994

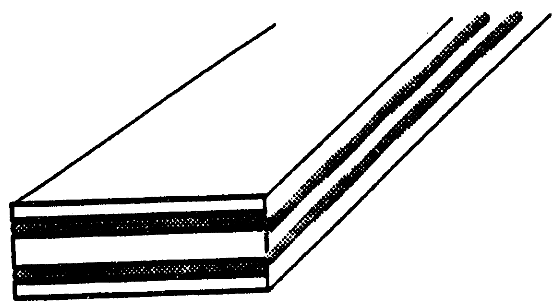
OXFORD

BSCCO-2212 Conductor Configurations

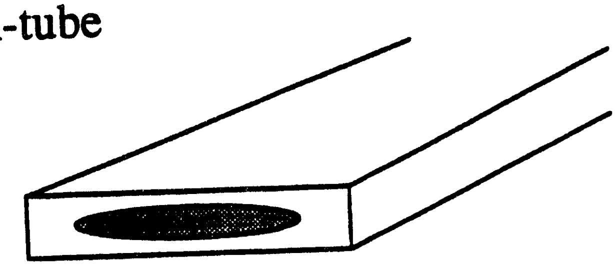
1. Bare dip coated



2. Ag-sheathed dip coated



3. Powder-in-tube



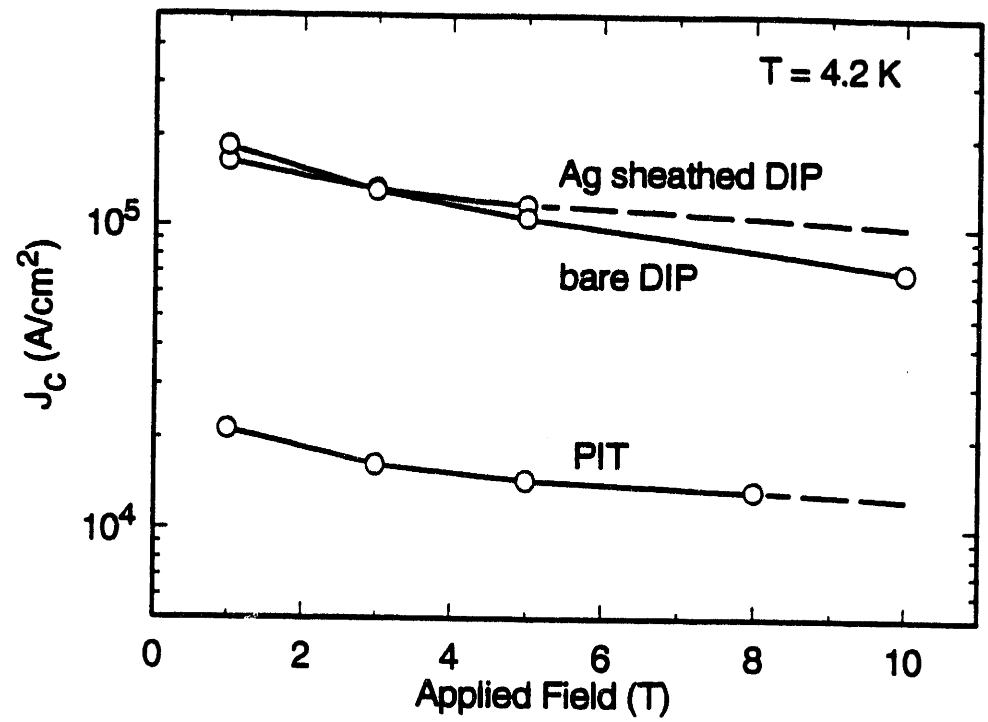


Figure 1. J_C(4.2K) in the ceramic layer

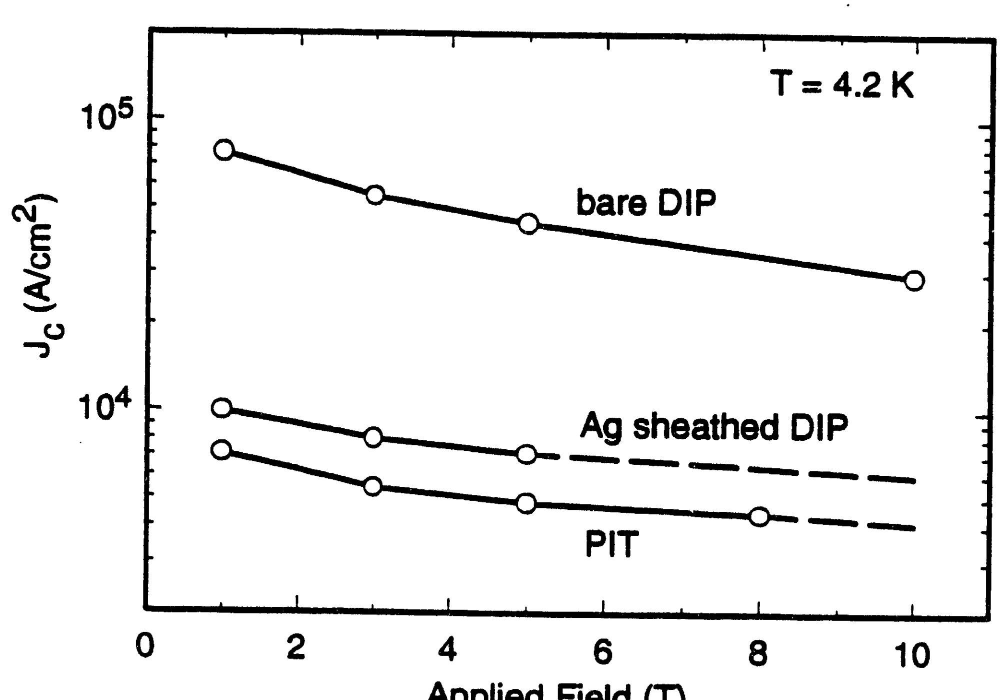


Figure 2. J_C(4.2K) in the overall silver plus ceramic cross-section

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Complexity of the Jc Problem

Powder

- size distribution
- morphology
- surface area
- stoichiometry
- impurities
- additives

Packing

- density
- diameter
- length

Coating

- density
- uniformity
- thickness

Conductor Forming

- method of cold work
- % area reduction
- speed of operation
- lubricant
- final thickness/width

Heat Treatment

- temperature
- time
- heat/cool rates
- atmosphere
- pressure

Measurement

- tape strain state
- sample damage
- I_C criterion
- current transfer length
- ceramic area

Jc

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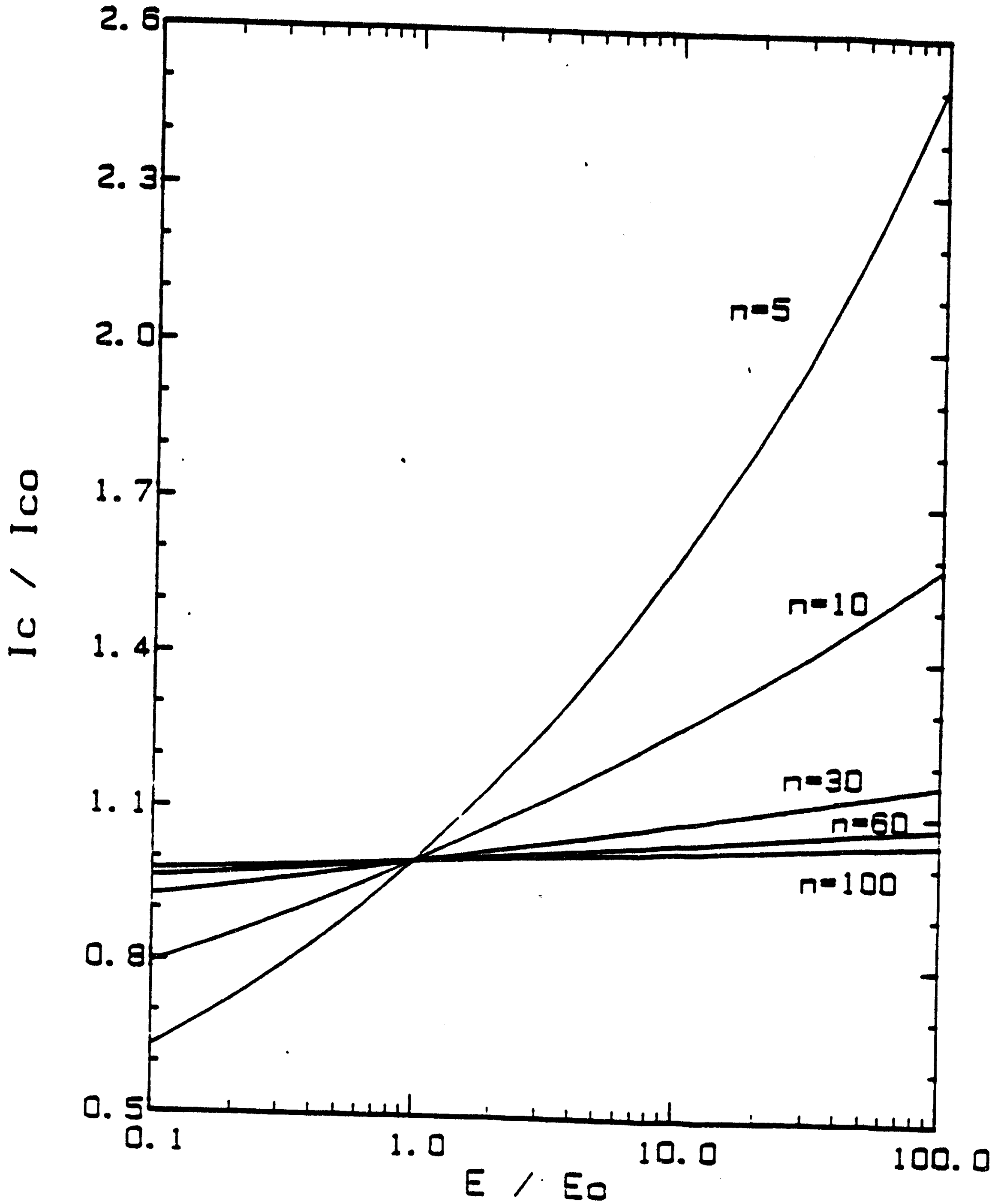

Fig. 4.1. The dependence of I_c on electric field criterion for various n values.

Gaps to Bridge:

1. J_c in short samples -- J_c in long samples
(4 cm) (1 to 20 m)

J_c(1m) typically 30 to 50% of J_c(4 cm),
J_c(20m) marginally worse than J_c(1m)

2. J_c in dip-coated -- J_c in PIT

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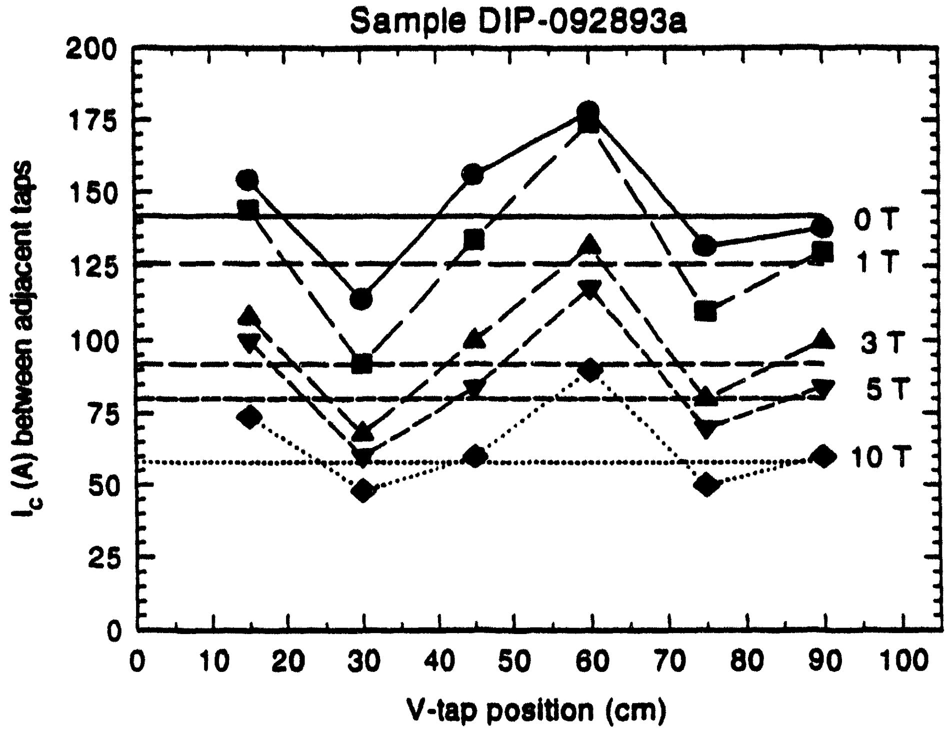
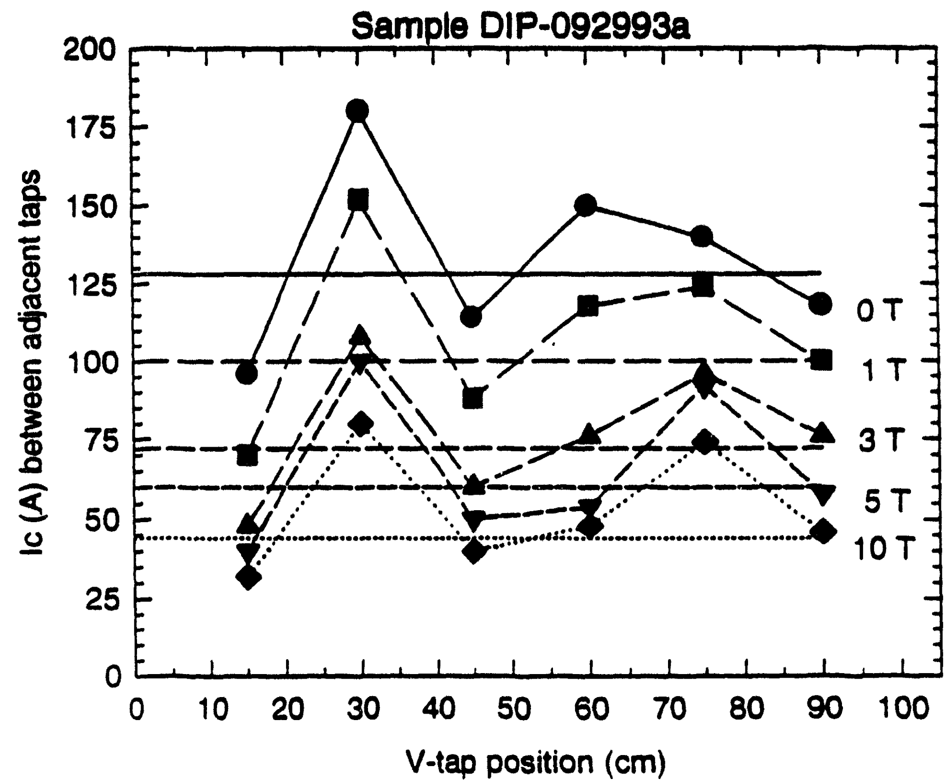


Sample DIP-092893a
I_c (A) between adjacent taps
V-tap position (cm)
0 T
1 T
3 T
5 T
10 T



Sample DIP-092993a
Ic (A) between adjacent taps
V-tap position (cm)
0 T
1 T
3 T
5 T
10 T

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Why does Jc decrease with longer length?

1. Macrostructural Limitations
   - Cracks in the ceramic:
     can result from stresses: mechanical, electromagnetic, thermal
   - Voids in the ceramic:
     can result from improper or irregular compaction, gas evolution during heat treatment, additional densification upon melt/recrystallization cycle
   - Ceramic layer non-uniformities:
     variations in the PIT core thickness or morphology, variations in the dip-coated layer thickness

2. Microstructural Limitations
   - Second phases: non-superconducting or low J_C phases
   - Grain size variations
   - Grain alignment variations

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POWDER PARAMETER ISSUES:
OST Experience

- Somewhat different requirements for PIT and dip coat

- PIT:
  - -powder sealed in tube prior to melt
  - -crucial to minimize impurities, especially carbon
  - -larger particles favor less contaminants from surface
  - -powder flow, packing characteristics are issues
  - -mechanical deformation of composite, including consolidated powder, is an issue

- DIP:
  - -ceramic slurry requires small particles for suspension
  - -surface area needs control
  - -slurry is routinely milled, so particle size changes
  - -organics can be burned off

POWDER PARAMETER ISSUES:
Present OST View

Parameter	General	DIP	PIT
Size	-homogeneous -no strong agglomerates	-small (dispersion) -≤5 μm	-moderate distrib. -not big or small -5 to 15 μm
Shape	-platelets aid mechanical texturing	-platelets if rolling -effect on coverage?	-prefer platelets
Surface Area		-significant for slurry -need reproducible batch to batch	-prefer low to minimize agglomeration, surface impurities
Composition	-congruent melt would be an advantage -not optimized, need to vary for best post melt phase content	-prefer Bi rich	-lit. evidence that Ag additions reduce 2201 formation
Impurities	-minimize		-carbon problem
Phase Purity	-experience suggests not required for 2212 since melting and recrystallizing		
Additives	-seek stability of 2212 phase, maximum volume % after melt		

Dip Coating

General Observations Regarding Coating Process

- Factors affecting coating thickness :
  - -slurry viscosity
  - -tape speed

- Factors affecting uniformity of thickness:
  - -degree and stability of powder dispersion in slurry
  - -control of tape speed during coating

- Range of thicknesses obtained as coated:
  15µm to 225µm

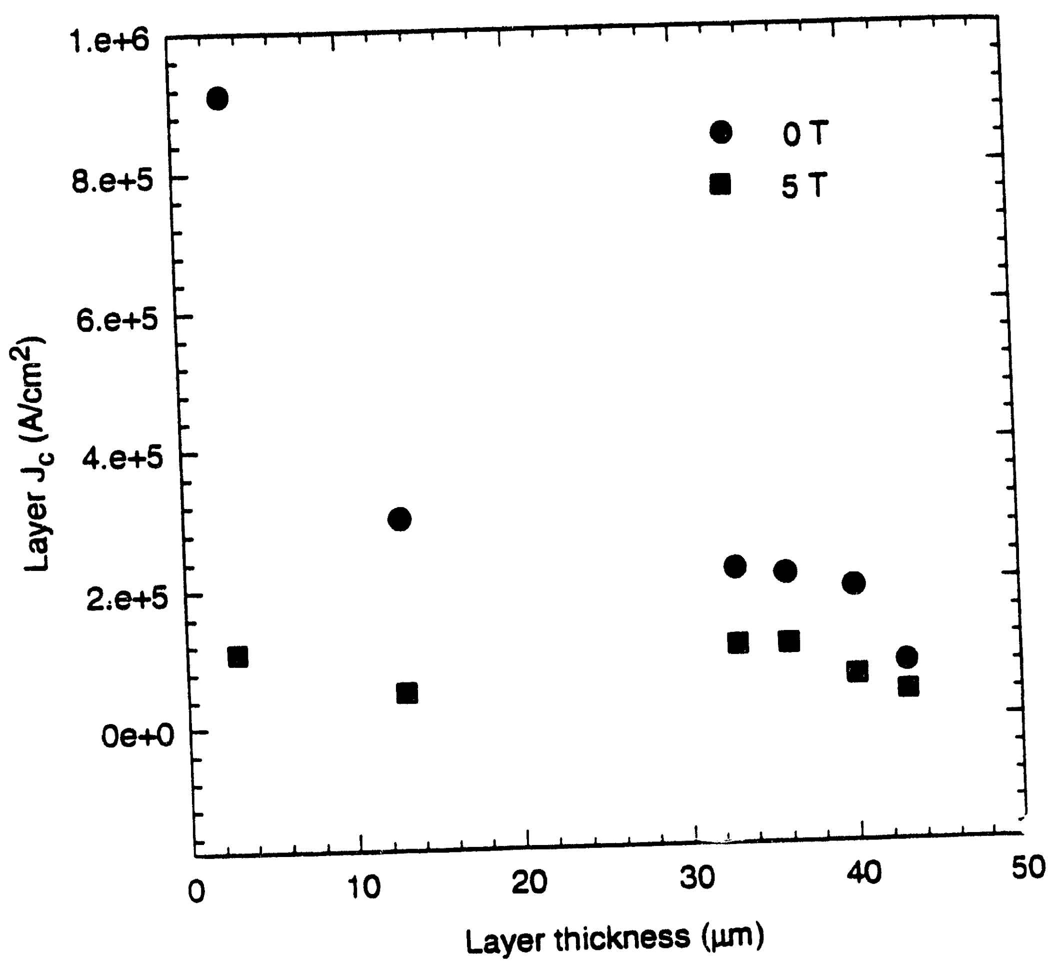
General Observations Regarding Heat Treatment

- Temperature control is critical: partial melt, no flow

- Control of composition during melt is an issue (particularly Bi)

- Grain growth appears important for good texture

Dip coat: Layer Jc vs. Layer Thickness



Long Length Production of HTS Composite Conductors Made by a Metallic Precursor Process

Larry Masur
American Superconductor Corporation

American
Superconductor
CORPORATION

Acknowledgments

American Superconductor

Alex Otto, Derek Daly, Eric Podtburg,
Chris Craven

Inco Alloys International

Gaylord Smith, Jack deBarbadillo, Jon Poole,
John Weber, Arun Watwe

Partial Support:

Inco Alloys International
Oak Ridge National Laboratory

American Superconductor CORPORATION

Outline

- Metallic precursors
- Long Length Conductor Properties
- Demonstration coil
- Opportunities for Development

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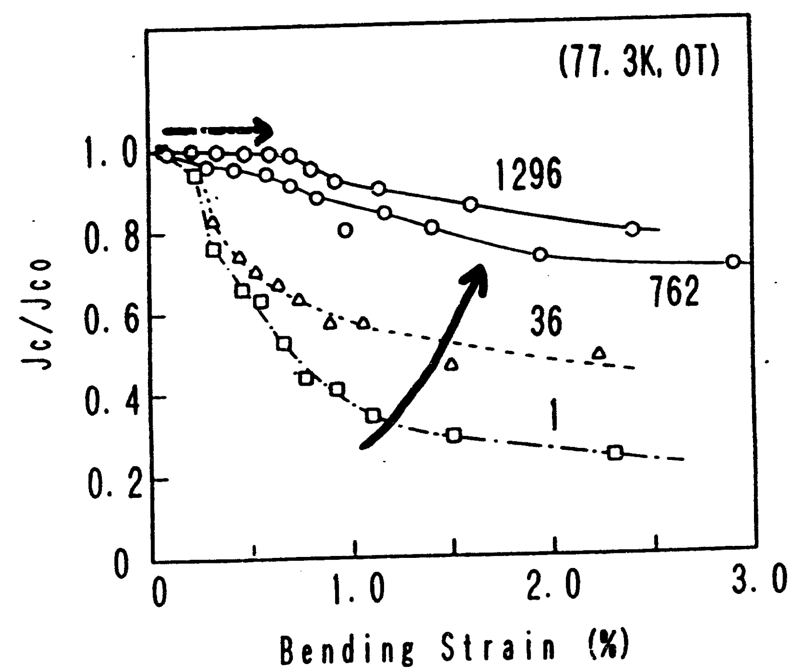
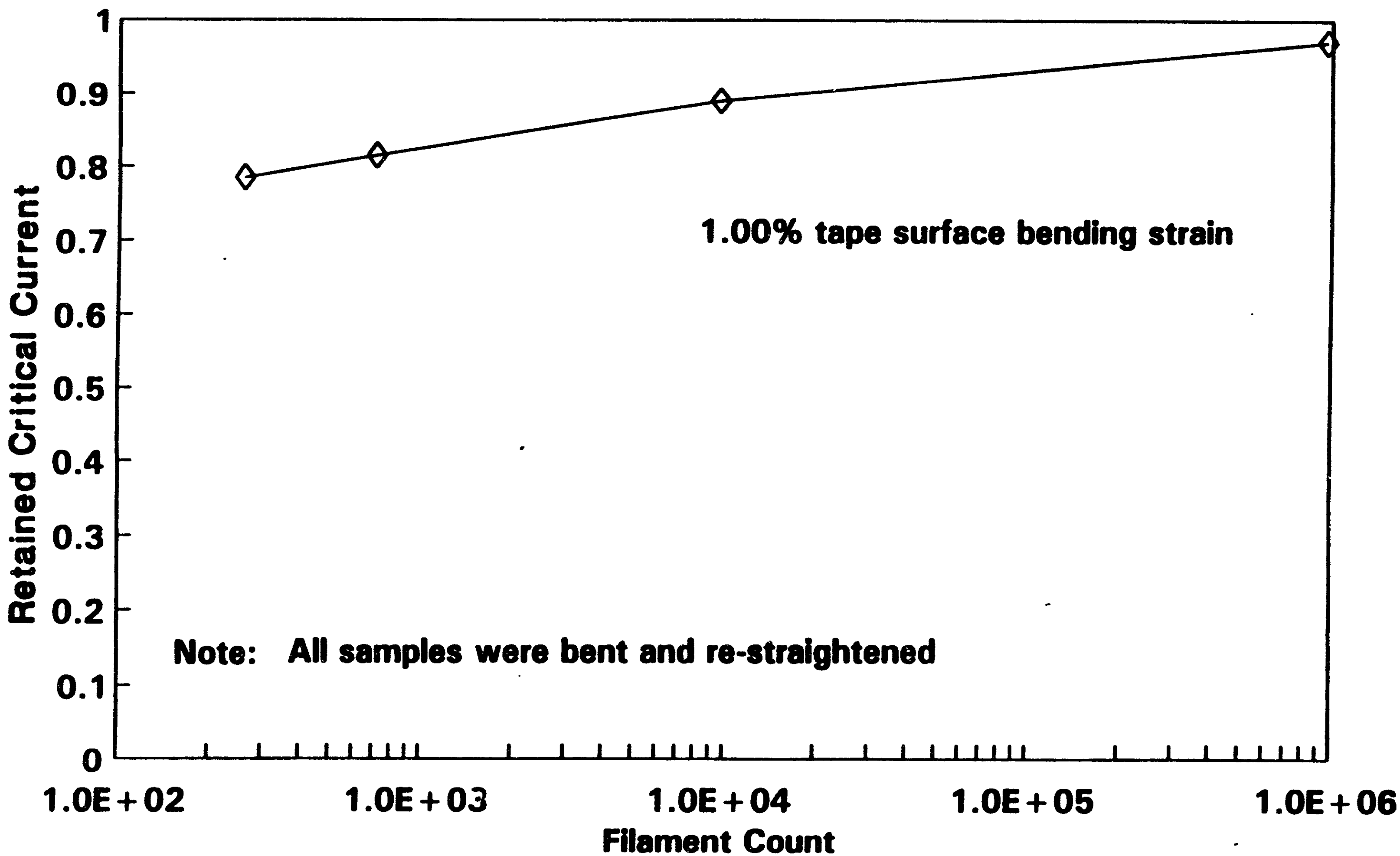
Mechanical Properties of HTS Composite Conductors



from Sato et al., IEEE Trans. Mag., 27, 1231, 1991.

Flexibility of Metallic Precursor Multifilamentary Composite Conductors



Metallic Precursor Conductors

- Bi-2223
- 361 filament composite conductor
- 18% fill factor
- 80 m lengths
- Conductor inventory for ORNL coil (to be completed in March, 1994)

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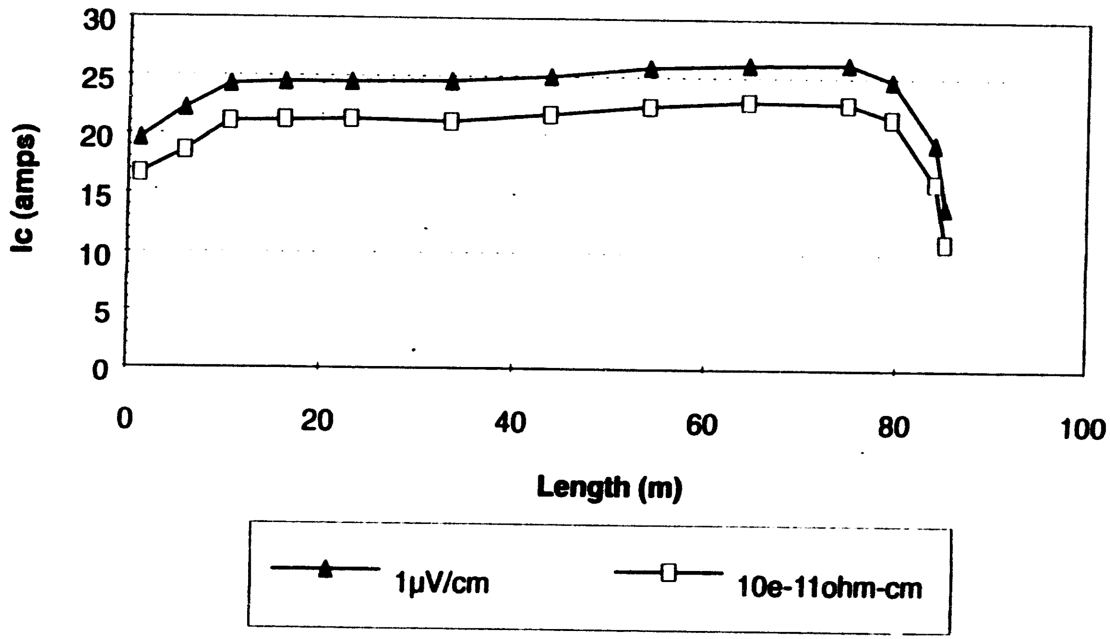
Uniformity Within Wire



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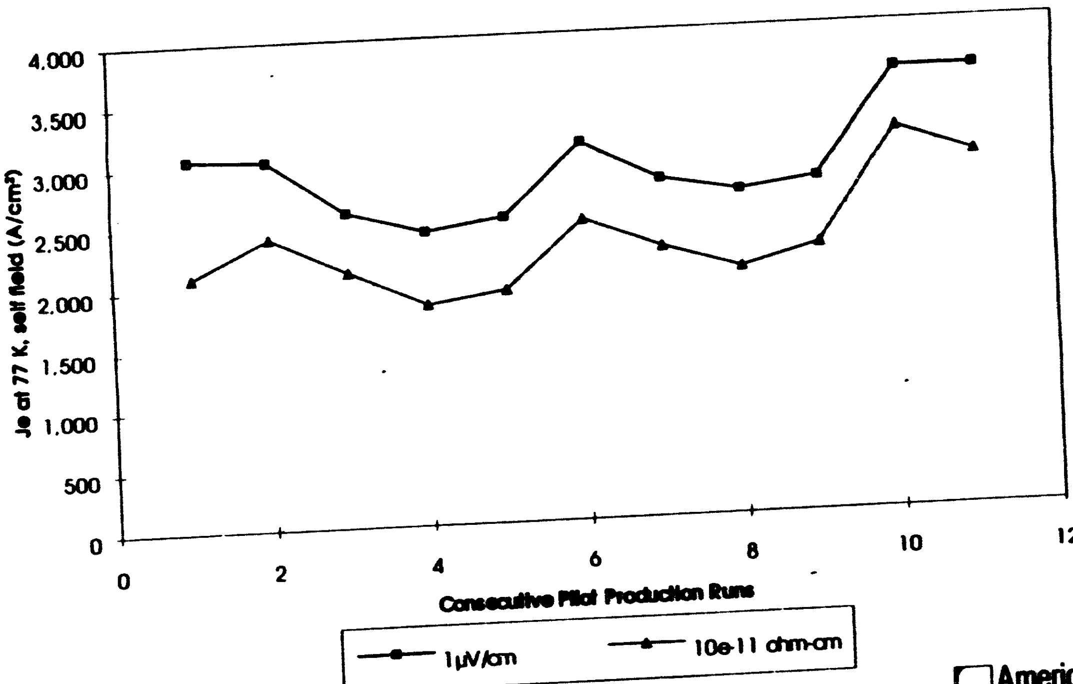
Conductor Performance (700 m total conductor)



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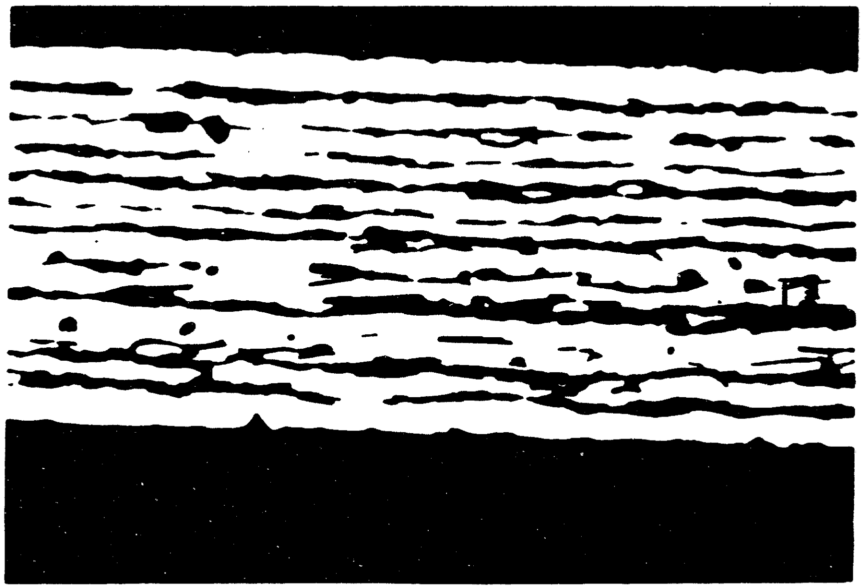
Microstructure of Metallic Precursor Composite Conductor



American Superconductor Corporation

Coil Properties at 4.2K
1μV/cm, including all joints
React and Wind

Outsert (partial completion of ORNL coil)

conductor length	310 meters
inner diameter	2.54 cm
bend strain @ ID	0.6%
field strength	0.85 Tesla

Insert

conductor length	6 meters
inner diameter	0.8 cm
bend strain @ ID	1.9%

Assembly

Ic	60.5 A
Field strength	1.02 Tesla

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Conclusions

The Metallic Precursor technology is an attractive alternative to OPIT for fabricating long lengths of conductor.

- Scale up to long lengths is relatively straightforward, at least for Jc's up to 20kA/cm²
- Within wire and run-to-run uniformity is quite good
- Given the present wire microstructures, there is enormous headroom for improved performance

American Superconductor CORPORATION

Opportunities for Development

- The Metallic Precursor technology should be pursued equally with OPIT.
- For both technologies the critical wire development issue is:

critical current density

→ understanding the current limiting mechanisms (microstructure-property relationships)

American Superconductor CORPORATION

Multifactor Experimental Design Addressing Thermomechanical Processing of Wire

DOE HTS Wire Development Workshop
Feb. 16–17, 1994
St. Petersburg, FL

LANL STC Team
J. Bingert (MTL-6)
R. Beckman and R. Picard (TSA-1)

Objectives

- Estimate Main Effects of Parameters
- Elucidate Interactions between Factors
- Determine Major Sources of Variance
- Provide Framework for Process-Structure-Property Causality
- Solidify Multidisciplinary Team

Design Considerations

- Define Parameters of Interest
  - Team Approach
- Anticipate Possible Interactions
- Determine Levels
- Response = Jc

Experimental Design

- Fractional Factorial
  - Blocked Design
  - Drawback
    - o Confounding Loses Higher Order Interactions
  - Benefit
    - o Reduce No. of Treatments to 120 + 58
- Incorporates Replicates–Estimate Variance
- All Main Effects and Most Two-Factor Interactions Remain Estimable

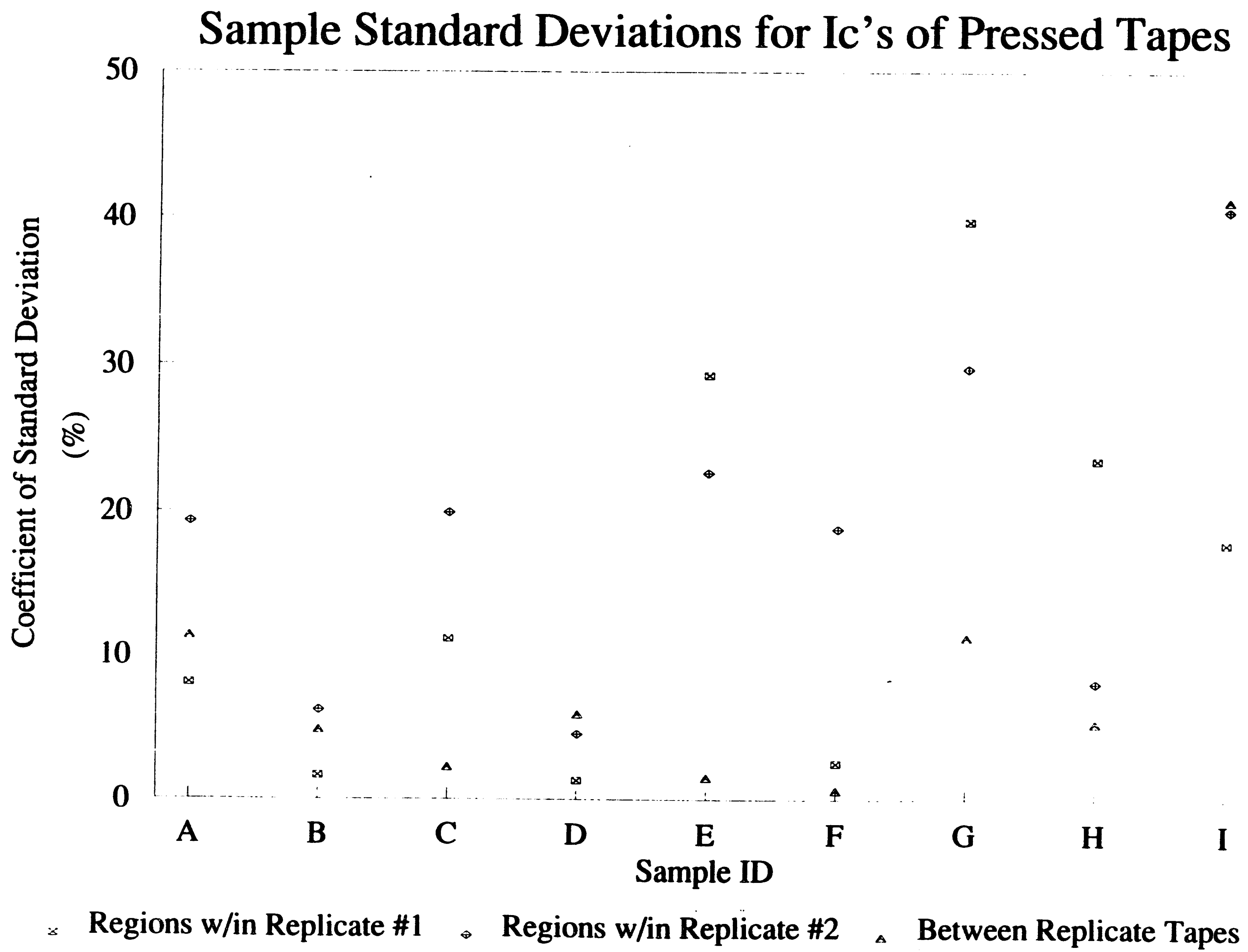
TABLE OF POSSIBLE TWO-FACTOR INTERACTIONS

	P	CT	SP	SR	T_1	t_1	R_1	T_2	t_2	R_2
P										
CT					X	X	X	X	X	X
SP										
SR										
T_1		X				X	X	X		
t_1		X			X		X		X	
R_1		X			X	X				
T_2		X			X				X	X
t_2		X				X		X		X
R_2		X						X	X	

TABLE OF FACTORS AND LEVELS

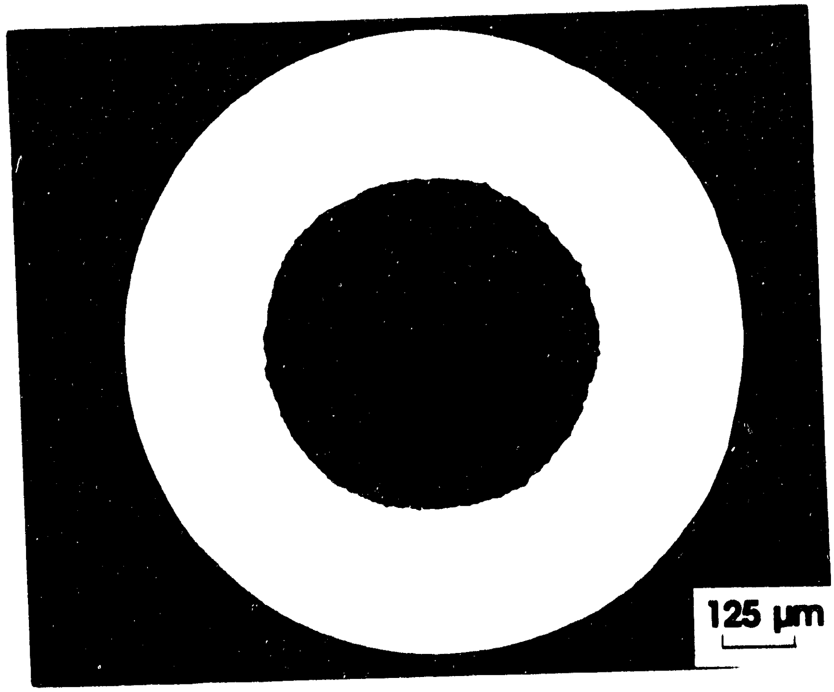
Level→ Factor↓	+	0	-
Packing Method (P)	CIP	-	Hand Pack
Core Thickness (CT)	60%	-	20%
Strain Path (SP)	Wide	-	Narrow
Strain Rate (SR)	10^3 sec^{-1}	-	10^2 sec^{-1}
Temperature-1 (T_1)	827°C	820°C	813°C
Time-1 (t_1)	48 hrs	-	24 hrs
Inter. Reduction (R_1)	30%	15%	5%
Temperature-2+3 (T_2)	827°C	820°C	813°C
Time-2 (t_2)	96 hrs	-	48 hrs
Final Reduction (R_2)	30%	15%	5%

2^6 x 3^4 Treatments for Full Factorial

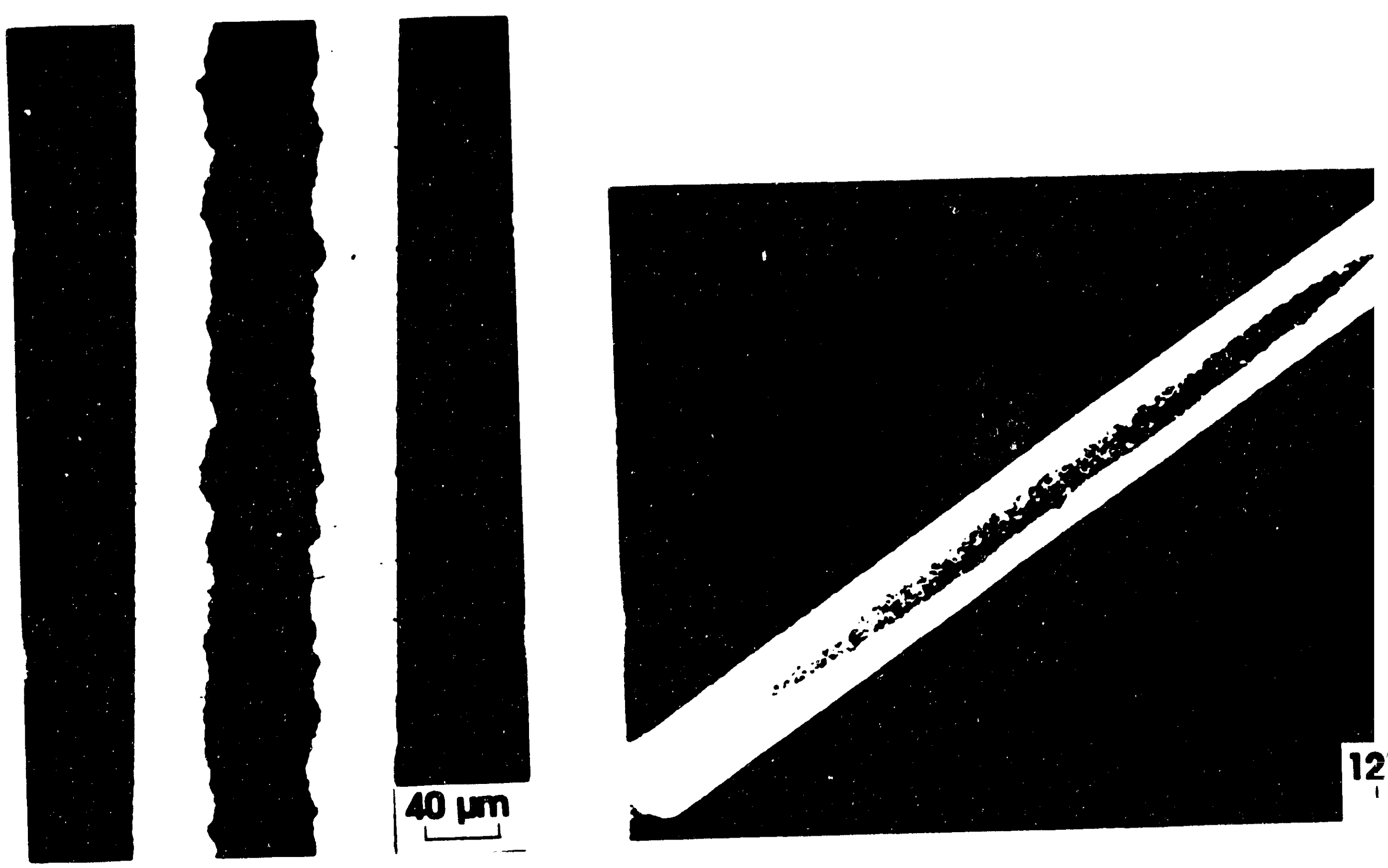


Sample Standard Deviations for Ic's of Pressed Tapes
50
40
30
20
10
0
Coefficient of Standard Deviation
(%)
A
B
C
D
E
F
G
H
I
Sample ID
Regions w/in Replicate #1
Regions w/in Replicate #2
Between Replicate Tapes

4N Ag - HP



1 mm (.04") Wire

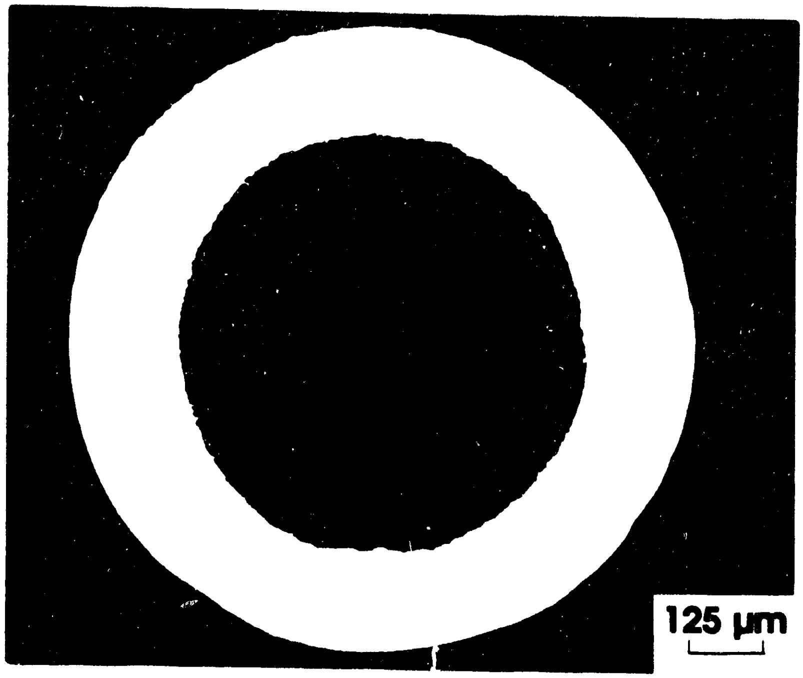


Longitudinal

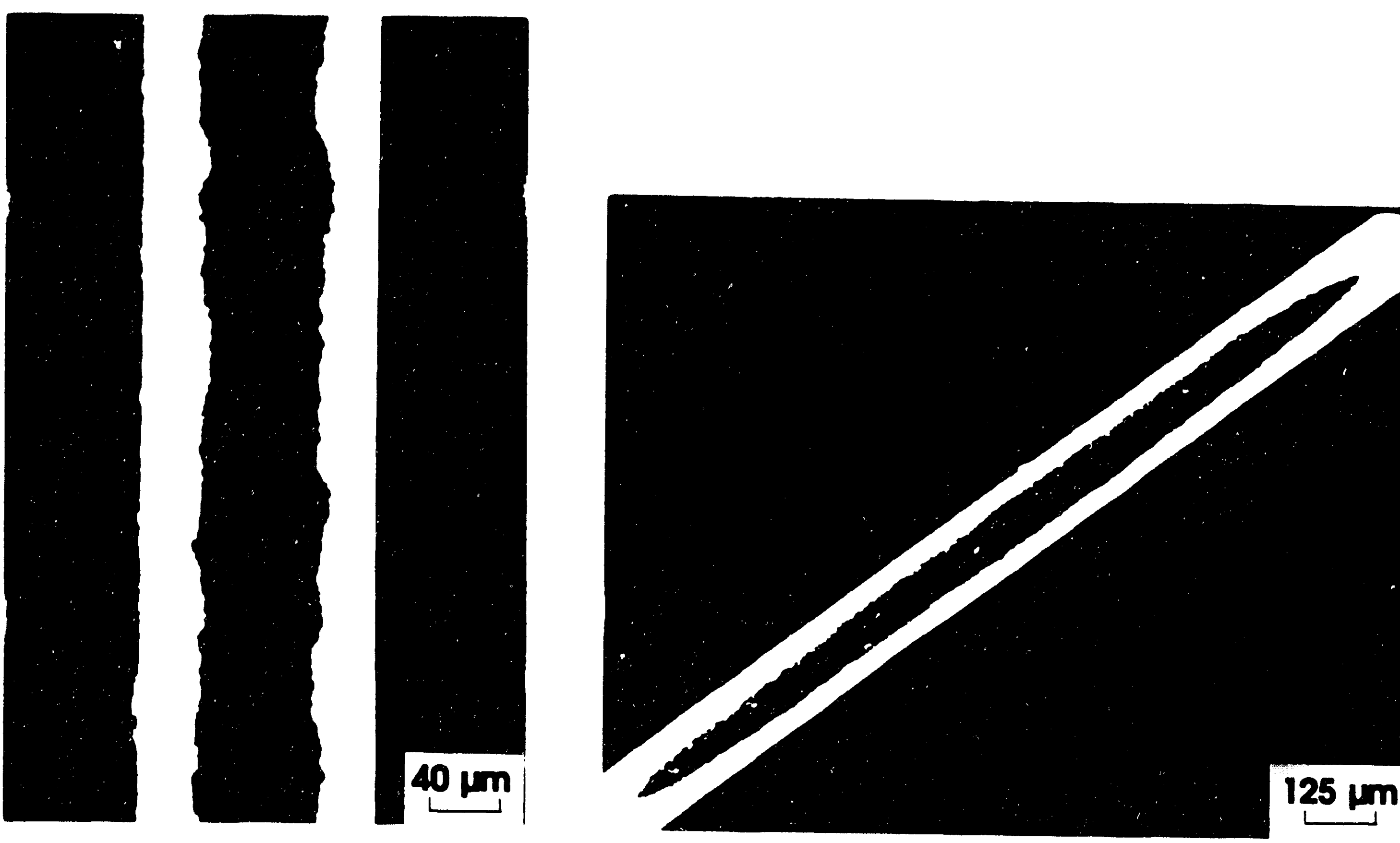
Transverse

150 µm (.006") Tape

4N Ag - CIP



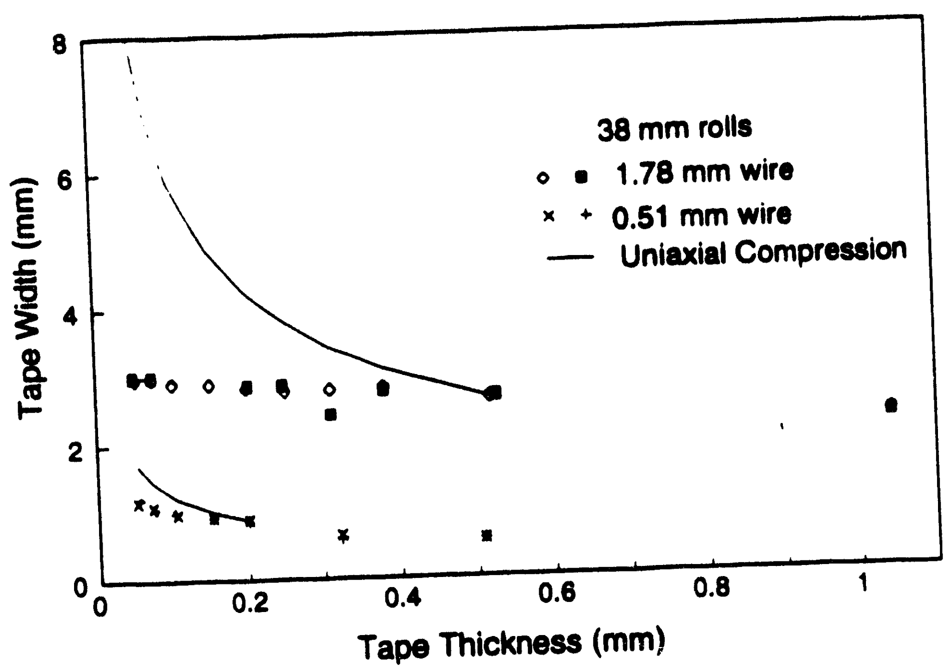
1 mm (.04") Wire

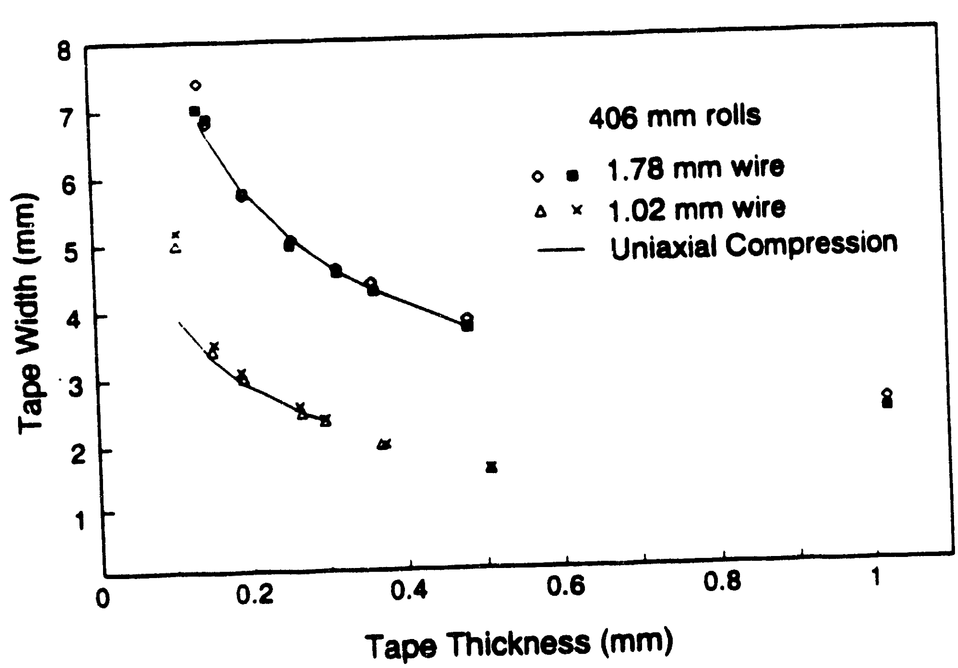


Longitudinal

Transverse

150 μm (.006") Tape


38 mm rolls
1.78 mm wire
0.51 mm wire
Uniaxial Compression
Tape Width (mm)
Tape Thickness (mm)
0
2
4
6
8
0.2
0.4
0.6
0.8
1


406 mm rolls
1.78 mm wire
1.02 mm wire
Uniaxial Compression
Tape Width (mm)
Tape Thickness (mm)
1
2
3
4
5
6
7
8
0
0.2
0.4
0.6
0.8
1

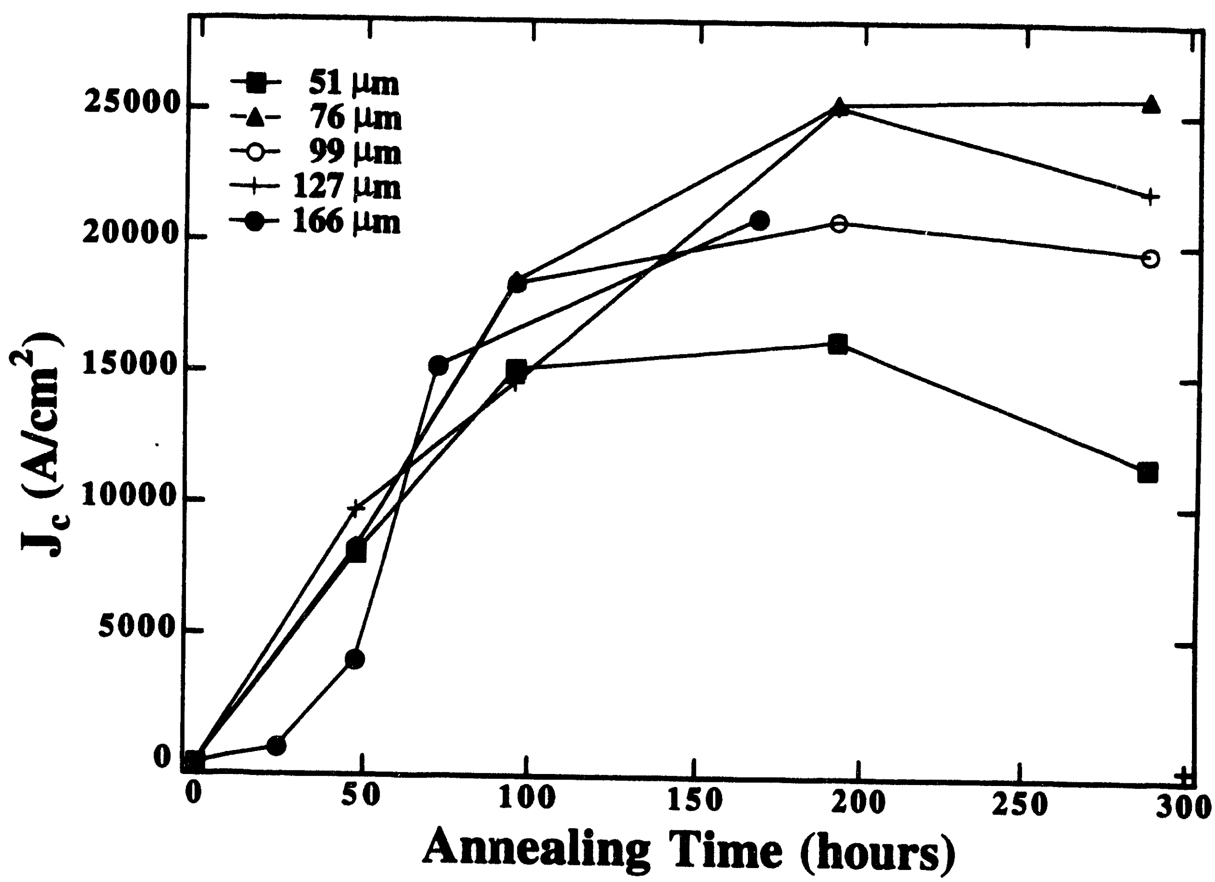
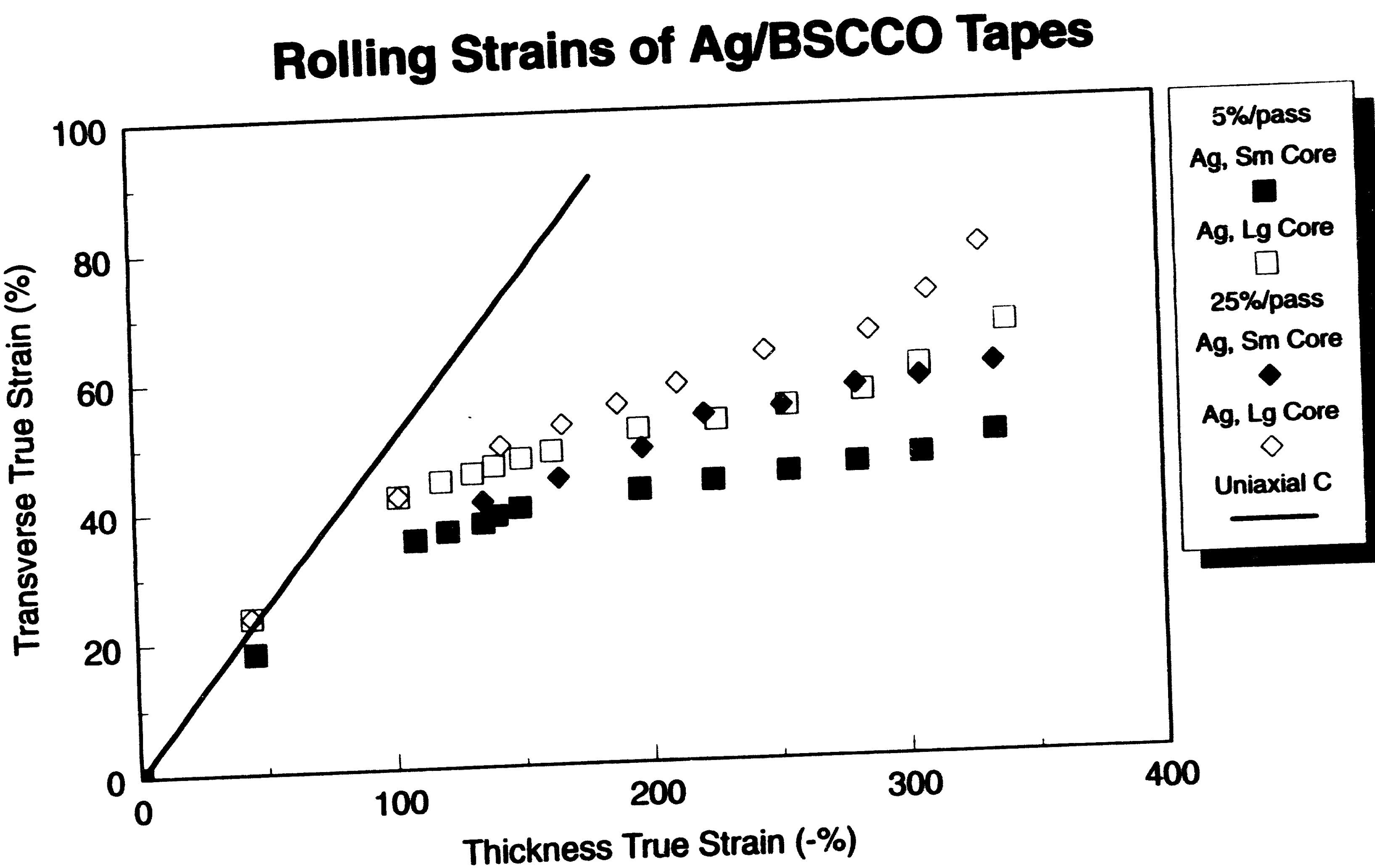
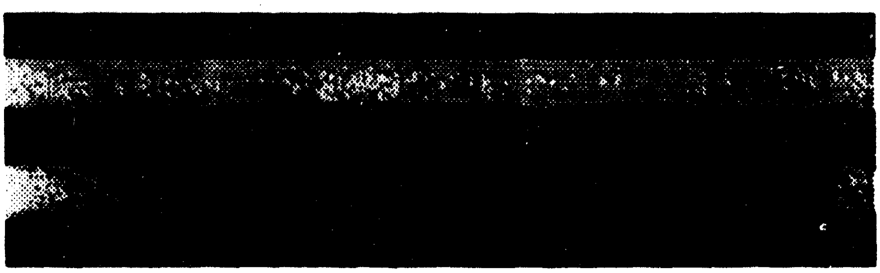


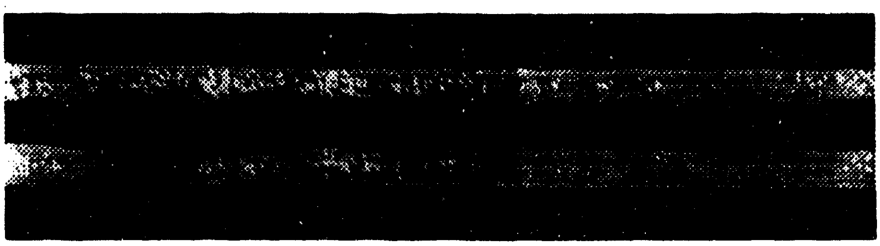
Fig. 5. Smith *et al.*


Rolling Strains of Ag/BSCCO Tapes
Transverse True Strain (%)
Thickness True Strain (-%)
0
20
40
60
80
100
0
100
200
300
400
5%/pass
Ag, Sm Core
Ag, Lg Core
25%/pass
Ag, Sm Core
Ag, Lg Core
Uniaxial C

125 um composite thickness



100 um



75 um

50 um

50 um

Longitudinal Sections from As-Rolled WB-1

ISSUES IN BULK PROCESSING OF POWDERS*

U. (Balu) Balachandran

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Argonne National Laboratory
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Collaborators:

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W. Ellingson
K. Goretta
M. Lanagan
V. Maroni
R. Poeppel

*Work supported by the U.S. Dept. 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.

ISSUES

*Carbon

*Stoichiometry

*Phase assemblage

*Flowability/Packing
(morphology)

*Batch size (scale-up)

Carbon Source

*Precursor material

*Milling/mixing process
(acetone, alcohol, etc)

*Containers

*Cleaning solution

*Atmospheric contamination

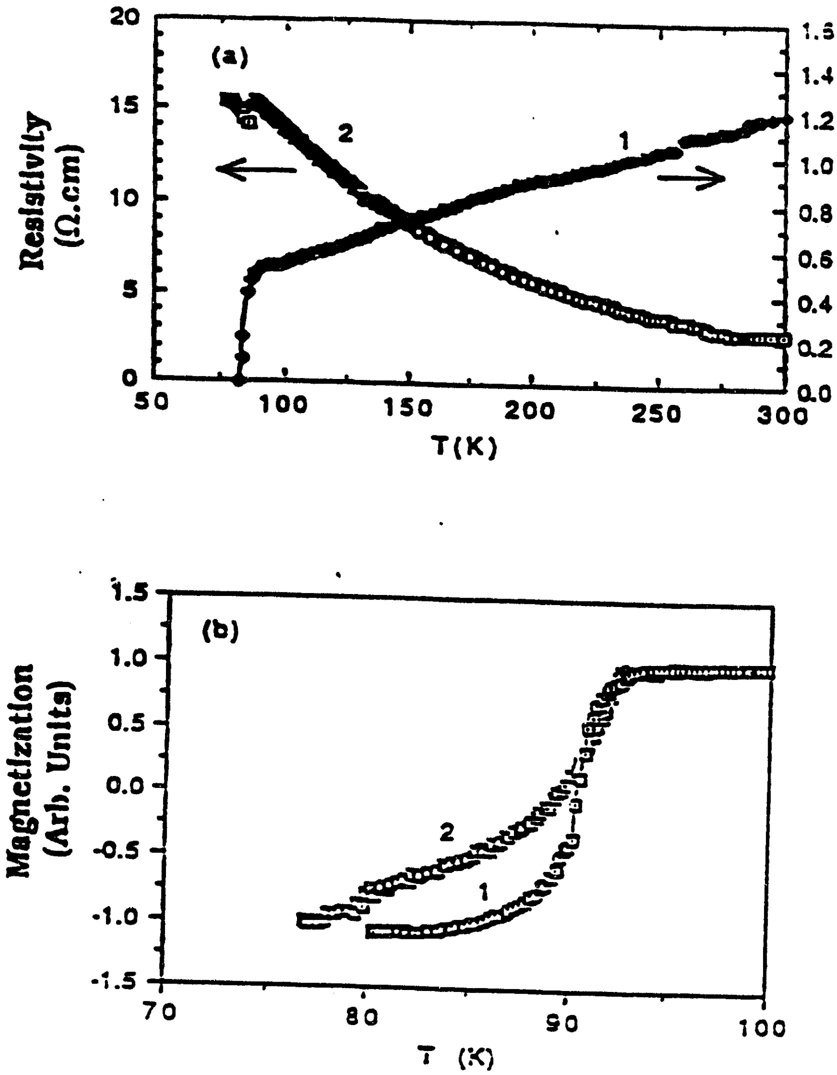


Fig. 1 (a) Resistivity vs temperature curves. and (b) magnetization vs temperature curves are shown for the samples sintered at 940 °C in pure O_2 marked by 1 and in 0.5% CO_2/O_2 marked by 2.

Mater. Lett. 9(10), 34F (June 1990).


158 nm

Carbon Contents
(Effect of Milling)

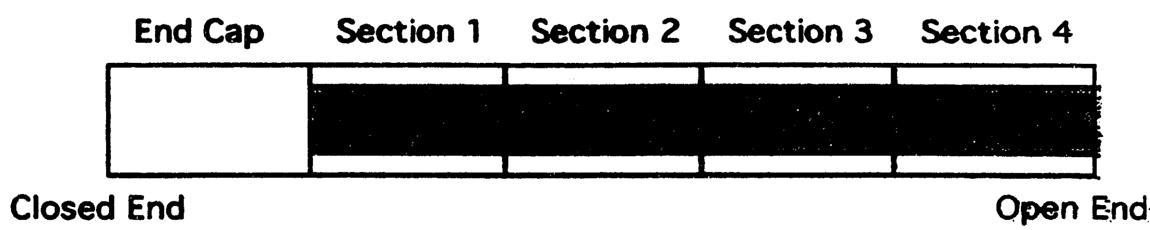
Sample	C-content (ppm) Before Milling	C-content (ppm) After Milling
400-92-1 SSC 2223 Calcined 1x	99, 98	1142
400-92-2 SSC $CaCuO_2$ Calcined 2x	148, 217	1406
381-55 SSC 2212 Calcined 1x	62	not measured
381-57 SSC 2212 Calcined 2x	66	not measured
381-58 SSC 2212 Calcined 3x	81	not measured
400-97 SSC 2212 Calcined 1x	101	not measured

Reduction of Carbon Contents

100°C/h → 720°C
3h @ 720°C
120°C/h → RT
2–3 torr flowing O_2
Powder in open boat

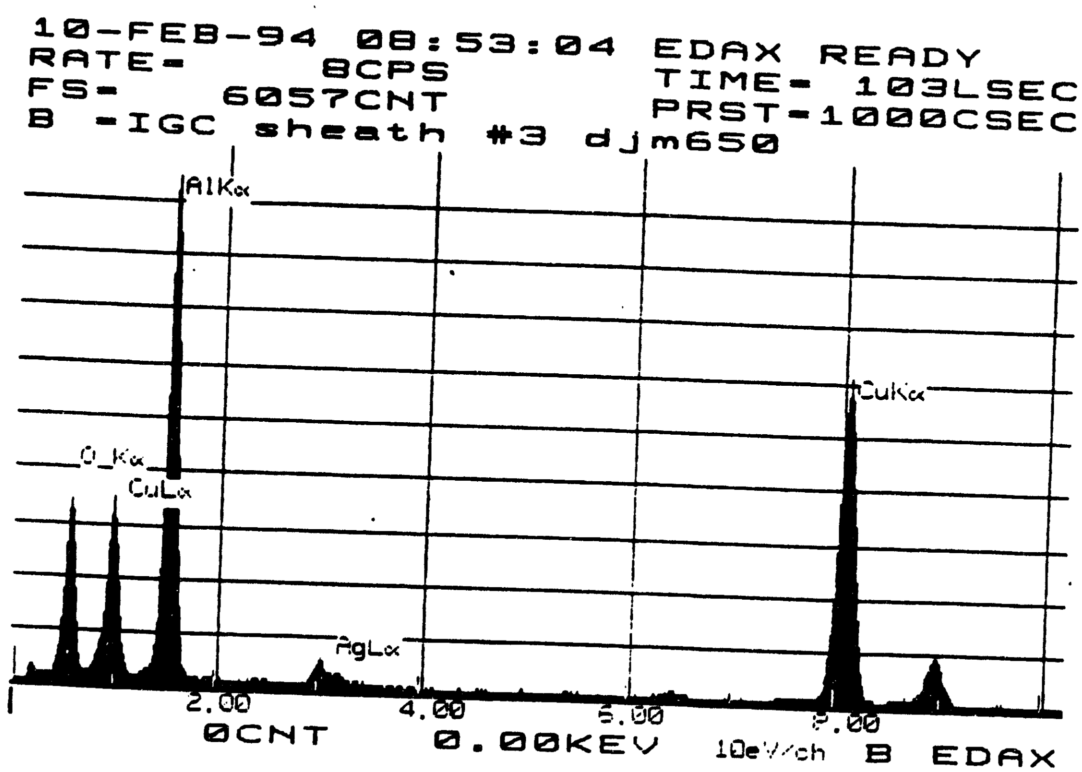
Sample	C–content (ppm) Before Anneal	C–content (ppm) After Anneal
400–114–1 (ANL "2223")	not measured	117
400–114–2 (ANL "2223")	5176, 5098	216
400–89–2 (ANL "2223")	2689	384

Low–T Anneal
(Powder inside Tube)

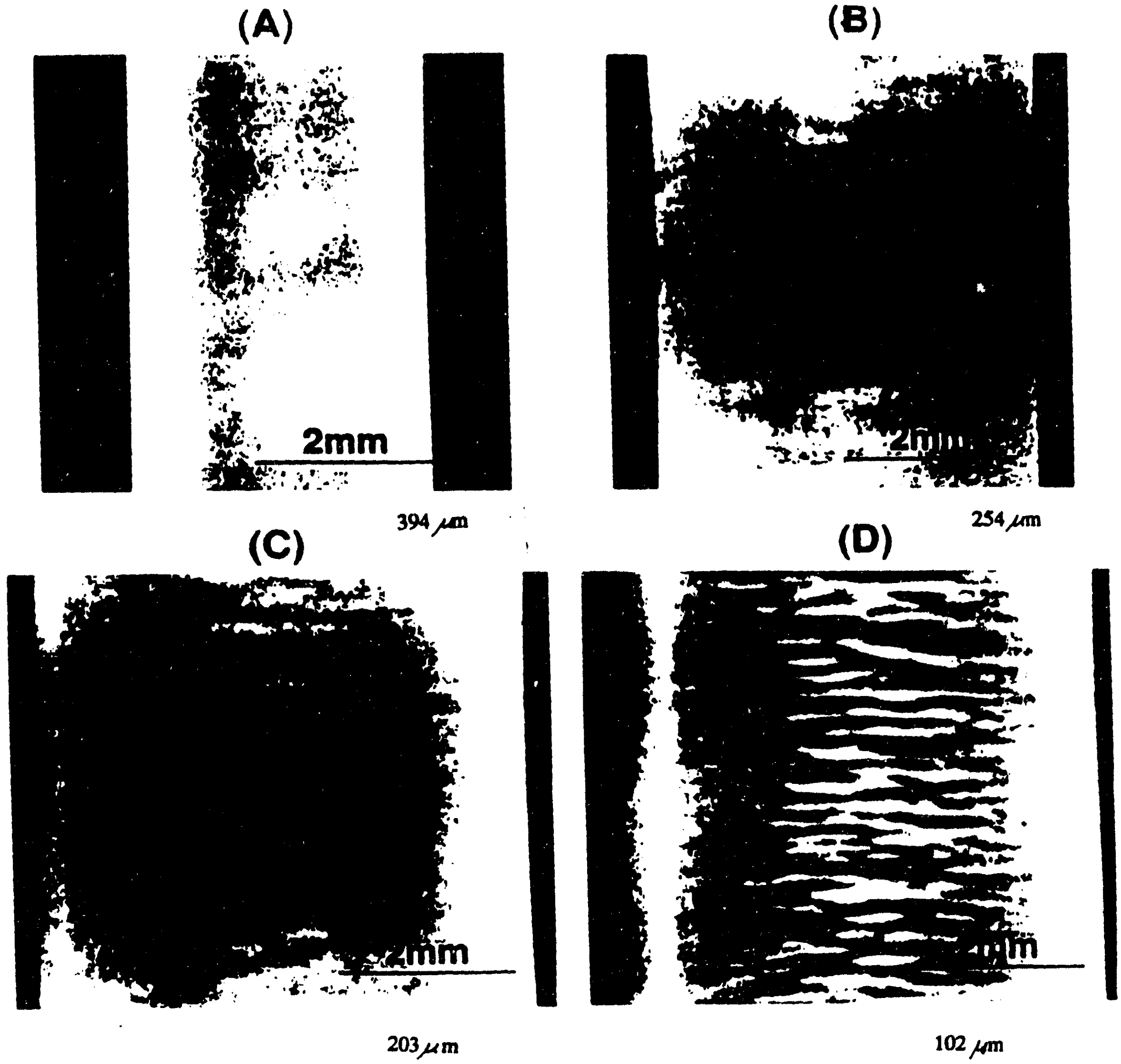


	32% Packing Density 100°C/h → 720°C 3h @ 720°C 120°C/h → RT 2–3 torr O_2	22% Packing Density 100°C/h → 660°C 20°C/h → 720°C 3h @ 720°C 120°C/h → RT 2–3 torr O_2
Powder	**C–Content (ppm)**	**C–Content (ppm)**
Original	3043, 3303, 3256	3043, 3303, 3256
Section 1	3532	2334
Section 2	3287	1489
Section 3	2942	708
Section 4	1501	Tube cut into three sections, not four

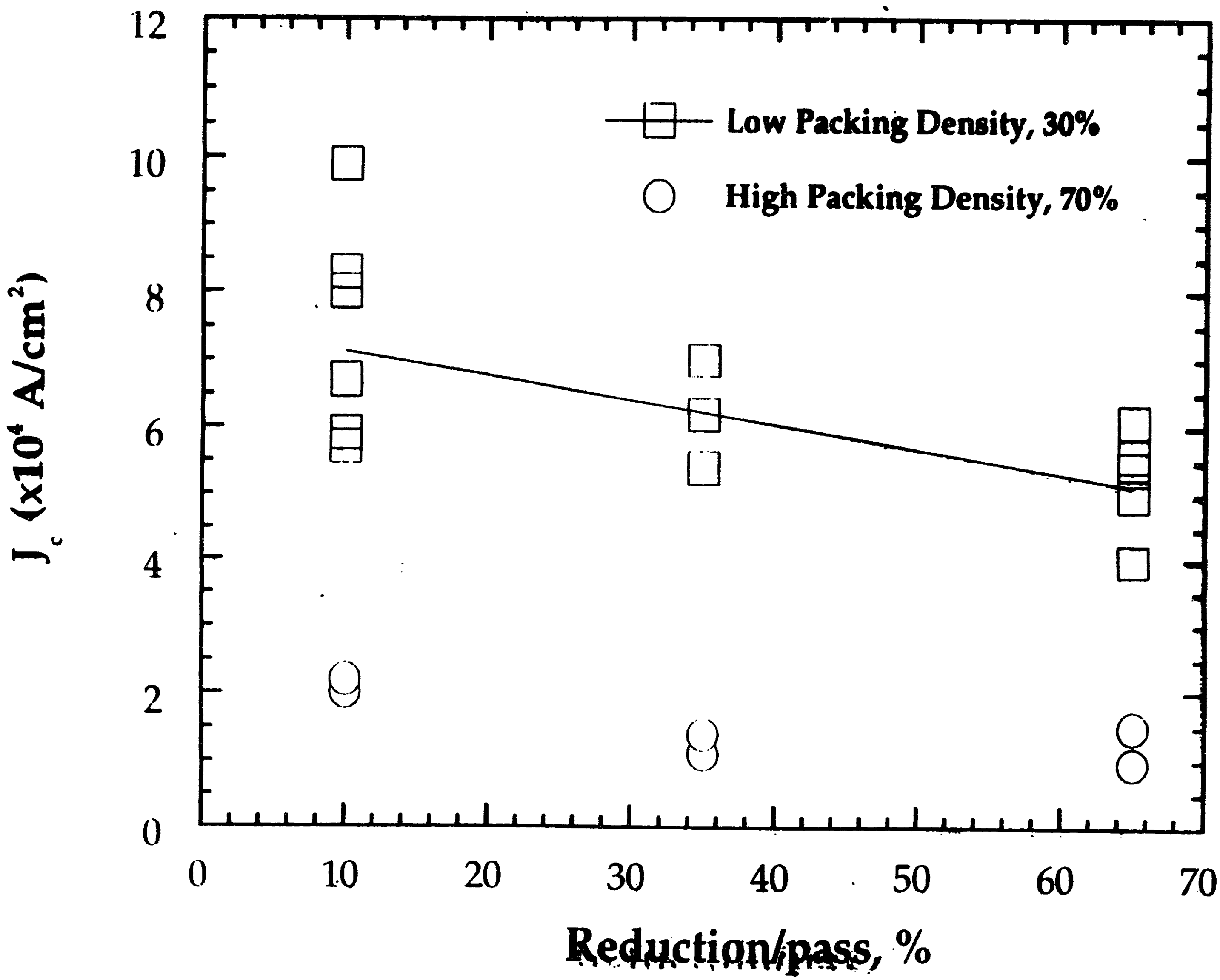
Sheath Material Showing Cu



Microfocus Digital X-Ray Images
Obtained Using Dual-Entry X-Ray Imaging Methods



Relation Between the Critical Current Density and Packing Density With Various Reduction/pass of Rolling (4.2 K, self field) of Ag-Clad BCSSO-2212 Tapes



SUMMARY

*Low-pressure, low-temp. anneal effectively reduces C-content

*Cu-migrates from the core into Ag-sheath (Cu excess "nominal" composition?)

*(Bi,Pb)-2212 and a Sr,Ca cuprate as precursor

*Easy flowing powder for continuous/automated packing to prepare billets (spray-drying?)

Improvement of Grain Connectivity in Thallium-based long Superconducting Tapes and Films

Zhifeng Ren, Chang An Wang & Jui H. Wang

NYSIS, SUNY/Buffalo

In collaboration with

Dean J. Miller, Argonne National Laboratory

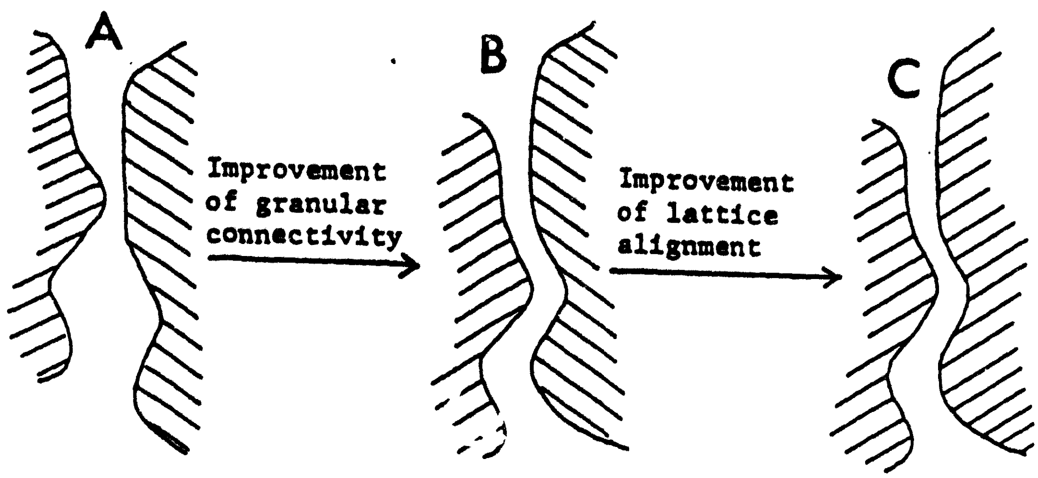
with assistance from:

Eiki Narumi
Mike Pitsakis
Gary Sagerman
Matt Michalski

Supported by: NYSERDA (via NYSIS)
UBF
DOE (via ANL)

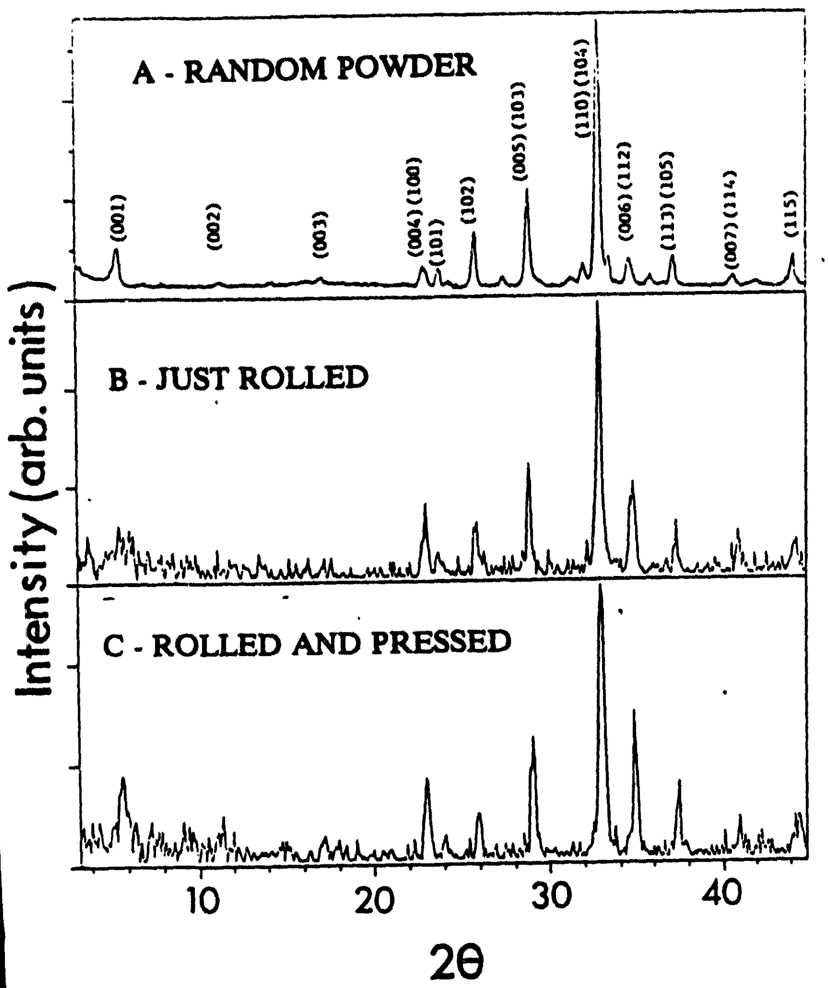
The J_c of long superconducting tapes is always limited by intergranular weak links:

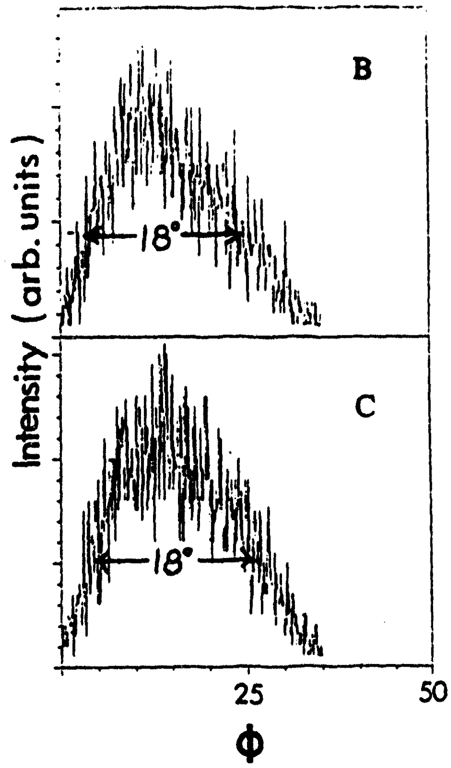
We can strengthen these weak links by improving granular connectivity which increases the area of close contact between adjacent grains, or by improving lattice alignment which is known to raise J_c in thin films.



For Tl-based tapes with similar lattice alignment as shown by X-ray diffraction, J_c can be raised by a large factor by improvement of granular connectivity via uniaxial compression.

Tapes with similar lattice alignment, but different granular connectivity (same material):





Sample	Fabrication	Jc (A/cm², 77 K)
(b)	Rolled, annealed 7.5 h at 840°C (0.122 mm)	13300
(c)	Rolled, annealed 2.5 h at 840°C pressed, annealed to 4.0 h again (0.122 mm→0.110 mm)	21500

Conclusion:

The deciding factor for achieving high J_c in bulk superconductors is intergranular conncectivity, not intergranular lattice alignment.

Enhanced formation of 1223 phase by partial replacement of Bi for Tl in in-situ synthesized silver-sheathed superconducting tape of $Tl_{1-x}Bi_xSr_{2-y}Ba_yCa_2Cu_3O_{9-\delta}$

Optimal formula by systematic study: $Tl_{0.78}Bi_{0.22}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_{9-\delta}$

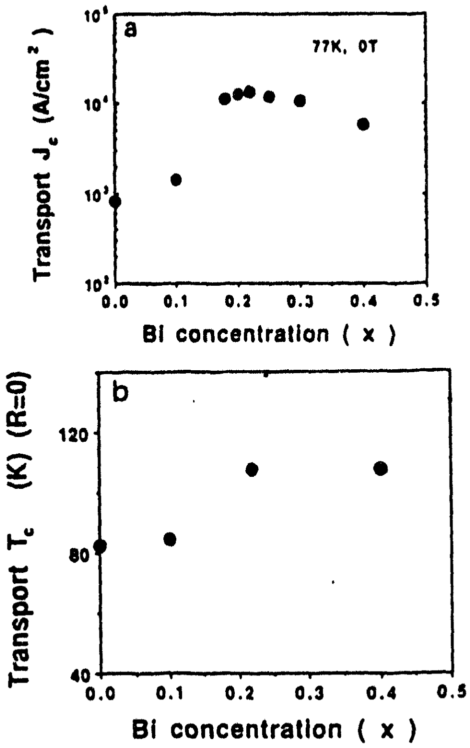


Fig. 2. Dependence of the transport J_c (77 K, 0 T) (a), and the transport T_c (b) on the Bi concentration in the in-situ synthesized silver-sheathed superconducting tapes of $Tl_{1-x}Bi_xSr_{1.6}Ba_{0.4}Ca_2Cu_3O_{9-\delta}$.

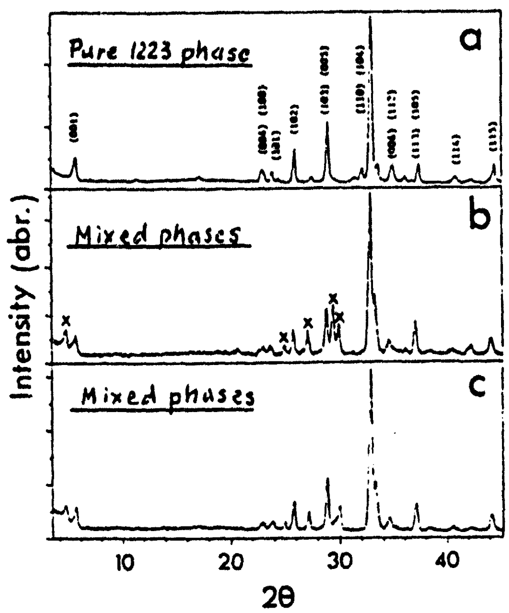


Fig. 3. X-ray powder diffraction patterns of pulverized pellets of (a) $Tl_{0.78}Bi_{0.22}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_{9-\delta}$, (b) $Tl_{0.5}Pb_{0.5}SrBaCa_2Cu_3O_{9-\delta}$ and (c) $Tl_{0.78}Bi_{0.22}SrBaCa_2Cu_3O_{9-\delta}$. All pellets were made by sintering at 880°C for 3.0–4.5 h in air and quenched in air at room temperature.

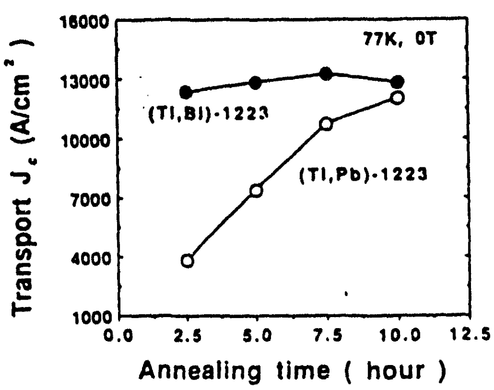


Fig. 4. Comparison of the effects of the annealing time on the transport J_c (77 K, 0 T) of the in-situ synthesized superconducting tapes of $Tl_{0.78}Bi_{0.22}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_{9-\delta}$ and $Tl_{0.5}Pb_{0.5}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_{9-\delta}$.

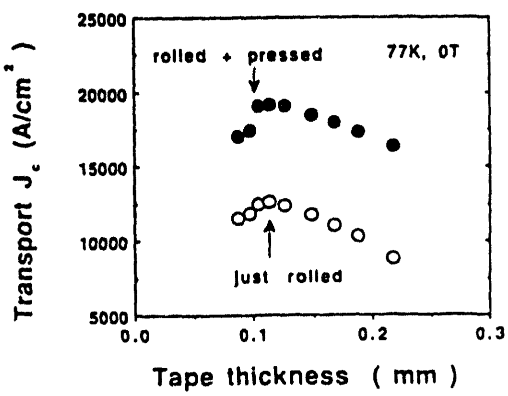


Fig. 5. The effect of the tape thickness and uniaxial hydrostatic compression on the transport J_c (77 K, 0 T) of in-situ synthesized silver-sheathed superconducting tapes of $Tl_{0.78}Bi_{0.22}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_{9-\delta}$.

Transport J_c reproducibility of in-situ synthesized silver-sheathed superconducting tapes of $Tl_{0.78}Bi_{0.22}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_{9-\delta}$ at 77 K (rolled only)

Sample	Total thickness (mm)	Total width (mm)	I_c (A)	J_c (A/cm²)
930111-1	0.125	2.0	7.60	12710
930112-2	0.124	2.0	7.81	13300
930114-1	0.125	2.0	7.55	12640
930114-2	0.126	2.0	7.40	12460
930115-1	0.124	2.0	7.55	12400
930116-1	0.124	2.0	7.60	12470
930117-2	0.126	2.0	7.65	12530
930125-5	0.127	2.0	7.60	12450
930216-2	0.124	2.0	7.77	12870
930217-1	0.125	2.0	7.89	12610
930217-2	0.123	2.0	7.56	12520
930402-2	0.124	2.0	7.48	12810
930402-4	0.124	2.0	7.48	12880
930404-2	0.124	2.0	7.48	12810
930405-2	0.124	2.0	7.25	12420
930405-5	0.124	2.0	7.68	13220

Transport J_c reproducibility of in-situ synthesized silver-sheathed superconducting tapes of $Tl_{0.78}Bi_{0.22}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_{9-\delta}$ at 77 K (rolled and uniaxially compressed)

Sample	Total thickness (mm)	Total width (mm)	I_c (A)	J_c (A/cm²)
930119-1	0.118	2.2	10.77	19200
930125-E	0.118	2.2	11.00	19300
930318-1	0.117	2.2	10.50	19000
930318-5	0.116	2.2	10.60	19200
930403-3	0.116	2.2	10.50	19000
930630-2*	0.110	2.2	12.00	21000

*Improved procedure

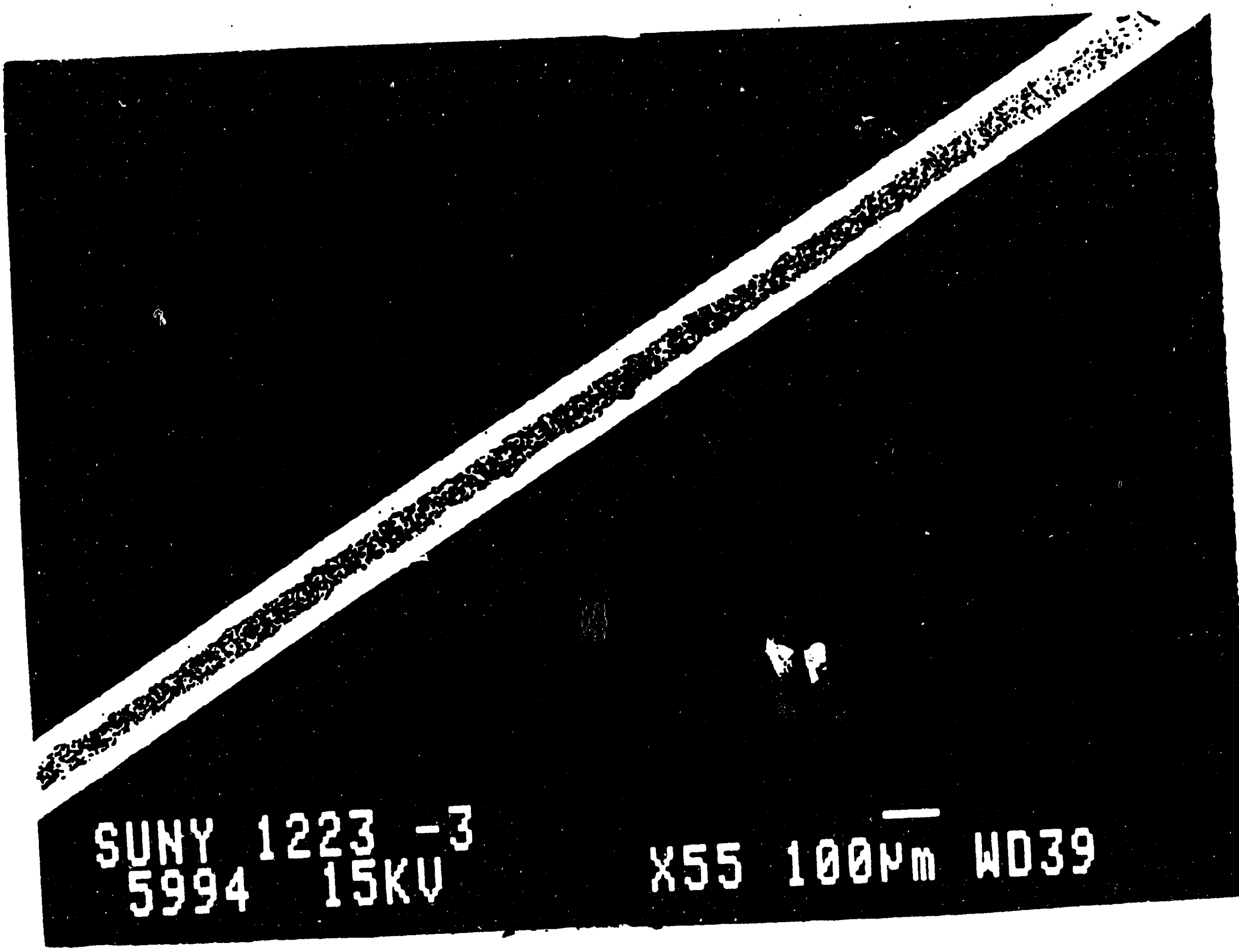
Criterion for the measurement of Jc:
$\Delta V = 1 \mu V$/total length (l' , up to l = 24 m.

The "rolled only" tapes can be bent into a 0.47-cm radius coil that still superconducts without further annealing.

The "rolled and uniaxially compressed" tapes are no longer as flexible.

Silver-sheathed $Tl_{0.78}Bi_{0.22}Sr_{1.6}Ba_{0.4}Ca_{2}Cu_{3}O_{9-\delta}$ tapes

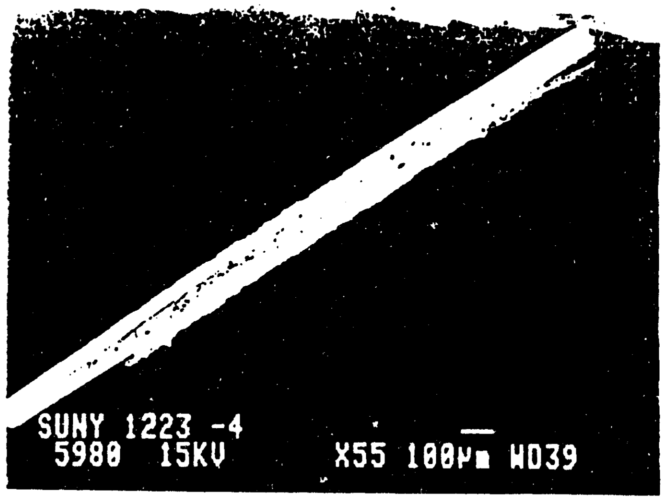
WIRE 3



No sausaging has ever been observed in these tapes.
(SEM pictures taken by D. Miller of ANL)

ɔngitudinal cross section WIRE 3

Transverse cross section WIRE 4

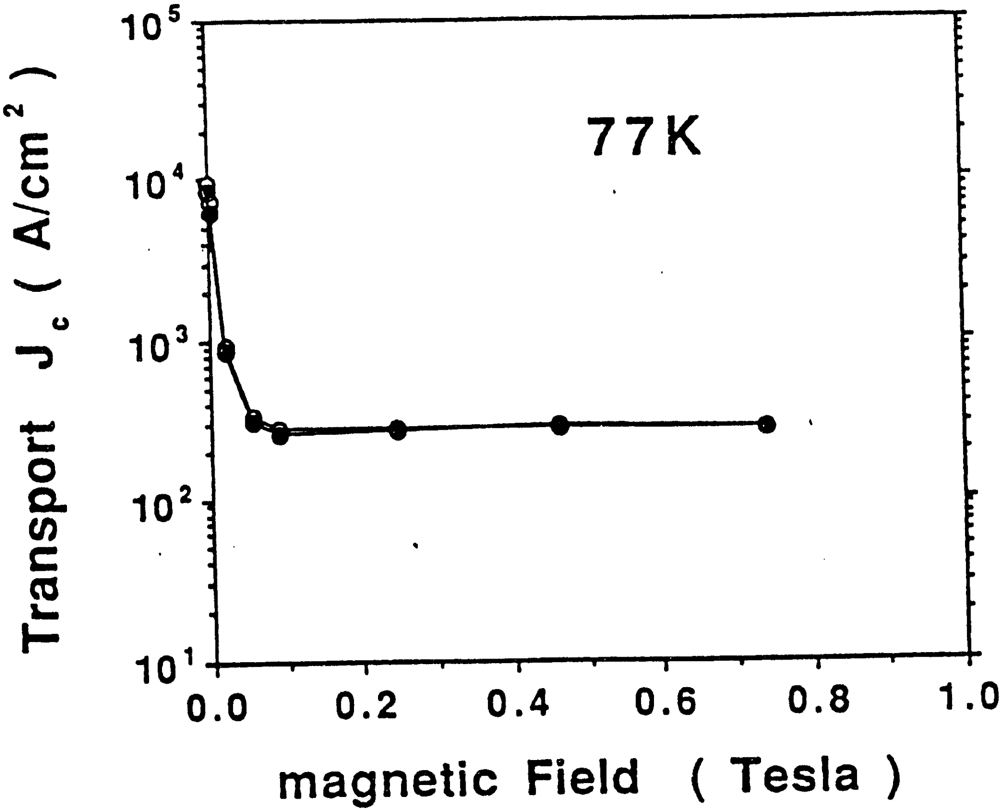


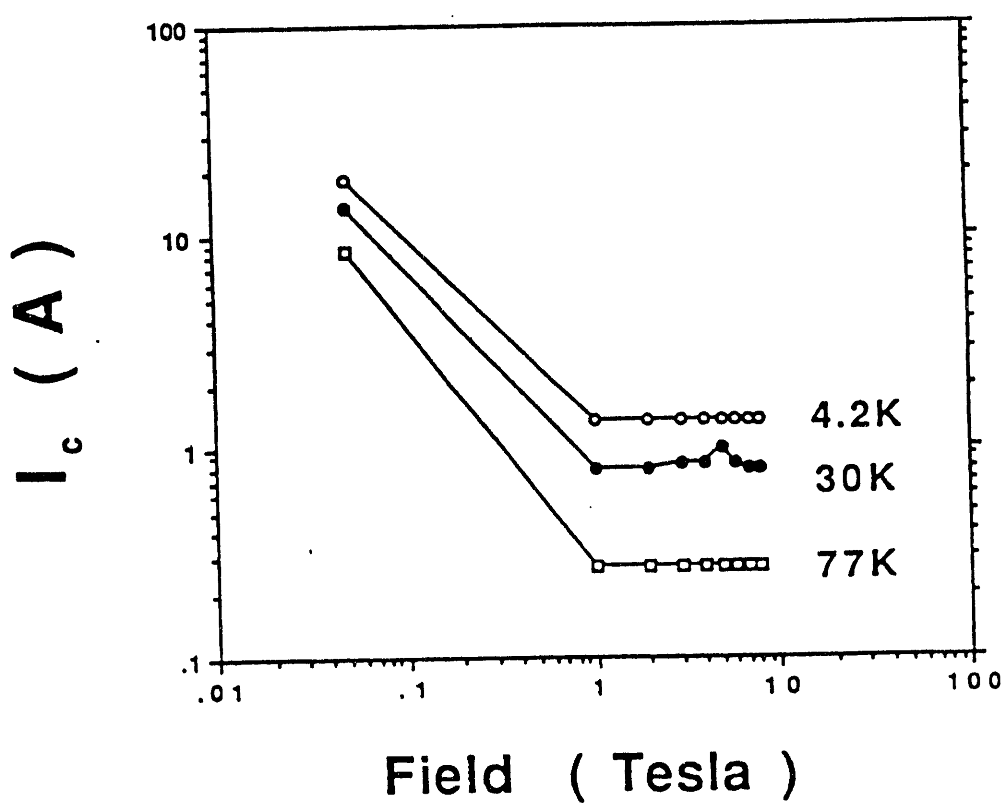
ed only

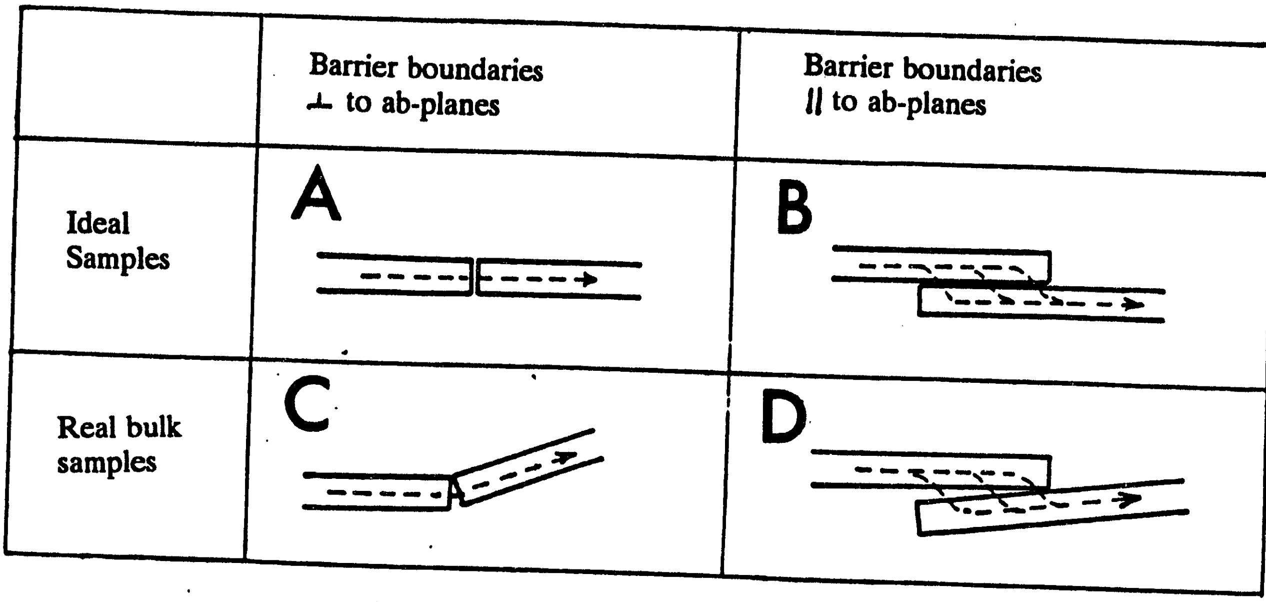
Rolled and then compressed

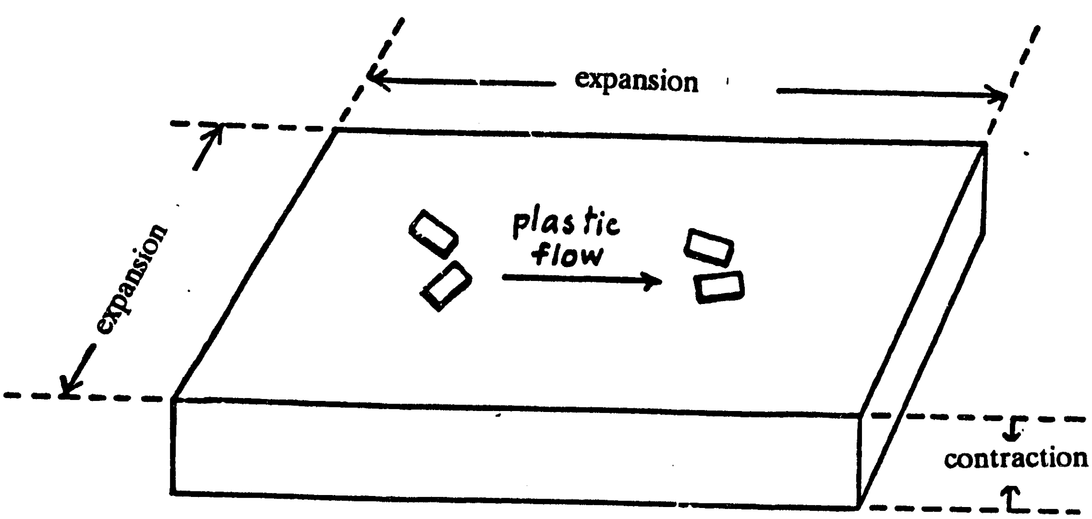
om for further improvement

Data from d615

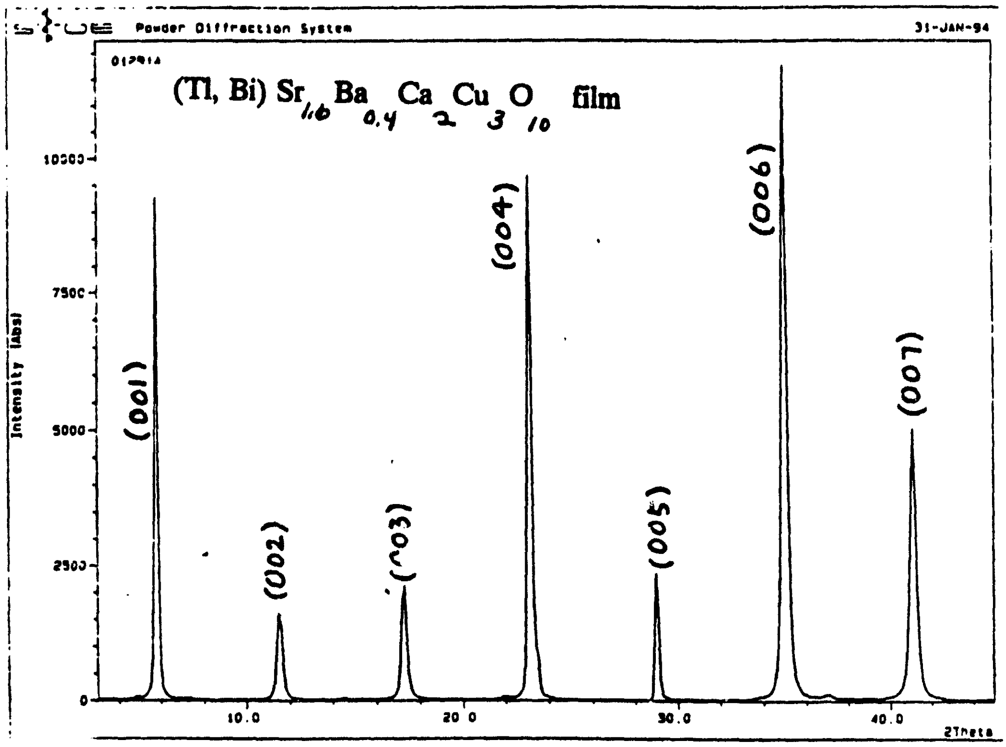


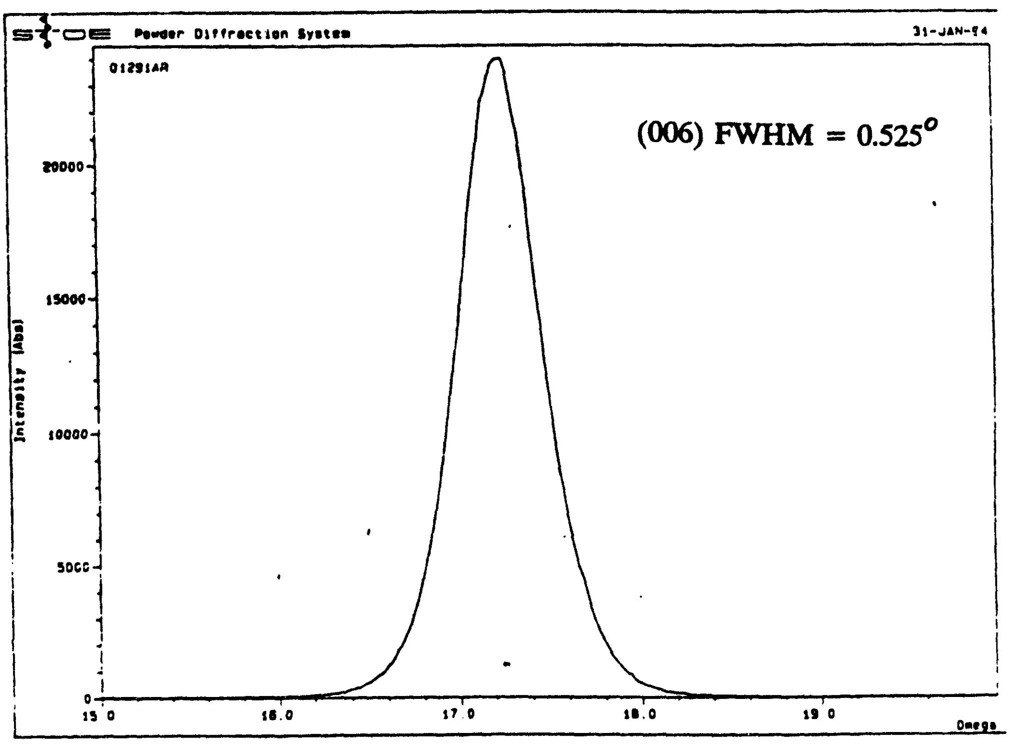



Barrier boundaries
⊥ to ab-planes
Barrier boundaries
// to ab-planes
Ideal
Samples
A
B
Real bulk
samples
C
D

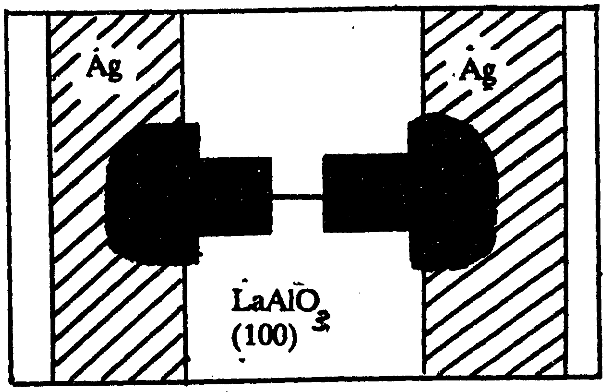

expansion
expansion
plastic
flow
contraction

(Tl, Bi)-1223 film





Characteristics of the (Tl, Bi) $Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_{10}$ film



Bridge dimensions:

Width: 90 μm
Thickness: 1.0 μm

T_c: 105.5 K or 111 K

J_c : 1 x 10^6 A/cm^2 (77 K, OT)

I_c : 1.85 A (77 K, OT)
1.4 A (77 K, 0.5 T, with H ⊥ film, ⊥ i)
0.12 A (77 K, 0.5 T, with H ∥ film, ⊥ i)

General Electric's Tl-"1223"

Silver Addition Process

Development/Scale-up Issues

John A. DeLuca
GE Research & Development
Feb. 16, 1994

"Single Tl-O Layer" Superconductors

- **High T_c**
- **Good pinning**
- **Strong links demonstrated in polycrystalline form**
  - *** silver-addition process**

GE's Tl-"1223" Silver Addition Process

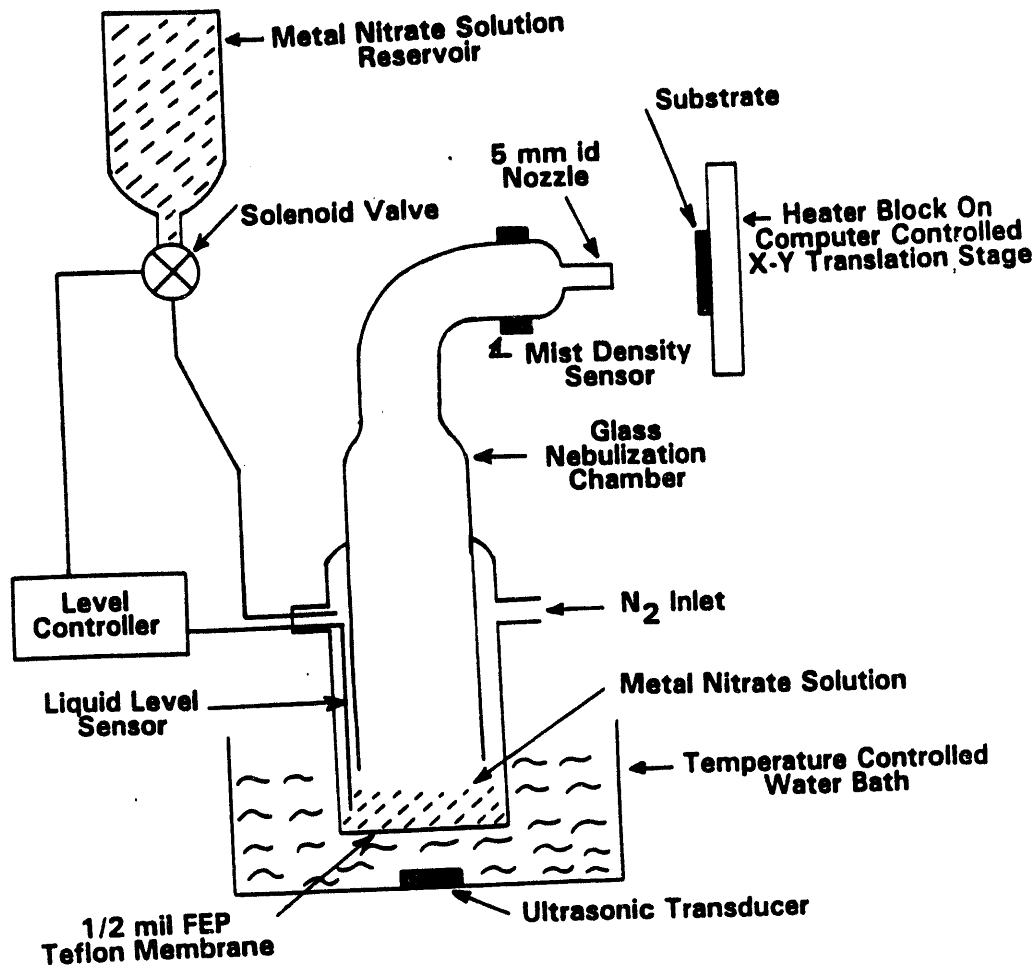
- **Precursor deposition/decomposition**
  - spray pyrolysis of aqueous nitrates at 275^{o}C
  - nitrate decomposition in oxygen at 850^{o}C
  - nominal $Ca_2Ba_2Cu_3O_7$:xAg

- **Thallium Oxide Vapor Reaction**
  - two zone reactor
  - Tl_2O/O_2 ambient

$Ca_2Ba_2Cu_3O_7$:xAg ---► $TlCa_2Ba_2Cu_3O_9$:xAg

- **Post Thallination Anneal**
  - 8 hrs/600^{o}C/O_2
  - 2-5X improvement in J_c

Spray Deposition Apparatus



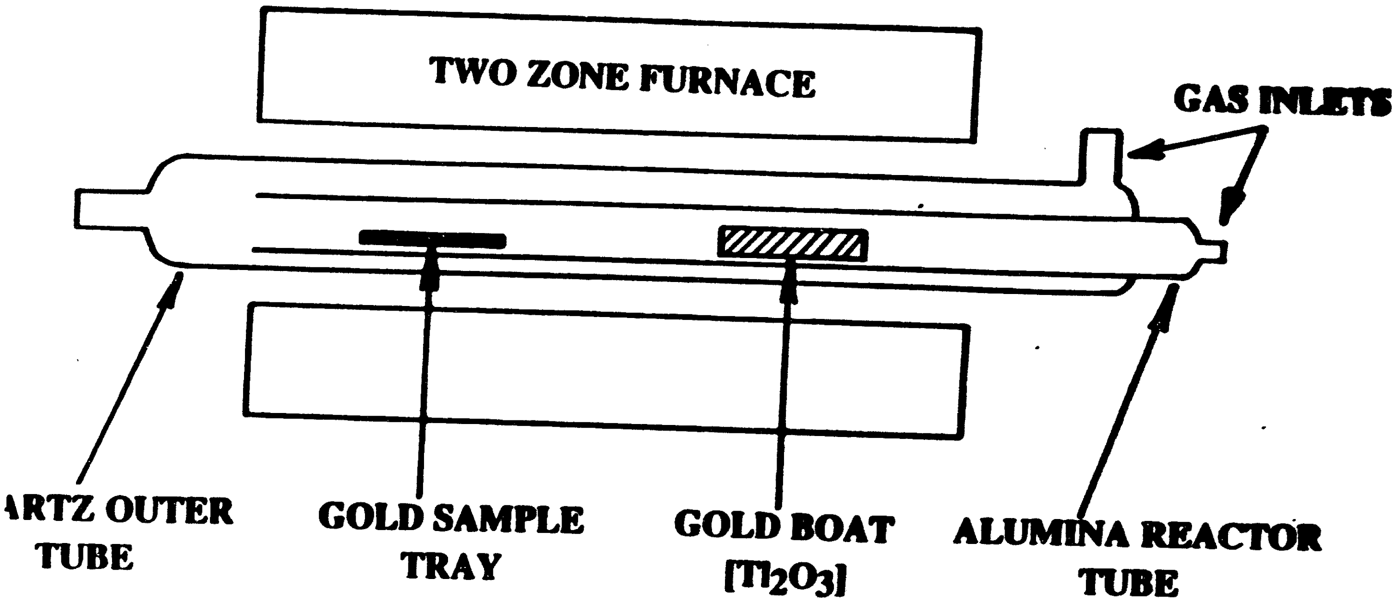
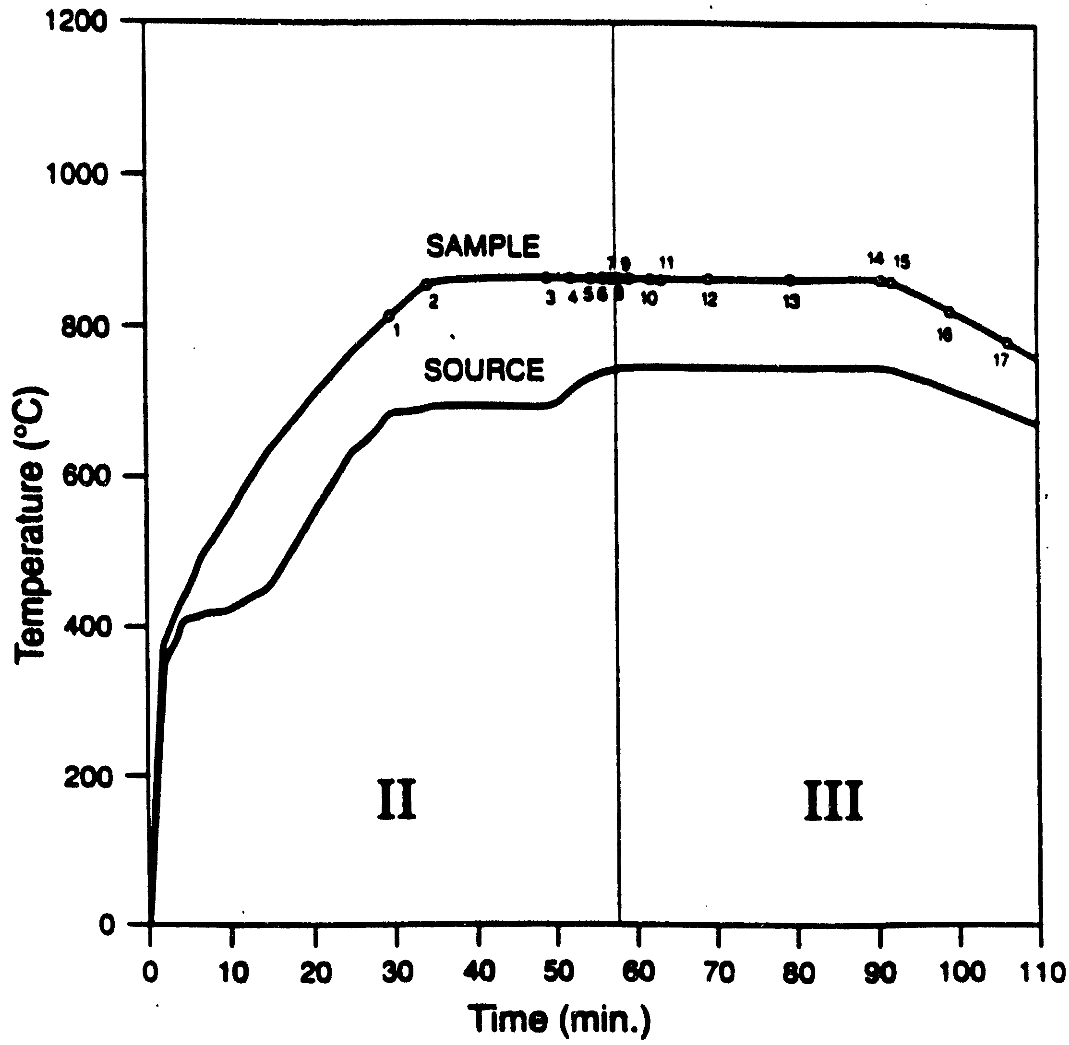

TWO ZONE FURNACE
GAS INLETS
ARTZ OUTER
TUBE
GOLD SAMPLE
TRAY
GOLD BOAT
[Tl_2O_3]
ALUMINA REACTOR
TUBE

FIGURE 4



1200
1000
800
600
400
200
0
Temperature (°C)
SAMPLE
SOURCE
II
III
0
10
20
30
40
50
60
70
80
90
100
110
Time (min.)

Silver Addition Process - Scale-Up Issues

- ♦ **Precursor deposition**
  - * coating/decomposing long lengths
    - batch vs continuous?
  - * time required for spray deposition
    - anything faster/better?

- ♦ **Thallium Oxide Vapor Reaction**
  - * temperature control is critical [$\pm 2^{o}C$]
  - * how critical are two-step process times?
  - * batch vs continuous

- ♦ **Post Deposition Anneal**
  - * present ~20 hr. schedule favors batch process
  - * can anneal process be modified/shortened?

AIIM

Association for Information and Image Management
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

4 of 6

Silver Addition Process - Pre-Scale-Up Issues

- **Goal**
  - * **flexible tape capable of 10 A/mm in 1-5 T at 40K.**

- **Current Best**
  - * **3μm "1223" films**
  - * **12.5x8mm poly-YSZ substrates**
  - * **2 A/mm - single sided coating [66,000 A/cm^2]**

- **Pre-scale-up development needs**
  - * **high performance films on flexible substrates**
  - * **increase A/mm**
    - **increase J_c?**
    - **increase thickness 2.5-5X and maintain J_c**

- **Longer term development need**
  - * **evaluate compatibility of silver addition process with potentially "better pinning" chemistries [eg. Tl,Pb]**

SECTION VIII

PHYSICAL PROPERTIES OF HTS COILS

HTS BI-2223 COIL & MAGNET MEASUREMENTS

PRADEEP HALDAR
INTERMAGNETICS GENERAL CORPORATION
GUILDERLAND, NY 12084

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IGC PERSONNEL:

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D. HAZELTON
M. PHLIPSAK
M. WELOTH
M.STAUB
G. GALINSKI
J. HOEHN, JR.
L.R. MOTOWIDLO

* PROGRAM PARTIALLY SUPPORTED BY THE U.S. DOE TO DEVELOP ELECTRIC POWER TECHNOLOGY

COIL AND MAGNET REQUIREMENTS

- HIGH OVERALL WINDING Jc
- GOOD INSULATION APPROACH FOR W&R AND R&W
- GOOD STRAIN PROPERTIES IN CONDUCTOR FOR WINDING
- IMPROVED MECHANICAL PROPERTIES OF COILS
- GOOD EPOXY INCAPSULATION TECHNIQUES
- LOW JOINT RESISTANCE FOR POWER DISSIPATION
- LOW AC LOSSES
- QUENCH PROTECTION
- 100 - 300 m LENGTHS SUFFICIENT FOR MOST APPLICATIONS FOR NOW

	REACT AND WIND	WIND AND REACT
COIL	1 X 34 m	1 X 34 m
CURRENT	8 Amps	7 Amps
NO. OF TURNS	131	131
AMP-TURNS	1048	917
Core J_c	6,500 A/cm^2	5,500 A/cm^2
OVERALL WINDING J_c (77K)	450 A/cm^2	500 A/cm^2

W & R DISADVANTAGES:

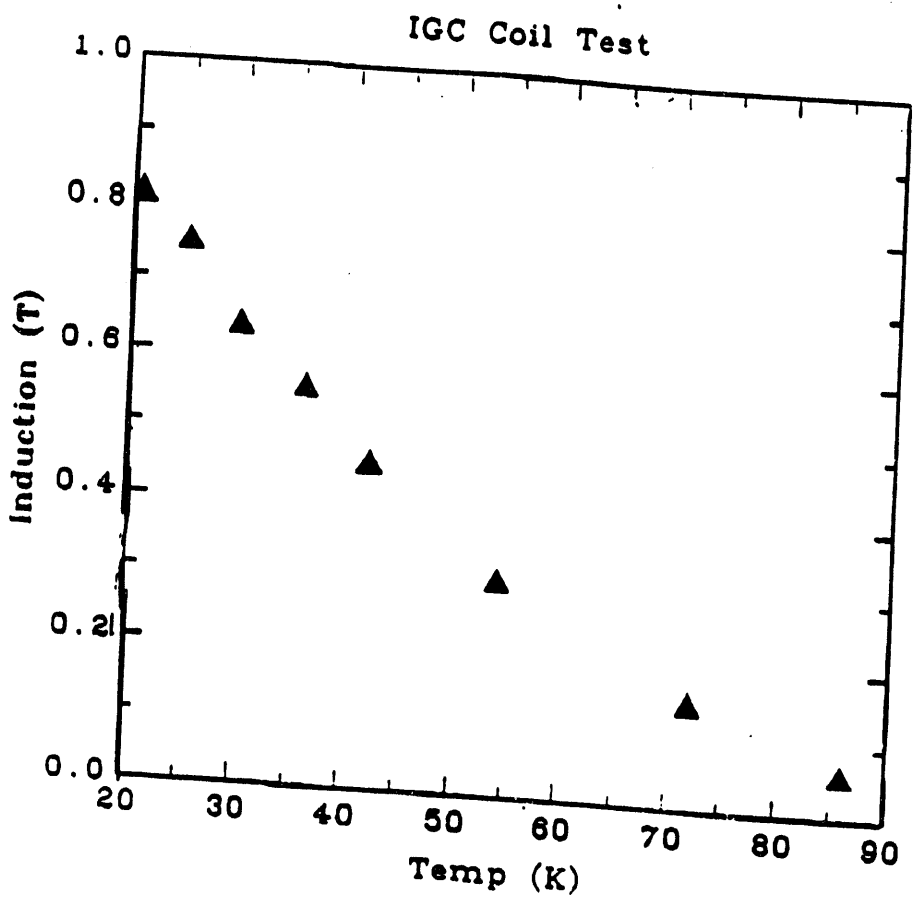
* HIGH TEMPERATURE FIXTURING AND INSULATION
* LARGER FURNACE FOR COIL HEAT TREATMENT

PRADEEP HALDAR_07/93

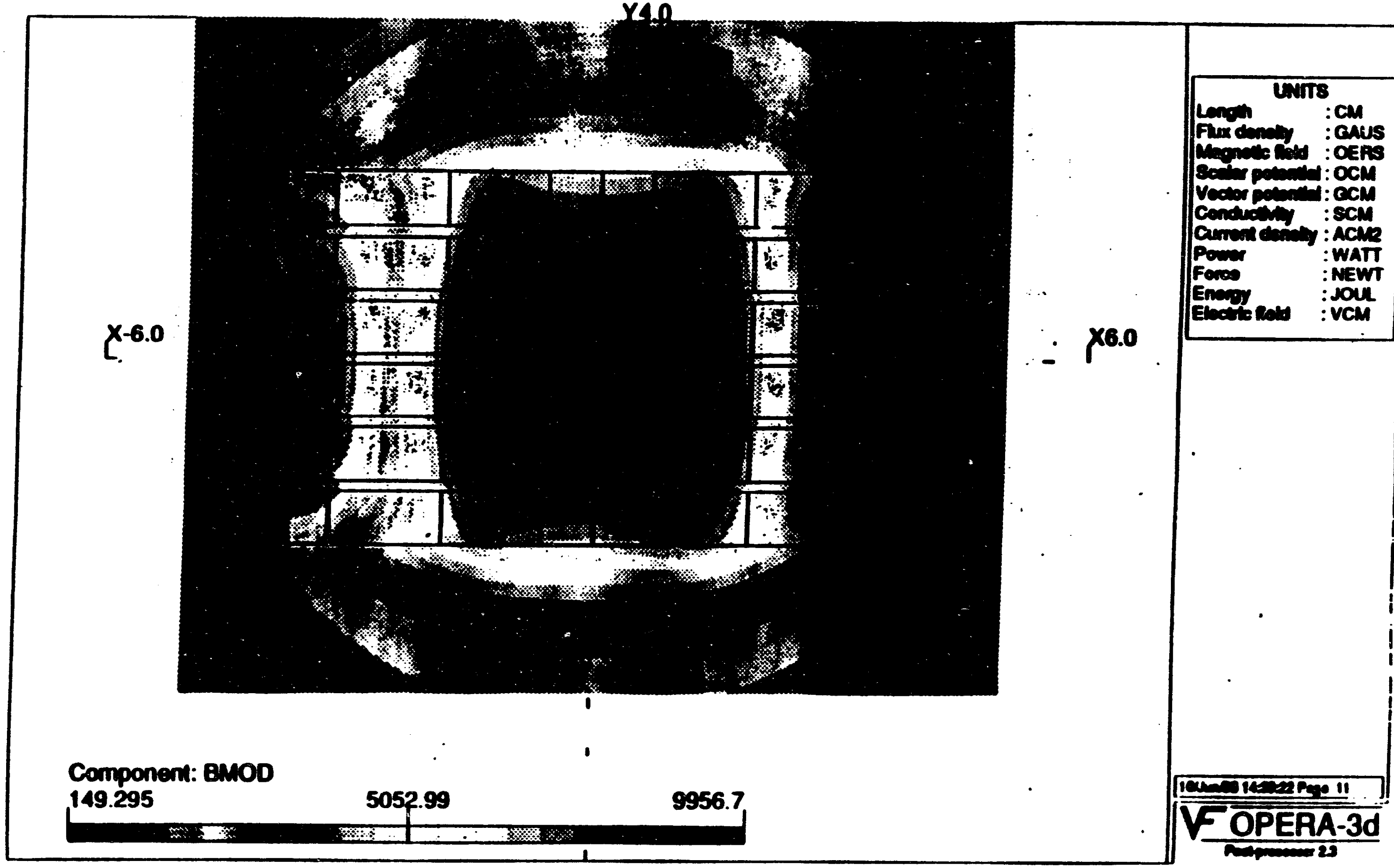
IGC
H T S

LATEST IGC HTS MAGNET DATA

	MAGNET 1 (JUNE 93)	MAGNET 2 (AUG 93)	MAGNET 3 (SEP 93)	MAGNET 4 (OCT 93)
WINDING INNER DIAMETER (CM)	2.50	2.50	2.50	2.50
WINDING OUTER DIAMETER (CM)	7.50	9.65	11.30	11.30
COIL HEIGHT (CM)	5.33	9.84	6.35	6.35
NO. OF CO-WOUND TAPES PER PANCAKE	3	5	3	3
TOTAL LENGTH OF TAPE IN MAGNET (M)	153	570	480	480
TOTAL NO. OF TURNS IN THE MAGNET	330	612	700	700
OVERALL WINDING CROSS-SECTION (CM^2)	0.0348	0.0532	0.0363	0.0363
NO. OF PANCAKE COILS	6	10	10	10
MAGNET CONSTANT (GAUSS/AMP)	62.9	64.7	109.7	111.2
77 K Ic MAX	19 A	41 A	22 A	32 A
Bo MAX	0.12 T	0.26 T	0.24 T	0.36 T
4.2 K Ic MAX	170 A	255	167 A	234 A
Bo MAX	1.01 T	1.65 T	1.83 T	2.60 T
27 K Ic MAX	125 A	171 A	130 A	160 A
Bo MAX	0.78 T	1.10 T	1.43 T	1.80 T



IGC Coil Test
Induction (T)
1.0
0.8
0.6
0.4
0.2
0.0
20
30
40
50
60
70
80
90
Temp (K)



Y4.0
X-6.0
X6.0
UNITS
Length : CM
Flux density : GAUS
Magnetic field : OERS
Scalar potential : OCM
Vector potential : GCM
Conductivity : SCM
Current density : ACM2
Power : WATT
Force : NEWT
Energy : JOUL
Electric field : VCM
Component: BMOD
149.295
5052.99
9956.7
OPERA-3d

LATEST IGC HTS MAGNET DATA

WINDING INNER DIAMETER (CM)	2.50
WINDING OUTER DIAMETER (CM)	11.30
COIL HEIGHT (CM)	6.35
NO. OF CO-WOUND TAPES PER PANCAKE	3
TOTAL LENGTH OF TAPE IN MAGNET (M)	480
TOTAL NO. OF TURNS IN THE MAGNET	700
OVERALL WINDING CROSS-SECTION (CM^2)	0.0363
NO. OF PANCAKE COILS	10
MAGNET CONSTANT (GAUSS/AMP)	111.2

77 K (MEASURED)

Ic MAX	32 A	Bo MAX	0.36 T
Ic MIN	19 A	Bo MIN	0.21 T

4.2 K (MEASURED)

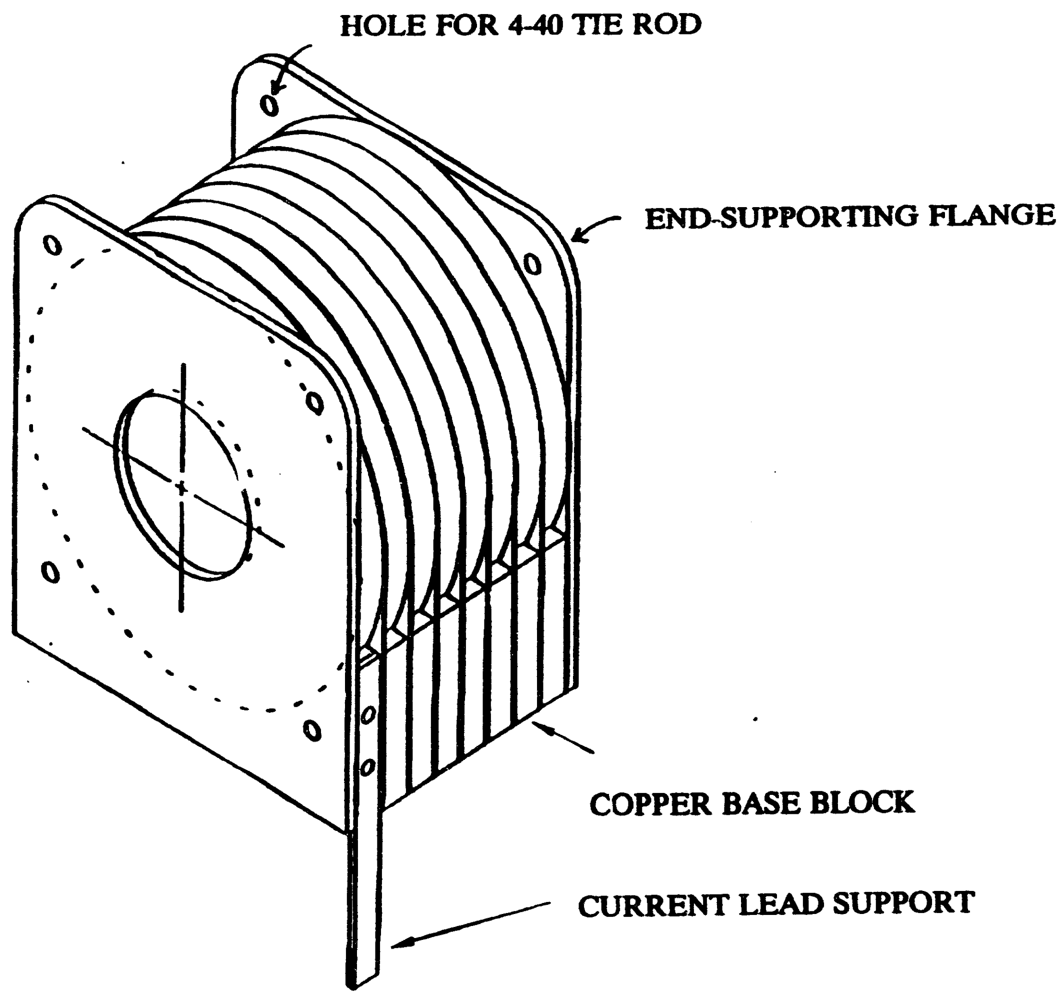
Ic MAX	234 A	Bo MAX	2.60 T
Ic MIN	140 A	Bo MIN	1.56 T

27 K (EXTRAPOLATED)

Ic MAX	160 A	Bo MAX	1.80 T

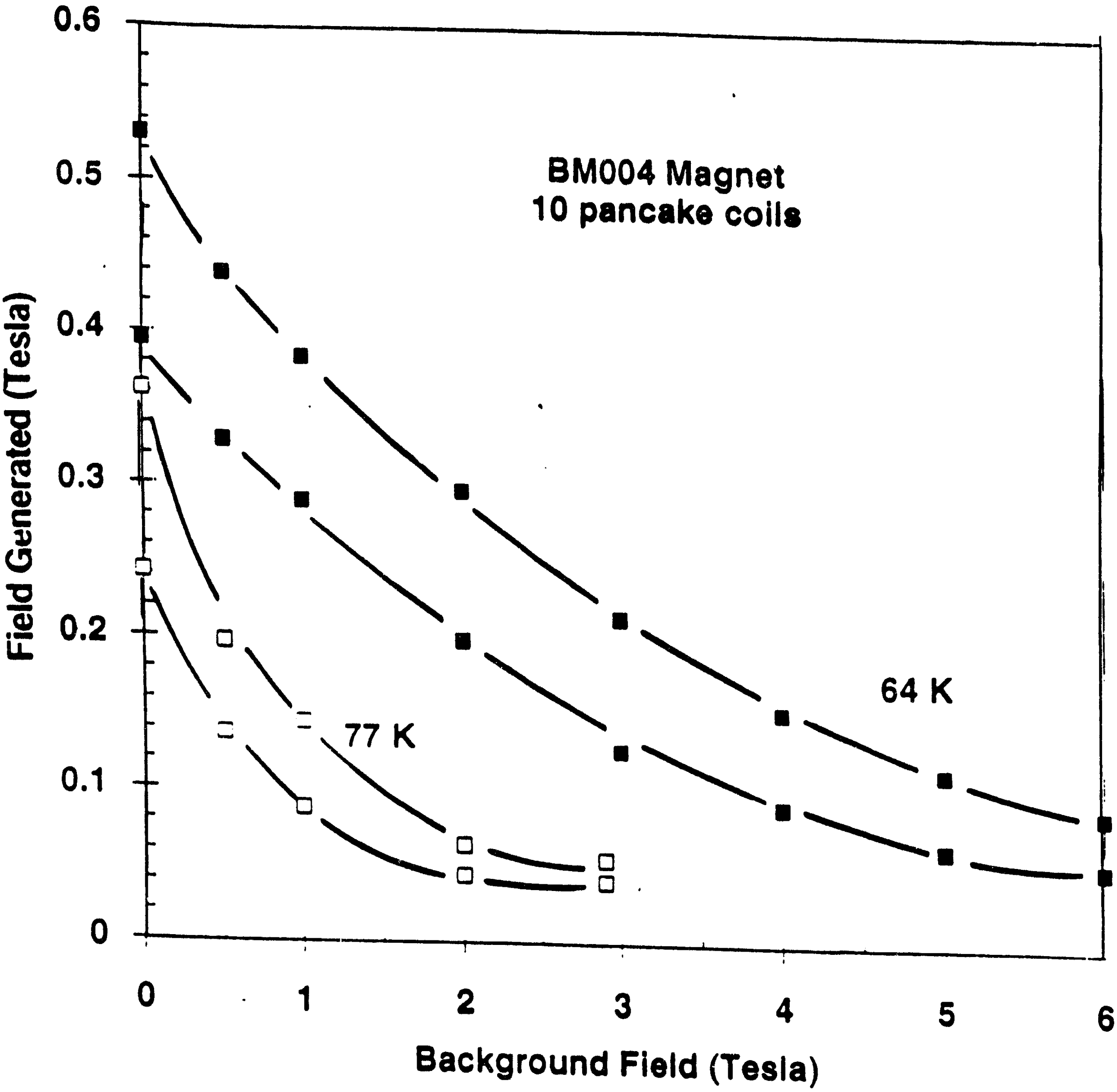
PRADEEP HALDAR. MEASURED AT IGC ON 10/13/93

IGC HTS



CRYOCOOLER HIGH-Tc MAGNET

IGC Magnet measured at MIT

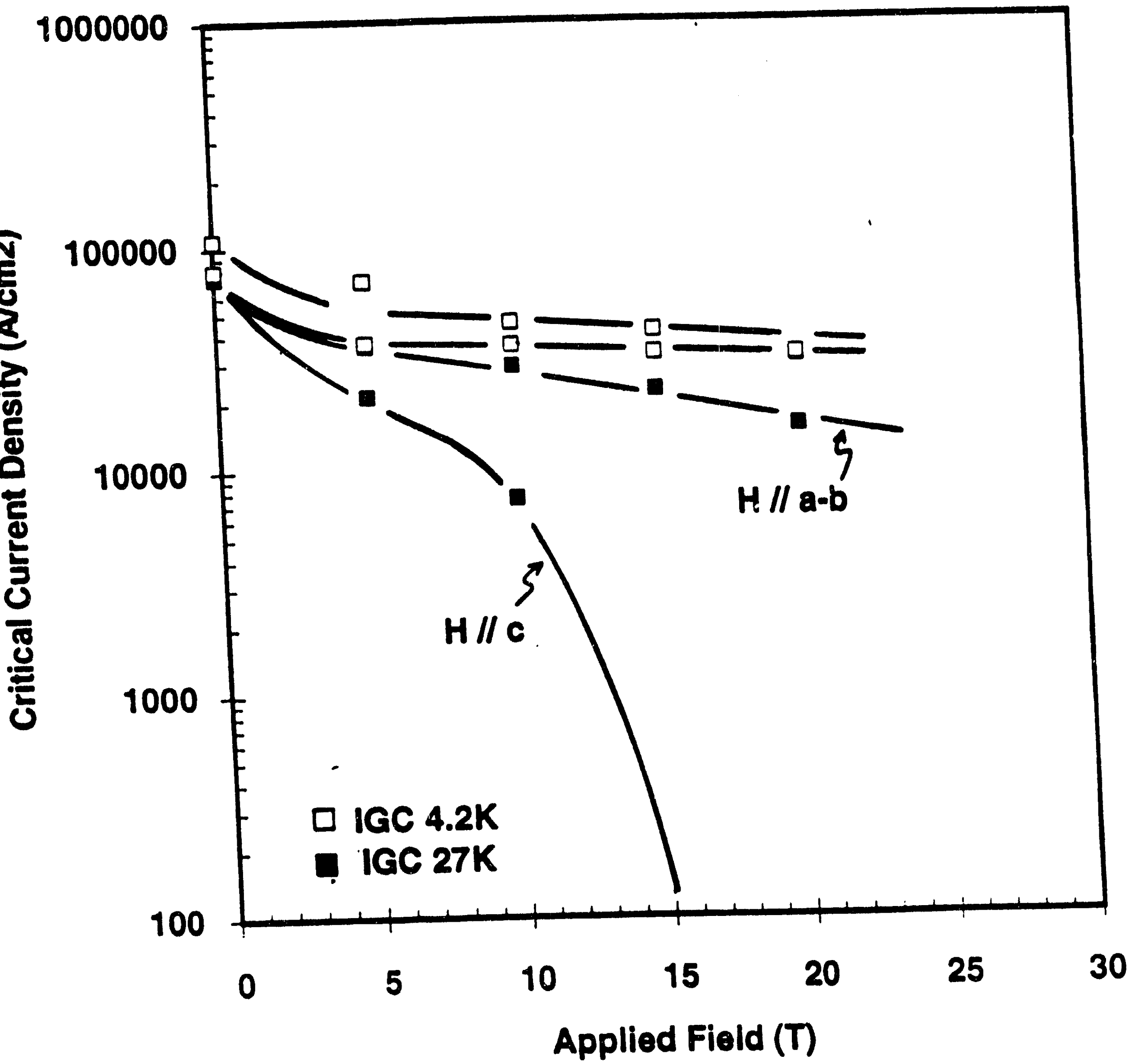


PRADEEP HALDAR

10/1/93

IGC HTS

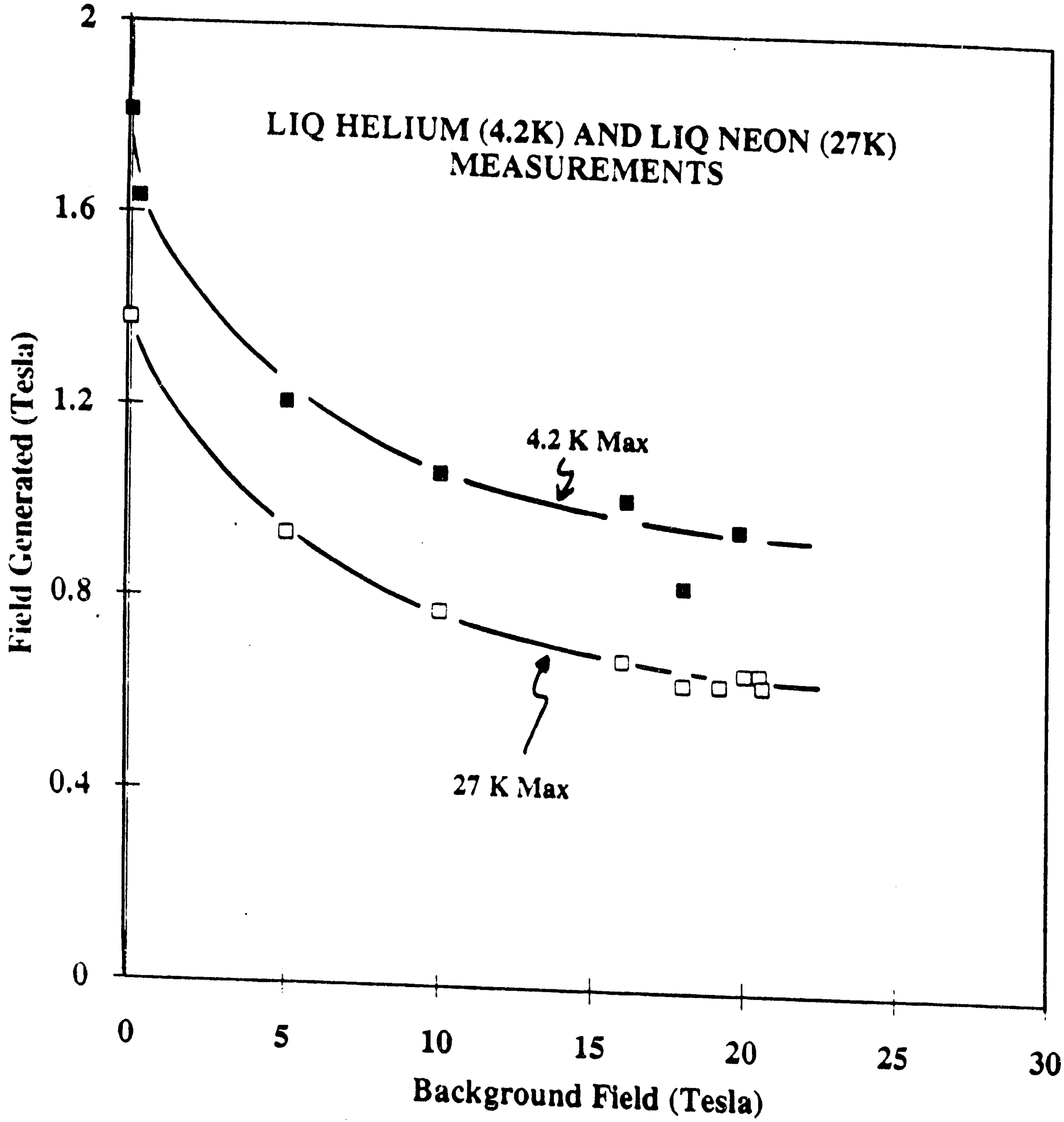
MIT Magnet Lab DATA



11/03/92

IGC HTS

MIT DATA



PRADEEP HALDAR

IGC MAGNET 2/10/94

IGC HTS

SUMMARY

- ACHIEVED HIGHEST FIELD OF 2.6 TESLA AT 4.2 K
- ACHIEVED HIGHEST FIELD OF 1.0 T AT 4.2 K WITH 20 T BACKGROUND
- DEVELOPED EFFICIENT WIND & REACT INSULATION APPROACH
- DEVELOPED EXCELLENT EPOXY IMPRGNATION TECHNIQUES
- DEVELOPED MAGNETS FOR USE IN CRYOCOOLERS
- DEVELOPING SUPERCONDUCTING JOINTS
- DEVELOPING IMPROVED PROPERTIES OVER LONG LENGTHS

HTS Coil Requirements for Motor Applications
DOE HTS Wire Development Workshop
February 16, 1994

HTS Motor Applications

Large motors (greater than 1000 hp) for pump and fan drives for utility and industrial markets. Motors will be powered by an adjustable speed drive.

Expected benefits of large HTS motors:

1. Higher motor efficiency. Expected total motor losses to be about 1/2 the losses of a conventional motor of the same rating.
2. Smaller motor size. Expected total motor volume to be 1/2 the volume of a conventional motor of the same rating.

Motor size and efficiency benefits can only be obtained with HTS wire that can operate in a high magnetic field.

Motor type:

Synchronous motor with rotating HTS field winding.

HTS Coil Requirements for Motor Applications

Electromagnetic HTS Material Specifications:

Critical current density in the HTS core of 10^5 amps/cm^2

Critical magnetic field of 5 Tesla

Wire length of 5 to 10 km per coil

Operating Temperature

Highest temperature possible, 77 K preferred.

HTS Coil Requirements for Motor Applications

Insulation Specifications

NEMA Standard for Large Synchronous Motor Field Windings

High Potential test of 1500 to 2500 volts.

Other considerations:

Operating voltage drop in coil becomes of interest during:

1. **Motor transients**

   The magnitude of coil voltage during motor transients is dependent upon the AC magnetic field that is allowed to reach the HTS winding.

   AC loss data on high performance HTS coils is needed to determine how much AC field it can withstand.

2. **Coil Quenches**

   Voltage stress occurs in the field coils during a quench. The details of quench propagation and voltage buildup for HTS coils are not well known so it is difficult to determine what the insulation requirements will be.

DOE Superconductivity Partnerships Programs
for Electric Power Systems

High Temperature Superconducting Wire Development Workshop

Normal Zone Propagation in HTS Coils

Y. Iwasa
Francis Bitter National Magnet Laboratory
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

at

St. Petersburg Hilton and Towers
St. Petersburg, FL

February 16, 1994

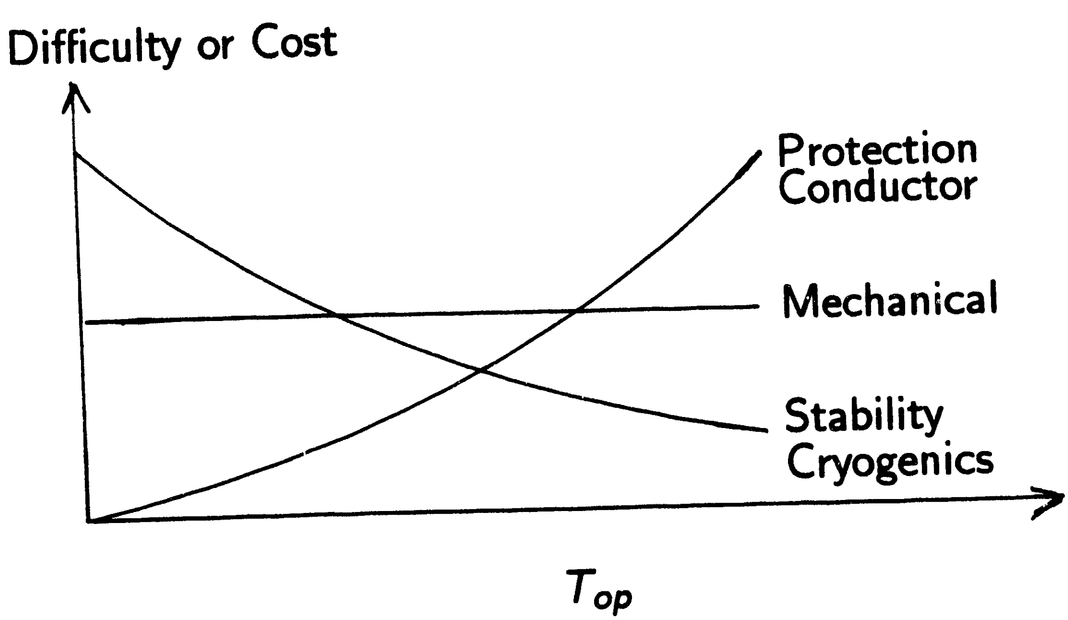
Magnet Issues

Major

- Mechanical integrity.
- Stability.
- Protection.

Minor—becomes Major when mass produced

- ◇ Conductor.
- ◇ Cryogenics.



Protection

- SCM is said to be *self-protecting* if it can be protected against overheating by having normal zone spread out – propagate – quickly over most of its winding volume.

- How fast this process takes place may be gauged by normal-zone propagation (NZP) velocity.

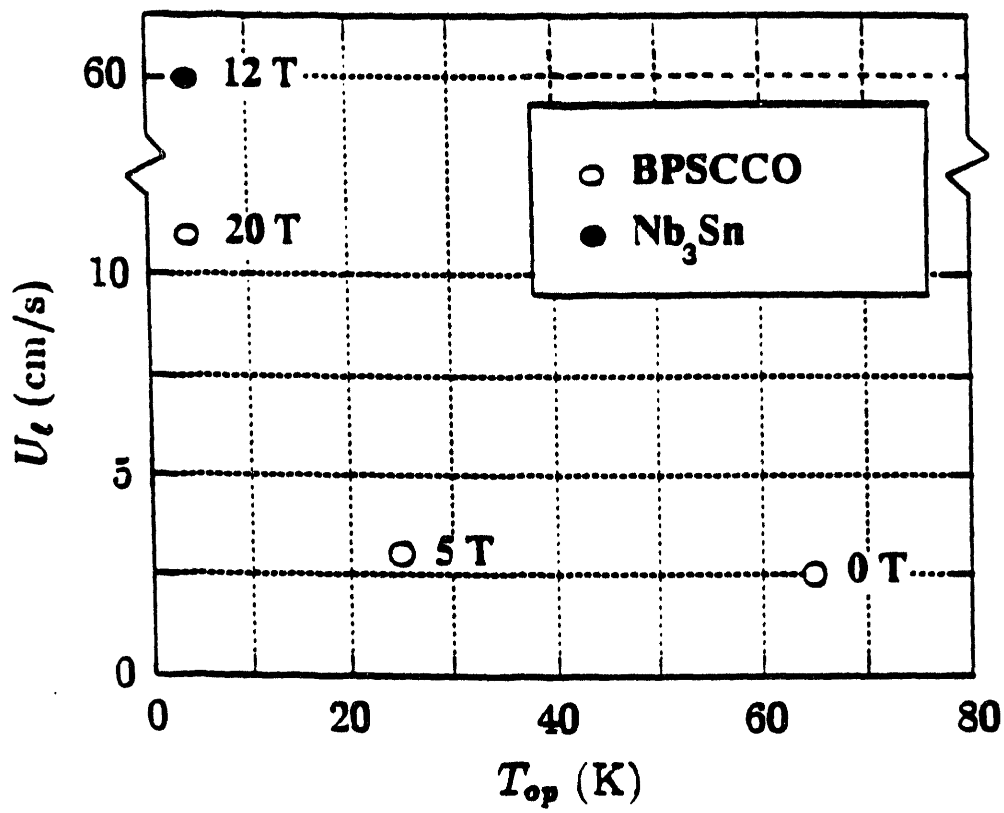
  ◇ Self-protecting SCM generally have "high" NZP velocities.

Normal-Zone Propagation Velocity

1. Short-Length Tape Results

Nb3Sn: $I_t = 111$ A; $J_m = 159$ A/mm^2.
[12 T, 4.2 K].

BPSCCO: $I_t = 70$ A; $J_m = 159$ A/mm^2.
[20 T, 4.2 K]; [5 T, 25 K]; [0 T, 65 K].



For a comprehensive description of the work, see:

R.H. Bellis and Y. Iwasa, "Quench propagation in high T_c superconductors, *Cryogenics* **34**, 129–144 (Feb. 1994).

Normal-Zone Propagation Velocity

2. Test Coils Results

Nb_3SN Coil: cryocooler-cooled (10 K).

Bpscco Coil: cryocooler-cooled (20 K; 36 K).

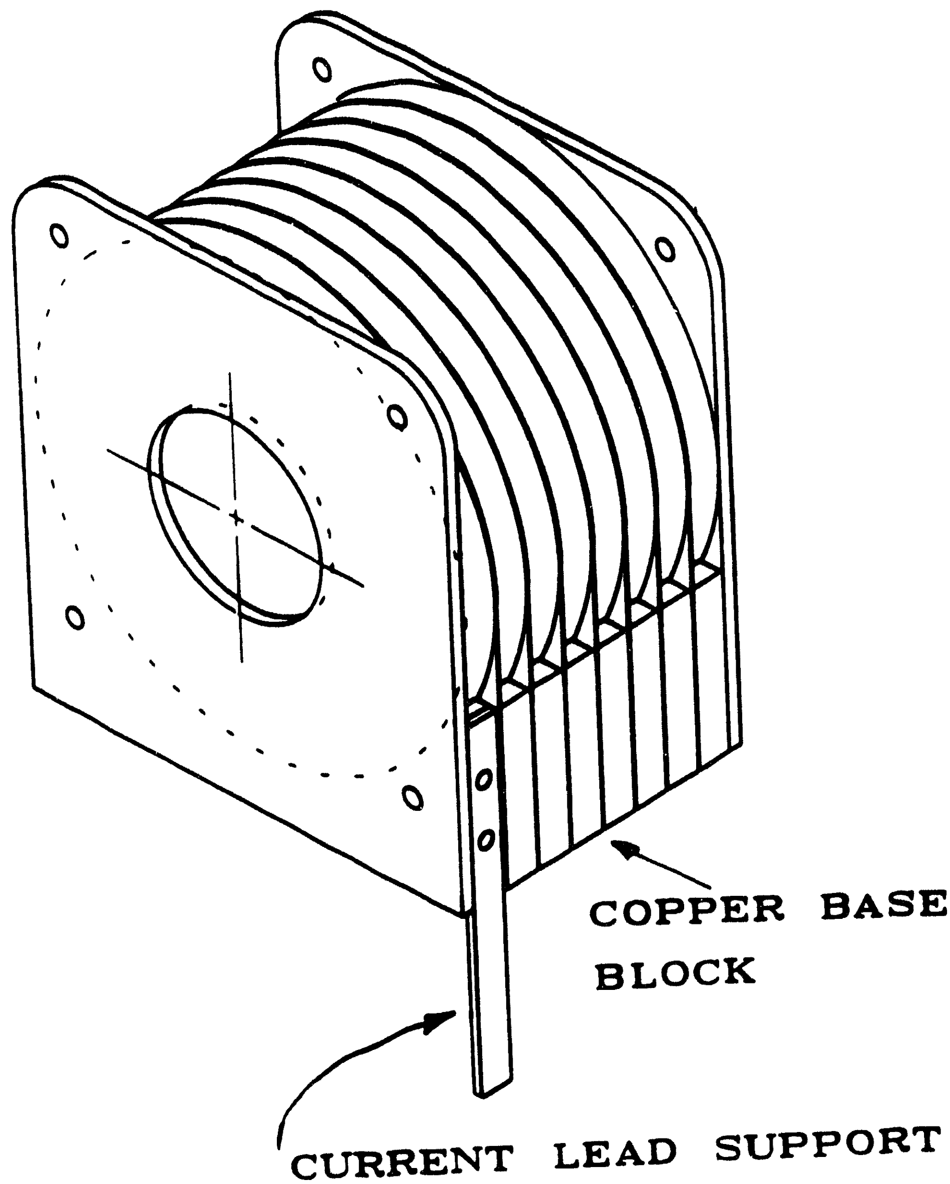
Table: IGC Magnet Parameters

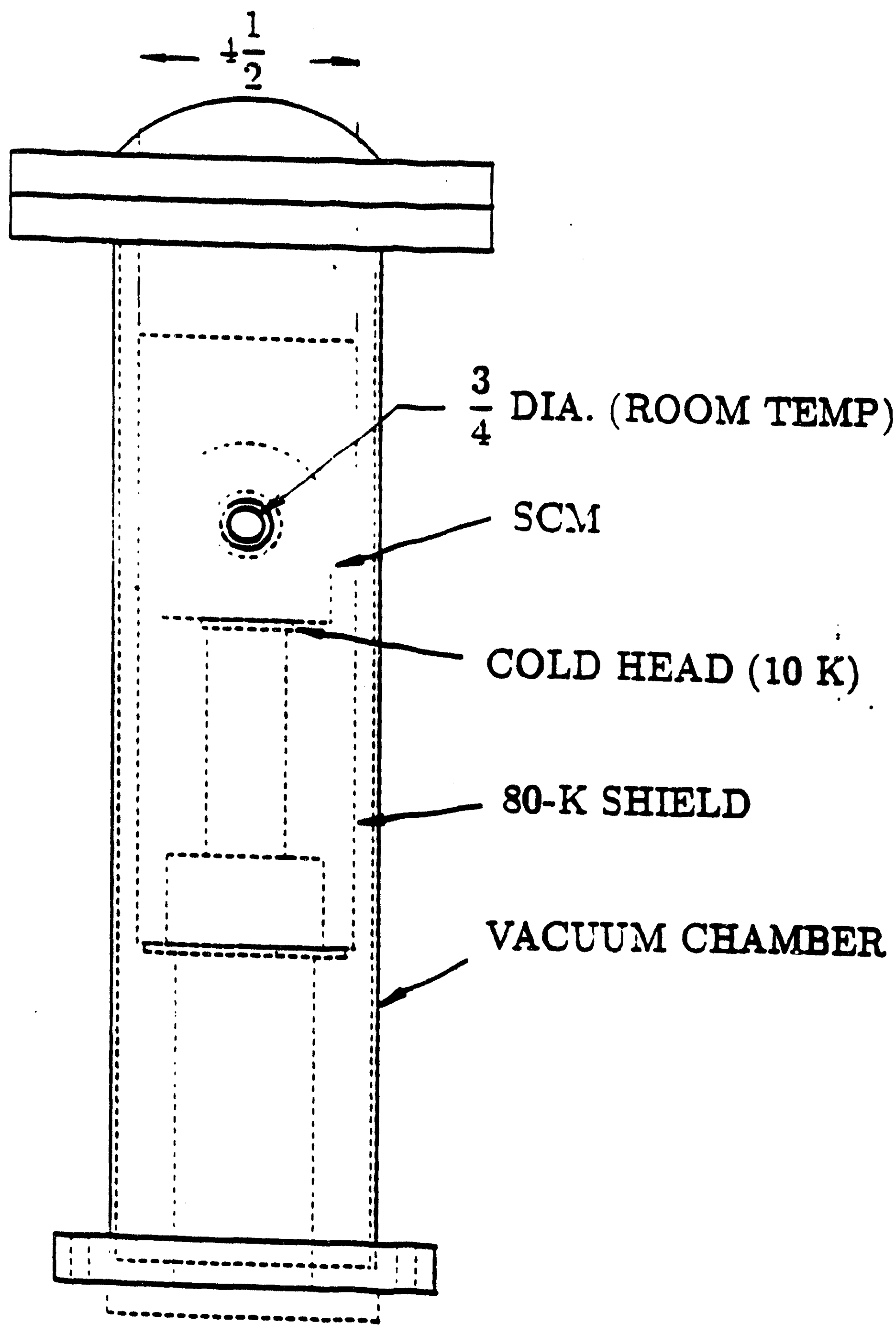
Parameter		
Overall tape thickness	(mm)	0.152×2
tape width	(mm)	4.44
turn-turn insul. thickness	(mm)	0.12
Magnet winding i.d.	(mm)	35.6
winding o.d.	(mm)	88.9
overall winding length	(mm)	44.4
P-P Ag spacer thickness	(mm)	0.5
DP-DP Cu spacer thickness	(mm)	0.8
# of double pancakes		4
# of turns/pancake		62.5
Center field at 100 A	(T)	0.83

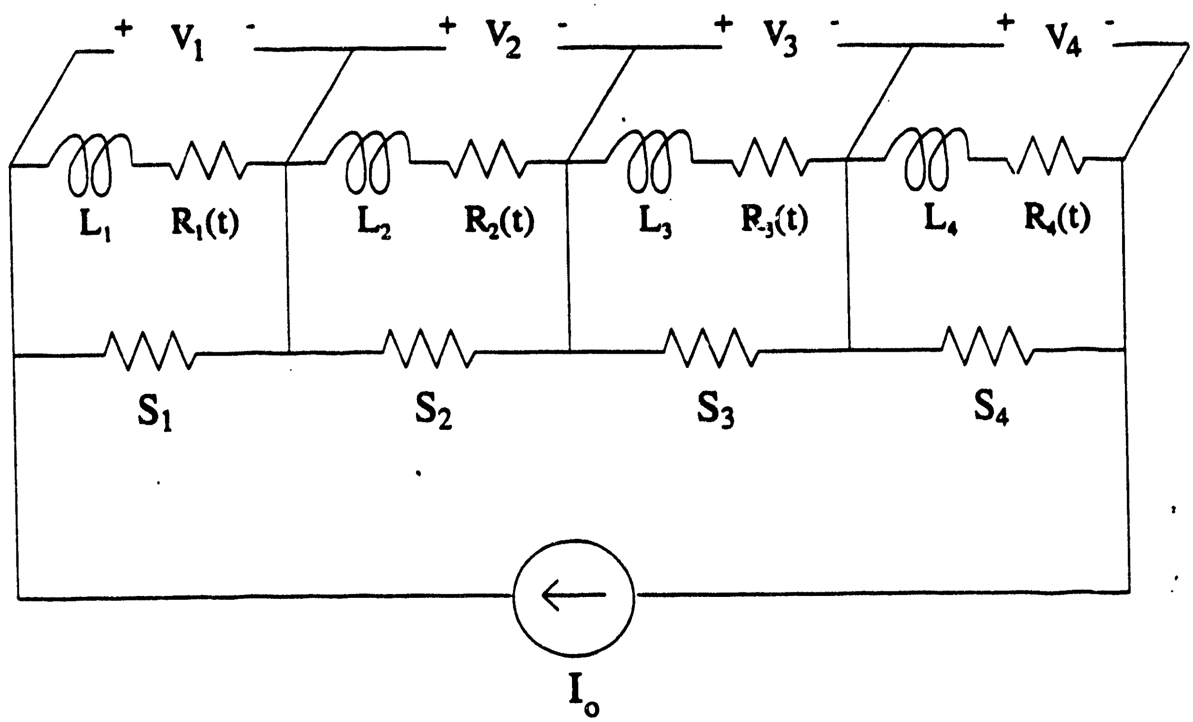
Special Features

- Operating temperature range: 10~70 K.
- Heaters to induce quench.
- Voltage taps to measure NZP velocities.

Assembly Drawing of the IGC Magnet

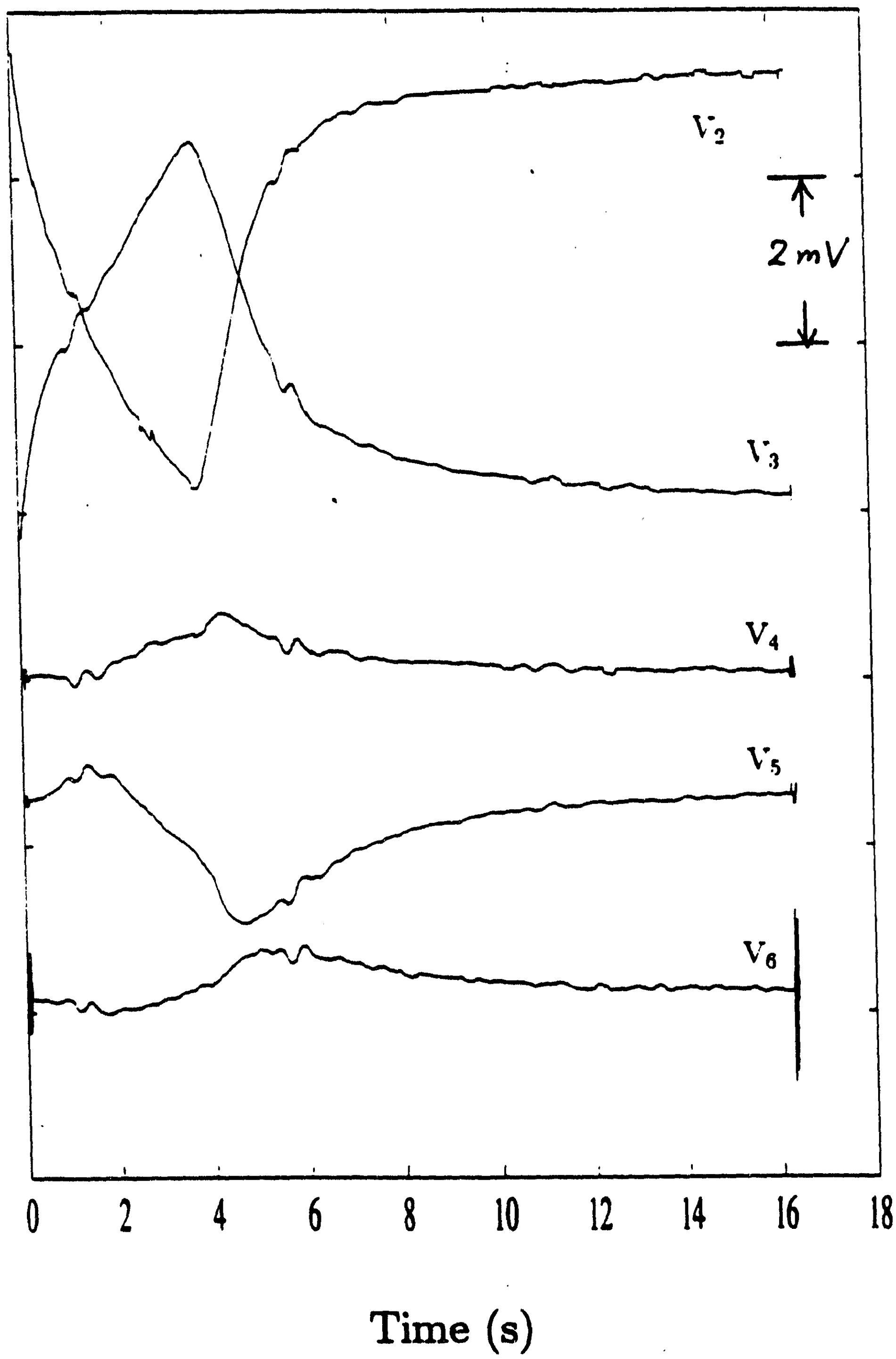



4 1/2
3/4 DIA. (ROOM TEMP)
SCM
COLD HEAD (10 K)
80-K SHIELD
VACUUM CHAMBER



+ V1 -
+ V2 -
+ V3 -
+ V4 -
L1
R1(t)
L2
R2(t)
L3
R3(t)
L4
R4(t)
S1
S2
S3
S4
Io

Heater-Induced Quench at 130 A, 20 K



Heater-Induced Quench at 86 A, 36 K

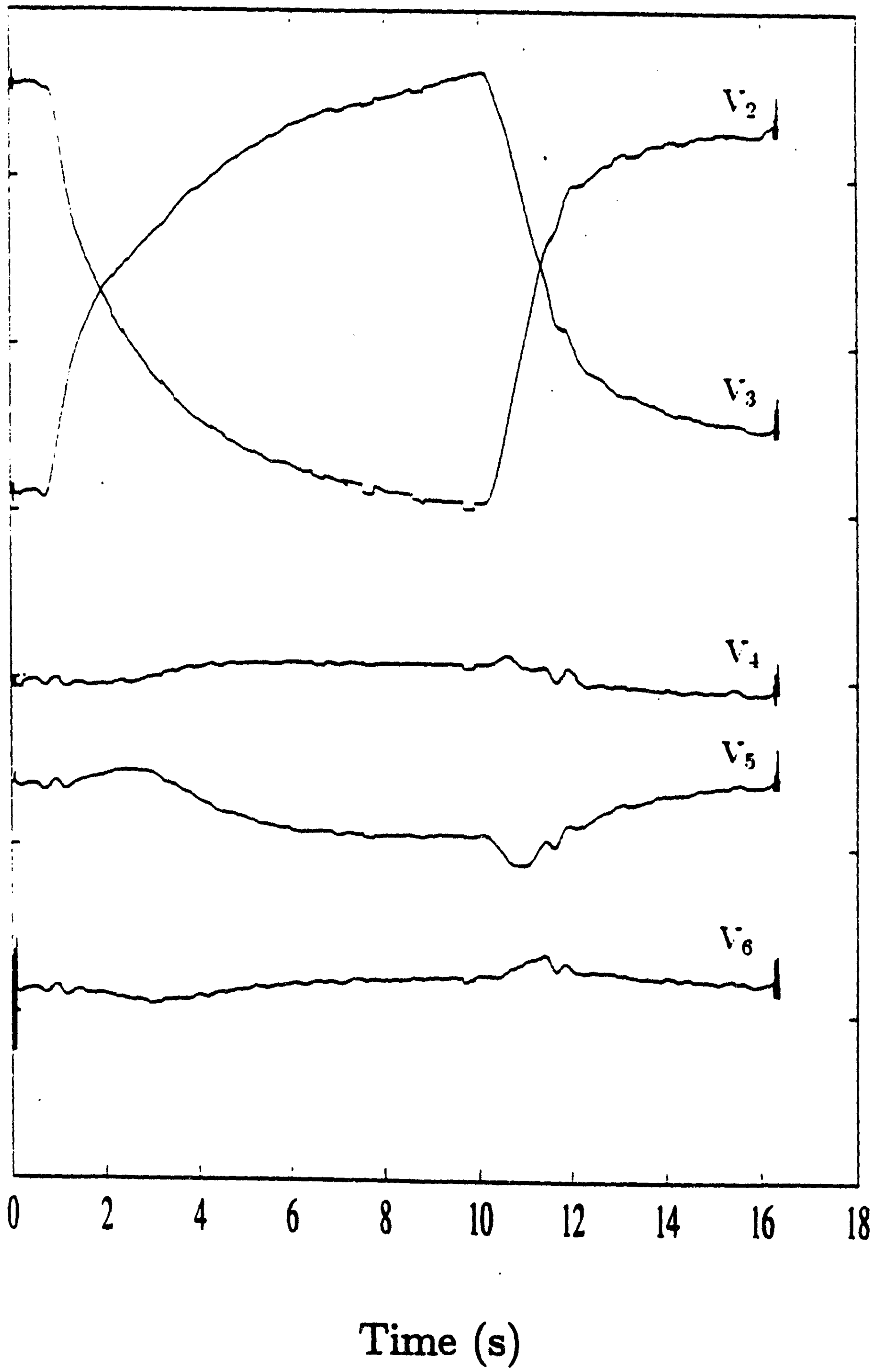


Table: NZP Velocity Data Summary

(Preliminary)

Coils	T_{op} (K)	I_{op} (A)	J_m (A/mm^2)	U_t (mm/s)
LTS	10	130	416	35
HTS	20	130	96	0.5
	36	86	63	0.08

Future Plans

Protection

- Complete description, both experimental and simulation, of normal-zone propagation in HTS (Bpscco) coils over the temperature range 20~60 K.
- Detailed temporal and spatial distributions, both experimental and simulation, of temperature in quenching HTS, short samples and coils.
- Development of protection techniques for "isolated" HTS magnets.

Evaluation Activities

- Continue I_c measurement of HTS coils (up to 115 mm o.d.) in background fields up to 22 T – @ 4.2 and 27 K.
- 300-mm o.d. HTS coils can also be tested in background fields up to 12.5 T – @ 4.2 and 27 K.

ENGINEERING ASPECTS OF HTS COIL DESIGN

Mark Daugherty

Los Alamos National Laboratory

HTS COILS SHOULD BE IMMUNE TO QUENCHES CAUSED BY MECHANICAL FRICTION AND CRACKING OF EPOXY OR INSULATION.*

The amount of energy required to raise the conductor from its operating temperature to the current sharing temperature is the enthalpy margin.

This margin and the maximum allowable movement of the conductor is shown below:

	Nb-Ti/Cu	Bi-2223/Ag	Bi-2223/Ag
T op	4.2	27	77
Tc	9.5	104	104
T cs	6.5	35	87
Enthalpy Margin (kJ/m^3)	5.3	3,700	23,000
Tolerable Motion (mm)	0.01	7	35

*G. Ries, Cryogenics Vol 33, No. 6, 1993

CAREFUL STRUCTURAL DESIGN WILL BE REQUIRED TO ENSURE THAT TENSILE STRAIN IN THE CONDUCTOR IS MINIMIZED.

HTS materials are brittle so tensile strain must be minimized. (1% strain will cause serious degradation.*)

As a toroid or solenoid is energized the conductors will experience a tensile hoop stress.

The conductors can be precompressed to ensure that they remain slightly in tension when at full charge.

Precompression can be achieved by either thermal contraction of support members or over wrapping with support material.

* J. W. Ekin et. al., Applied Physics Letters, (1992) 61, 858.

TWISTED MULTIFILAMENTARY COMPOSITE CONDUCTORS WILL GREATLY REDUCE EDDY CURRENT LOSSES IN ENERGY STORAGE, AC AND PULSED COILS.

$$Q_{eddy} \propto \frac{B^2 \; L^2}{\rho_{et} \; t}$$

L = twist pitch

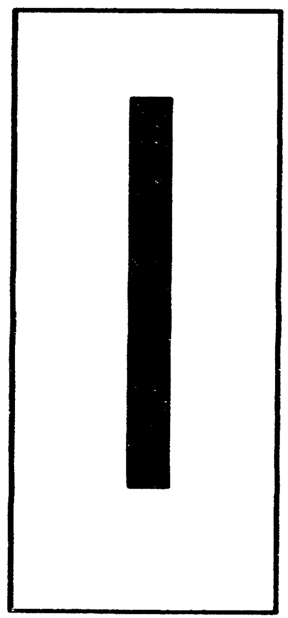
ρ_{et} = effective transverse resistivity

t = time from 0 to maximum field

Losses as high as 17% of stored energy per cycle have been estimated for twisted ribbons. These losses dropped to 0.3% with a tighter twist pitch of 12.5 cm in a multifilamentary composite. (R. B. Stephens, IEEE Transactions on Applied Superconductivity, Vol. 2, No. 3, 1992.)

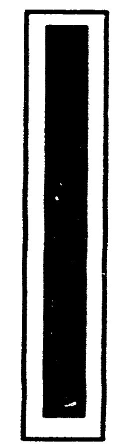
DEGRADATION IN CURRENT DENSITY DUE TO WINDING STRAIN MUST BE BALANCED AGAINST THE THICKNESS AND QUALITY OF THE REQUIRED ELECTRICAL INSULATION.

Wind and React Requires High Temperature Insulation



Jc Conductor = 20,000 A/cm^2
t Cond. = 0.015 cm, w Cond. = 0.25 cm
t Insulation = 0.030 cm
Jc Effective = 3,225 A/cm^2

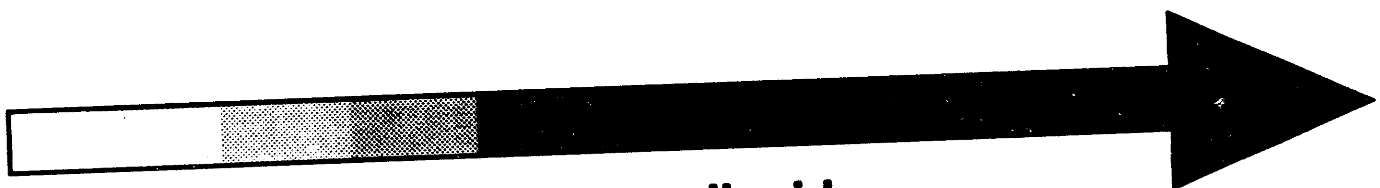
React and Wind Permits Use of More Effective Insulation



Jc Conductor = 5,600 A/cm^2
t Cond. = 0.015 cm, w Cond. = 0.25 cm
t Insulation = 0.005 cm
Jc Effective = 3,225 A/cm^2

COOLING REQUIREMENTS ARE TYPICALLY DETERMINED BY THE FUNCTION AND OPERATION OF THE COIL.

dc coil | energy storage coil | ac or pulsed coil



conduction | vapor | liquid

minimal cooling requirements

large cooling requirements

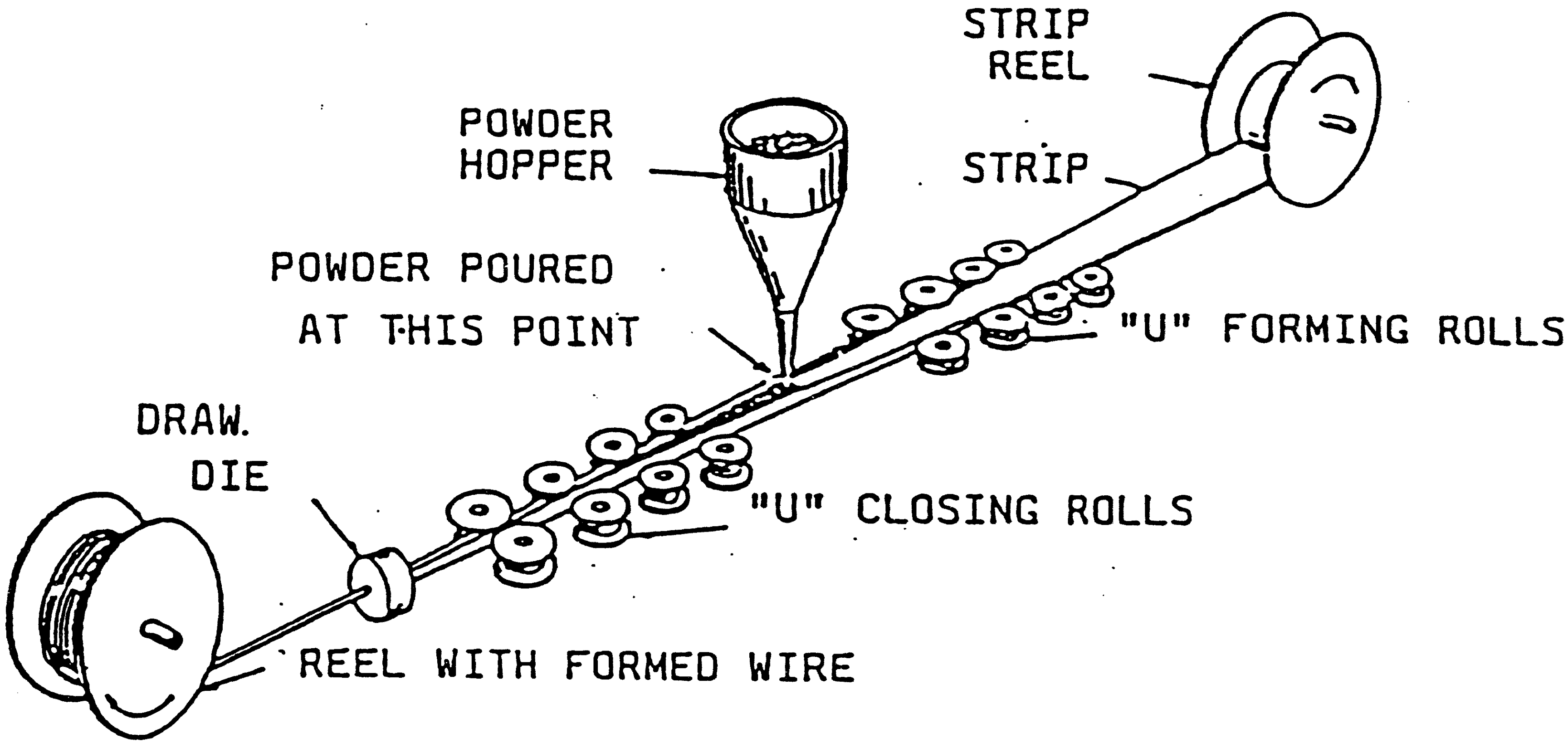
dc coil:
joints
I*V losses
heat leak

energy storage coil:
joints
I*V losses
heat leak +
moderate or intermittent:
hysteresis
eddy current

ac or pulsed coil:
joints
I*V losses
heat leak +
large or continuous:
hysteresis
eddy current

SECTION IX

TECHNOLOGY DEVELOPMENT AND TRANSFER OPPORTUNITIES FROM THE PROGRAM


STRIP
REEL
POWDER
HOPPER
STRIP
POWDER POURED
AT THIS POINT
"U" FORMING ROLLS
DRAW.
DIE
"U" CLOSING ROLLS
REEL WITH FORMED WIRE

FACTS ABOUT TUBULAR WELDING WIRE

400 MILLION POUNDS PRODUCED WORLD WIDE
ANNUALLY (100 BILLION FEET PER YEAR)

DRAWN TO DIAMETERS AS SMALL AS 0.023 INCH
DIAMETER

STRIP MATERIALS THAT HAVE BEEN USED :
ALLOYS OF STEEL, STAINLESS, ALUMINUM, NICKEL,
SILVER, COPPER

POWDER MATERIALS:
METALS- FE, MN, NI, CR, MO, W, CO, OTHERS
OXIDES, CARBONATES, FLUORIDES OF CA, BA, NA,
OTHERS

UNIFORMITY:
HAS TO BE LESS THAN +/- 1 % BY WEIGHT
(IF GREATER, CHEMISTRY OF DEPOSIT WILL NOT
MEET SPEC.)
(IF GREATER THAN +/-2% THE WELDER WILL SEE A
DIFFERENCE IN THE ARC IN MOST CASES)

BENEFITS OF PLASTRONIC TUBULAR WIRE PROCESS (PTW)

INFINITE LENGTHS

CONTINUOUS MANUFACTURING PROCESS

CAN BE USED FOR MONO AND MULTI-FILAMENT

PROVEN INDUSTRIAL PROCESS AND EQUIPMENT

SILVER STRIP IS LOWER COST THAN SILVER TUBE
- BASED ON $5.00 SILVER
- STRIP-$7.00 PER TROY OZ
- TUBE- $14.00-21.00 PER TROY OZ
- (IF YOU PROCESS 10,000 LB OF SILVER SAVE $1,000,000.)

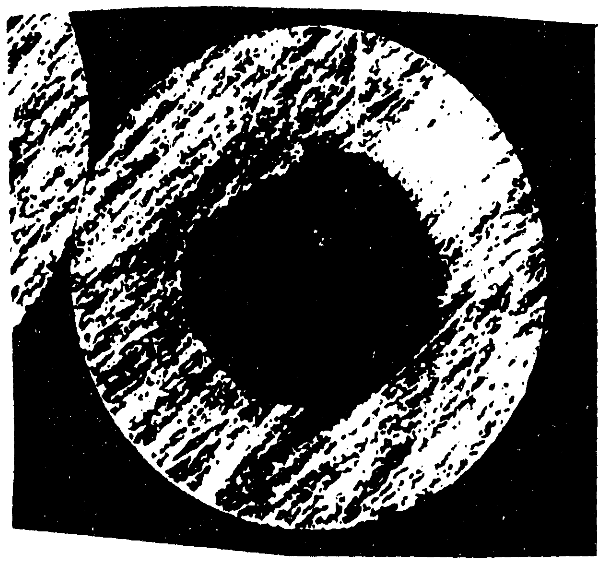
CAN BE USED WITH OXIDE POWDER AND METAL PRECURSOR POWDER

MONO-FILAMENT CAN BE WELDED OR UNWELDED

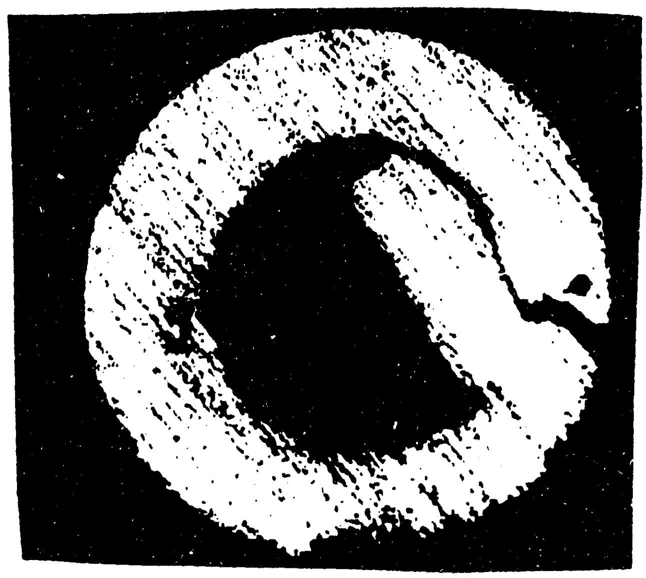
DRASTICALLY REDUCED MANUFACTURING STEPS FOR LONG LENGTHS,
- NEAR NET SHAPE , CURRENT STARTING WIRE SIZE IS 3/16 BUT COULD BE 3/32 INCH DIAMETER
- LABOR SAVINGS:
  - FILL TUBES - 1000-5000 FT OF 3/16 TUBE PER SHIFT (20,000 - 100,000 FT OF FINAL TAPE)
  - REDUCED SWAGING AND DRAWING STEPS FOR 3/4 INCH VERSES 3/16 TUBE DIAMETER SAVE UP TO 20 DRAWING AND SWAGING STEPS FOR 10% REDUCTION SCHEDULE

LOWER SILVER/ POWDER RATIOS ARE POSSIBLE
- FOR MONO AND MULTI-FILAMENT

Typical Cross Section of a Tubular-Wire Formed at 0.180 Inch Diameter, Welded, and Compacted by Drawing to 0.062 Inch Diameter



Typical Cross-section of A Tubular-Wire Formed at 0.180 Inch Diameter, Drawn to 0.062 Inch Diameter without Any Intermediate Welding on the Seam.



Typical Cross-Section of the Tubular-Wire After Sintering and Flattening.

(Top) Overlapped Wire With Welded Seam

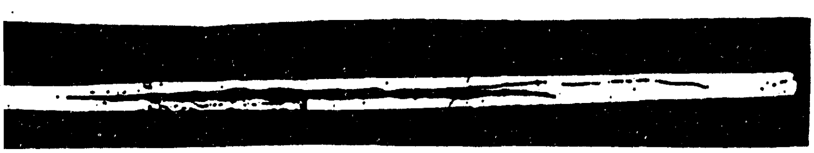
(Bottom) Overlapped Wire With Unwelded Seam

TOP

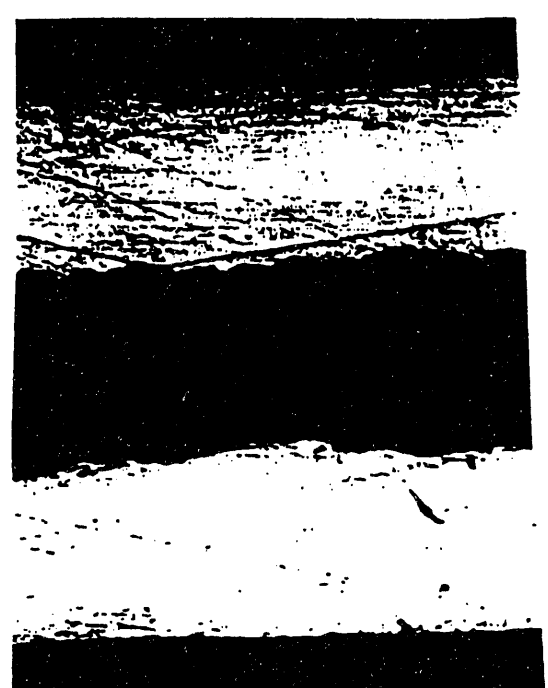
18X

450X

19X



400X



CHARACTERISTICS OF BSCCO AND SILVER TUBULAR WIRE

VARIATION OF FORMED AND FILLED TUBES
LESS THAN +/- 1.0 % BY WEIGHT OF POWDER

VARIATION OF WIRE DRAWN TO MAXIMUM COMPACTION
LESS THAN +/- 4.0 % OF THEORETICAL COMPACTION FOR BSCCO POWDER

VARIATION OF SUPERCONDUCTOR CURRENT IN TAPE CONDUCTOR +/- 2 AMPS

CURRENT FILLING RATE 2 FT /MIN (EQUIVALENT TO 1 SHIFT PRODUCTION RATE OF 20,000 FT OF MONO-FILAMENT TAPE

TASKS FOR NSF PHASE II SBIR-CONCENTRATING ON UNIFORMITY OF % COMPACTION

EVALUATING THE EFFECT OF POWDER FROM DIFFERENT SOURCES

EVALUATING VARIOUS METHODS OF POWDER FEEDING

EVALUATING DIFFERENT DRAWING DIE SCHEDULES

EVALUATING DIFFERENT STRIP THICKNESSES

EVALUATING DIFFERENT AS FORMED DIAMETERS.

PLASTRONIC INC. (OTHER ACTIVITIES)

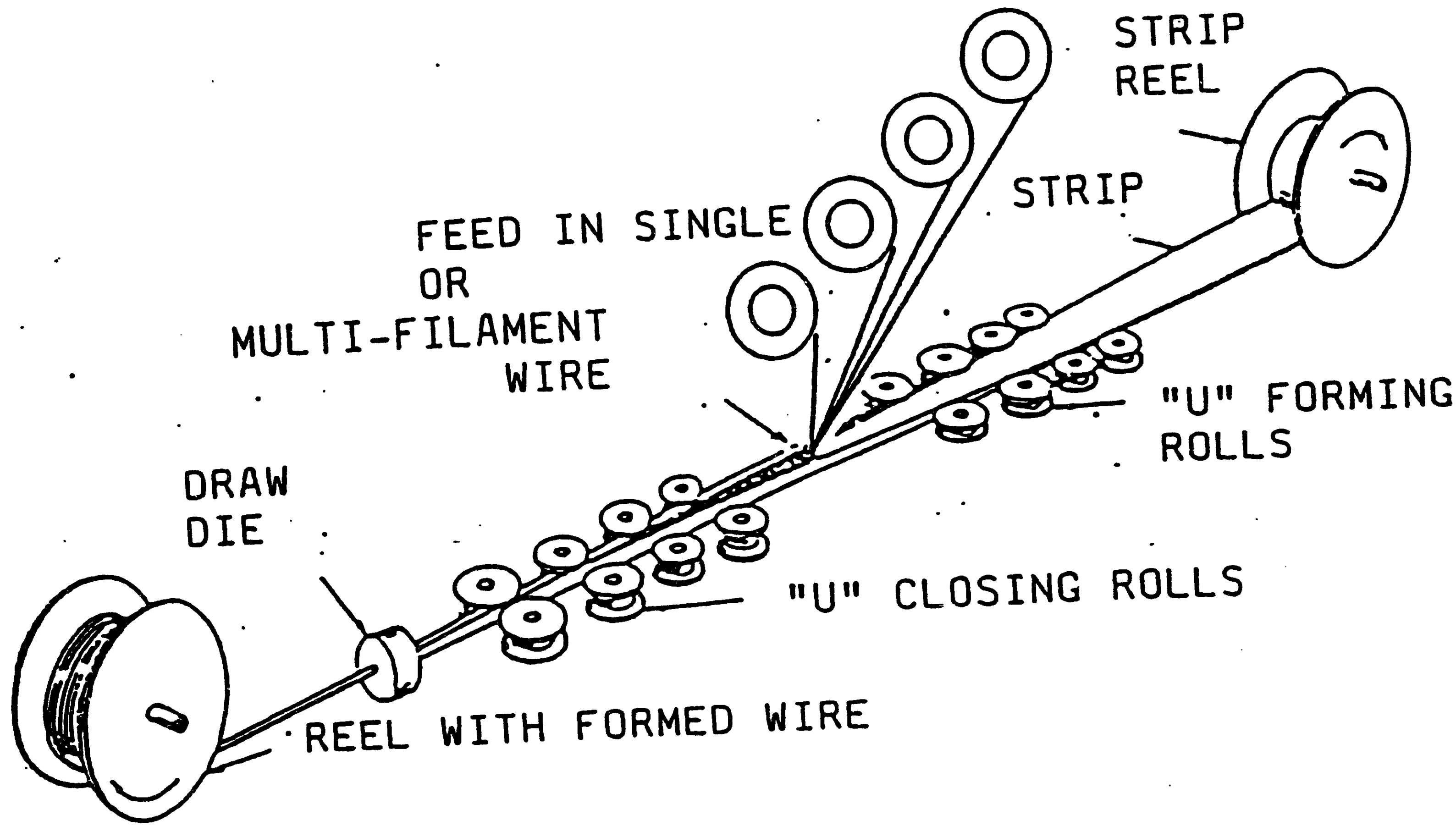
LONG LENGTH PRESSING

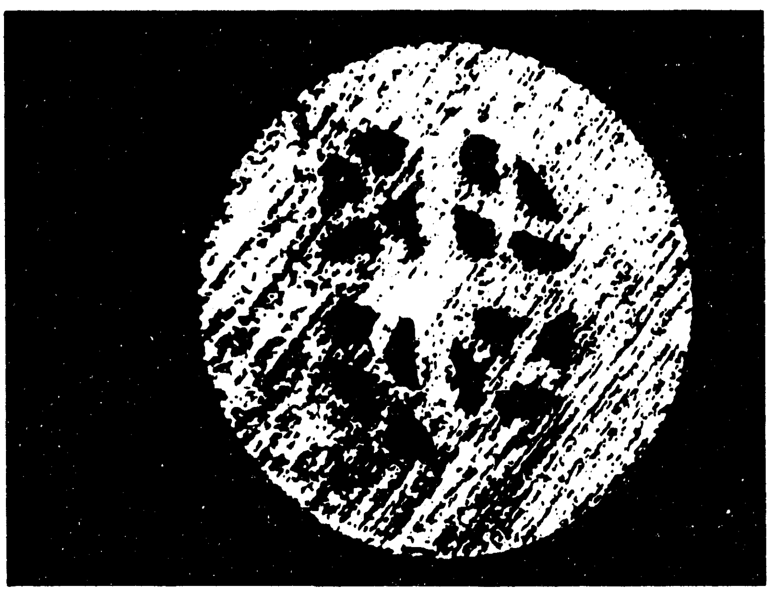
A) FUNDING INTERNALLY ONE METHOD OF LONG LENGTH PRESSING THAT LOOKS PROMISING

B) HELPING TO EVALUATE A LONG LENGTH PRESSING METHOD DEVELOPED BY IAP RESEARCH SPONSORED BY EMTEC

C) WORKING ON OPTIMIZING OF POWDER, DRAWING, ROLLING AND SINTERING TO IMPROVE J_c

LIKE TO GIVE CREDIT TO DR. ASOK SARKAR OF UNIVERSITY OF DAYTON RESEARCH INSTITUTE, WRIGHT PATTERSON AIR FORCE BASE AERO PROPULSION LABORATORY, EDISON MATERIAL TECHNOLOGY CENTER, IAP RESEARCH INC., OAK RIDGE AND ARGONNE NATIONAL LABORATORY


STRIP
REEL
STRIP
FEED IN SINGLE
OR
MULTI-FILAMENT
WIRE
"U" FORMING
ROLLS
DRAW
DIE
"U" CLOSING ROLLS
REEL WITH FORMED WIRE



WE ARE LOOKING FOR PARTNERS AND FUNDING SOURCES FOR VARIOUS AREAS.

ALL OUR CURRENT WORK HAS BEEN WITH BSCCO 2223 AND SILVER

WE WOULD LIKE TO ESTABLISH PROJECTS FOR:

1 MULTI-FILAMENT WIRE AND TAPE

2. BSCCO 2212 AND SILVER SYSTEM

3. METAL PRECURSOR AND SILVER SYSTEM

4. MANUFACTURING PROCESS TO INCREASE DENSITY AND FLUX PINNING SITES

5. CONCEPTS FOR REDUCING THE AMOUNT OF SILVER

6. LONG LENGTH CONTINUOUS PRESSING

7. OTHER POWDER SYSTEMS- YBCO, THALLIUM, ETC.

WHAT ARE WE SELLING?

MANUFACTURING WIRE PROCESSING EQUIPMENT

FOR THE WELDING INDUSTRY WE HAVE DESIGNED AND BUILT TUBULAR WIRE EQUIPMENT, WIRE DRAWING EQUIPMENT, SPOOLING EQUIPMENT

WE HAVE SOLD WIRE DRAWING AND SHAPING EQUIPMENT FOR HIGH TEMPERATURE SUPERCONDUCTORS TO TWO LABORATORIES.

WE CAN PROVIDE FILLED PREFORMS FOR OTHERS TO PROCESS TO TAPE PER THEIR DESIRED PROCEDURES.

WE COULD ALSO PROVIDE LONG LENGTH PRESSING AS A SERVICE.

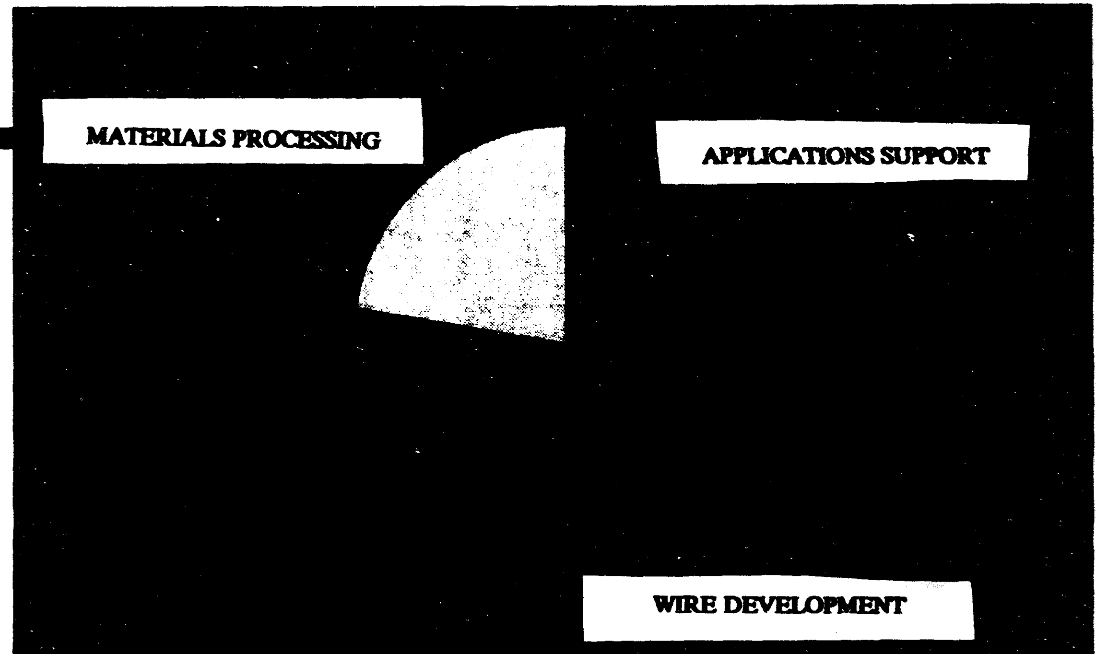
WE CAN BE A PROCESSING SERVICE FOR RESEARCHERS IF THEY WANT TO TAKE THEIR NEW POWDERS AND HAVE A FAST SCALE UP TO LONG LENGTHS. WE HAVE PRODUCED SAMPLES USING AS LITTLE AS 10 GRAMS OF POWDER.

WE HAVE DRAWING, ROLLING, LONG LENGTH PRESSING AND SINTERING EQUIPMENT TO PROCESS FINAL TAPES.

WE ALSO HAVE HOT EXTRUSION EQUIPMENT AND ONCE THE SIZE OF STRIP IS DEFINED. WE BELIEVE IT IS POSSIBLE TO EXTRUDE THE STRIP TO SIZE, WHICH WOULD LOWER THE COST OF THE SILVER STRIP.

SNL Development Opportunities

- *Cryogenic engineering analysis*
- *HTS powder processing of thallium precursor*
- *Non destructive testing, e.g. x-ray tomography*



Technology Transfer and Development Opportunities

- *New products from industry*
- *New licensing opportunities from the National Laboratories*
- *New commercial opportunities*
- *Partnering opportunities for new developments*
- *What development is required for future applications?*

Technology Development and Transfer Opportunities

Roger B. Poeppel

Director, Energy Technology Division

Argonne National Laboratory

Argonne, IL 60439

High Temperature Superconducting Wire Development Workshop

St. Petersburg, FL

February 16 & 17, 1994

Energy Technology Division
Argonne National Laboratory

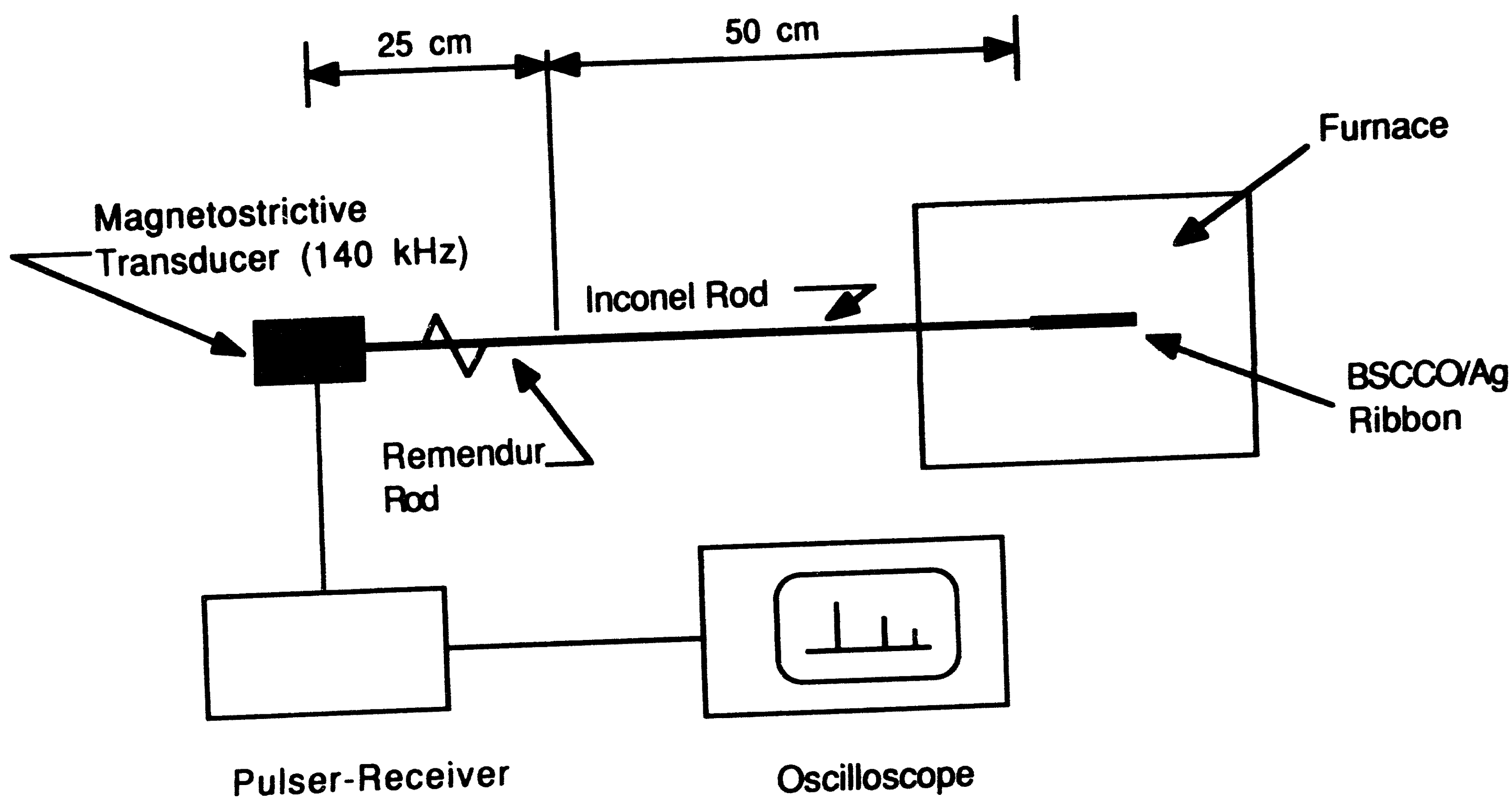
Ultrasonic Velocity of Sound Determination of Microstructure Evolution

- High–temperature sound velocity measurements can be used to help optimize critical current density by monitoring liquid phase during fabrication of BSCCO/Ag ribbons.
- Monitoring the liquid phase during fabrication is critical to the production of a high current wire (ribbon).
- At the present time, there is no real time information regarding when the liquid phase forms and when it disappears.

Approach

BSCCO/Ag Ribbons

- BSCCO/Ag ribbons are sintered at 845°C while the velocity of sound (140 kHz) is monitored to detect liquid phase.
- Control experiment is carried out where the temperature is continually increased at a fixed rate.
- Velocity of sound in the ribbon depends on the amount of liquid present.
- An ultrasonic technique could be easily adapted to a production line environment with minimum safety hazards while still providing an effective system for process control and quality assessment.



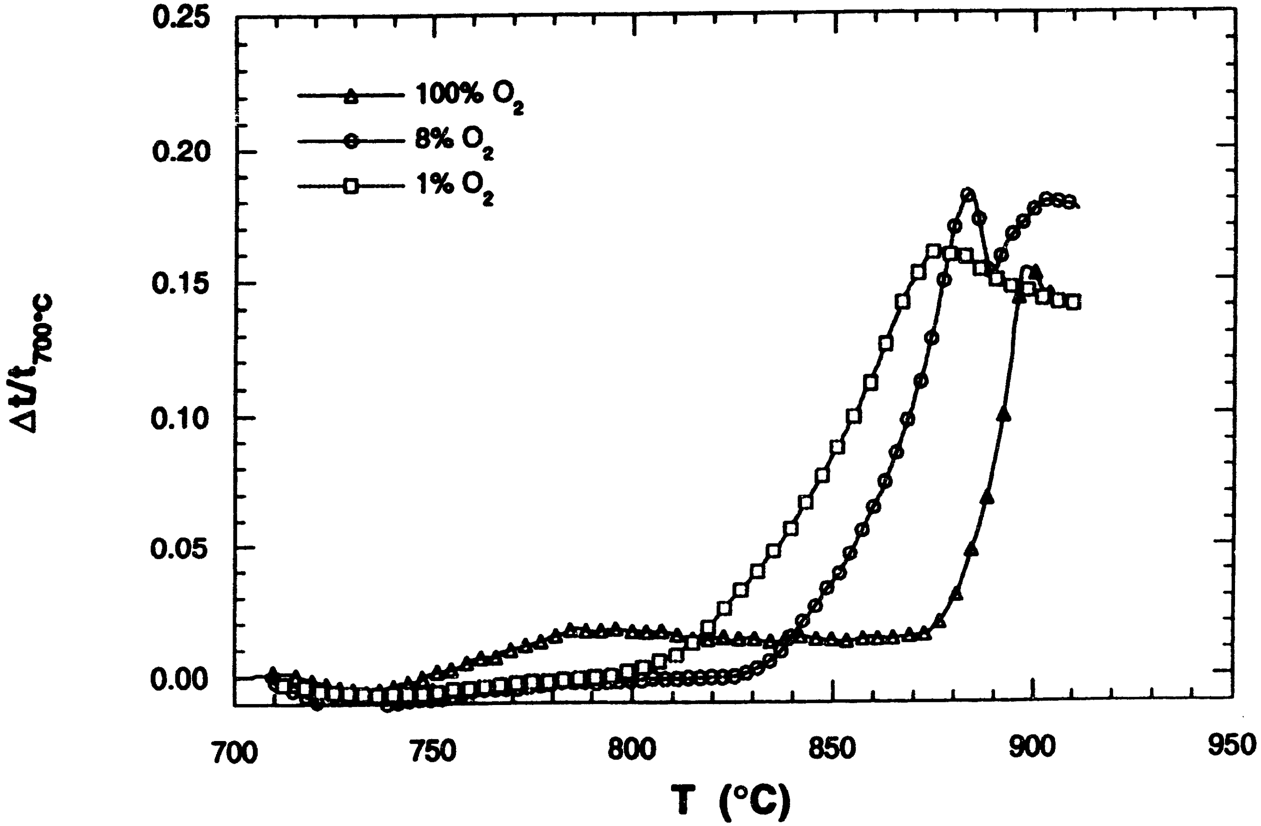
25 cm
50 cm
Furnace
Magnetostrictive
Transducer (140 kHz)
Inconel Rod
BSCCO/Ag
Ribbon
Remendur
Rod
Pulser-Receiver
Oscilloscope

GE Doped TBCCO

RUNS: 100% - TA11/w
10% - TA10/w
1% - TA9/w

100% - PPa, rank 5
other - XCa, rank 5

Phase Pure TBCCO/Ag
Relative Transit Time Variations



High Thermal Conductivity High Electrical Isolation Connection

General Application

- Electrical conductors can require cooling to absorb the heat generated along their length due to ohmic losses (I^2R).
- Cooling can be through connections at discrete points at the surface of the conductor.
- The connections should have the following essential characteristics:
  - * High thermal conductance
    - – Low temperature differential
  - * High electrical isolation
    - – Low leakage current
    - – High voltage breakdown
  - * Long term reliability

High Thermal Conductivity High Electrical Isolation Connection

Background

- A thermal interference junction, which connects an inner metallic disk, an intermediate composite tube, and an outer metallic ring was developed at Fermilab.
- The junction was extensively evaluated in the laboratory, in model SSC magnets, and in prototype SSC magnets and found to satisfy all design requirements.
- The junction has been patented by Fermilab (U.S. Patent No. 4,696,169).
- The junction has and/or is planned for use in the support members of superconducting magnets that include the Fermilab Low Beta Quad, the SSC, and the CERN Large Hadron Collider.

High Thermal Conductivity High Electrical Isolation Connection

Background

- The Superconducting Super Collider (SSC) magnet support members require junctions between composite tubes and metallic end connections.
- The junctions have high mechanical strength (greater than that of the composite tube), long term reliability, are unaffected by thermal cycling between room and cryogenic temperatures, are manufacturable by conventional means and are cost effective in nature.

High Thermal Conductivity High Electrical Isolation Connection

Potential Uses

- Superconducting magnet current leads
  - * Superconducting Magnetic Energy Storage
  - * Particle accelerator facilities
  - * Magnetic ore separation
  - * Space based cryogenic systems
- Cryocooler thermal connections
- Power bus cooling/isolation
- Power supply cooling/isolation

Technology Transfer & Development Opportunities at Los Alamos National Lab

- Facilities
  - Materials Science Laboratory
  - Thallium Processing Lab
  - Wire/Coil Fabrication
  - Superconductor Characterization
- Enabling Technologies
  - Physics/Chemistry/Ceramics
  - Mechanical Engineering
- Applications Development
  - Engineering Design/Analysis
  - Prototype Testing

Los Alamos

Development Thrust Areas at Los Alamos

- **Bulk Superconductors** (Y123, Bi-2212, -2223, Tl-1223)
  - Powders
  - Wires & Tapes
  - Thick Films
  - Coils
- **Application Opportunities**
  - Magnetic Separator
  - Current Lead
  - Power Switch
  - Variable Resistor
  - Magnetic Shield

TECHNOLOGY TRANSFER OPPORTUNITIES
OAK RIDGE NATIONAL LABORATORY

presented by

Robert A. Hawsey, Manager
Superconductivity Partnerships Program
OAK RIDGE NATIONAL LABORATORY
P. O. Box 2008
Oak Ridge, Tennessee 37831-6040
615-574-8057, Fax 615-574-6073

presented to

HIGH TEMPERATURE SUPERCONDUCTING WIRE DEVELOPMENT WORKSHOP

February 16-17, 1994
St. Petersburg, Florida

ornl

SUPERCONDUCTIVITY PROGRAM FOR ELECTRIC POWER SYSTEMS
OAK RIDGE NATIONAL LABORATORY

SUPERCONDUCTING TECHNOLOGY AVAILABLE FOR LICENSE

ESID No.	Title/Description
1384-X	*Process to Enhance Superconducting Phase Formation, Grain Alignment, and Fracture Properties of High Temperature Superconductors* Method to provide a large area template of silver on which the superconducting phase can form rapidly and grow in an aligned fashion. The process also results in improved mechanical properties of the resultant wires.
1193-X	*Process for Fabricating Continuous Lengths of Superconductor** A process for fabricating continuous lengths of superconductor composed of one or more thin, high-temperature superconducting oxide layers between metallic substrates.

*Industrial participant may have certain rights to this technology.

ornl

SUPERCONDUCTING TECHNOLOGY AVAILABLE FOR LICENSE

ESID No.	Title/Description
1467-X	*Superconducting Structure and Method for Making Same* An inexpensive method for producing protective coatings on oxidation resistant alloys is described. This in turn permits substitution of relatively inexpensive yet strong alloys for silver as a high T_c substrate.
1450-X	*Improved Efficiency High T_c Superconducting Magnet Lead Materials* Textured high T_c materials are being developed as current leads for helium cooled magnets, etc. They operate between 77 and 4.2 K. Oriented 123 is currently not as good as the two Bi-Pb compounds because its thermal conductivity is higher and this leads to more heat leakage and He evaporation. This invention lowers the heat leakage by reducing the thermal conductivity of the 123 compounds, allowing use of 123-type leads for high stray field applications.

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SUPERCONDUCTIVITY PROGRAM FOR ELECTRIC POWER SYSTEMS
OAK RIDGE NATIONAL LABORATORY

SUPERCONDUCTING TECHNOLOGY AVAILABLE FOR LICENSE

ESID No.	Title/Description
343-X	*Electric Dispersion Reactor*

This system produces ultra-fine ceramic particles of desired shapes and sizes. The control over shapes and sizes provided by the device could eliminate tiny flaws that eventually become cracks in normally brittle ceramics, especially in composites made from more than one material. In addition, such control could eliminate structural problems that diminish superconductivity in bulk superconducting materials. The new approach to producing ceramics could improve the electrical current-carrying capacity of high-temperature superconducting materials.

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SUPERCONDUCTIVITY PROGRAM FOR ELECTRIC POWER SYSTEMS
OAK RIDGE NATIONAL LABORATORY

SUPERCONDUCTING TECHNOLOGY AVAILABLE FOR LICENSE

ESID No.	Title/Description
1039/ 1040-X	*Method for Preparation of $(BiPb)_2 Sr_2Ca_2Cu_3$ Oxide Powders and Method for Preparing Superconducting Wires from Oxide Powders*

An aerosol pyrolysis technique is disclosed that enables production of submicron-sized powders with little or no lead loss.

Conductors made with aerosol powders and a powder-in-tube technique with a continuous fabrication process are described. Short heat treatment times, high fractions of the desired superconducting phase, and small non-superconducting secondary phase particles are some of the advantages of this method.

For information, please contact:

R. Russell Miller
Office of Technology Transfer
Martin Marietta Energy Systems
P. O. Box 2009
Oak Ridge Tennessee 37831-8242
615-574-8746, Fax 615-574-9241

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The Power System Technology Program Integrates Expertise

- **Analysis**
  - — Power System Steady State and Transient Behavior
  - — Equipment Modeling
  - — Benefits Assessment
  - — Utility / Manufacturer Standard Practices

- **Technology Research**
  - — Dielectric Material Physics
  - — Electromagnetic Field Theory
  - — Biotechnology
  - — Control and Protection Systems
  - — High Voltage Phenomena

- **Partnerships**
  - — Inter / Intra Laboratory
  - — Utility Industry

POWER SYSTEM TECHNOLOGY PROGRAM

- **Goal:** **Develop technologies to increase capacity, efficiency, and flexibility of electric power delivery**

- **Research Focus Areas:**
  - — **Electromagnetic Field Effects**
  - — **Advanced Power System Analysis and Control**
  - — **Compact, High Capacity Transmission Options**
    - o **High Voltage dc**
    - o **High Phase Order ac**
  - — **Efficient Electric Motor Systems Development**
  - — **Dielectric Materials in Power Equipment**
  - — **Electric System Disturbances**
    - o **Geomagnetic storms**
    - o **Lightning phenomena**
  - — **Renewable Resource Integration**
  - — **Integration of Energy Storage (SMES and Flywheels)**

UNIQUE MEASUREMENT CAPABILITIES AVAILABLE TO INDUSTRY

HTS WIRE RAPID SCREENING SYSTEM:

- Critical currents to 100 A continuous (Future: Pulsed currents)
- Refrigerated: 20 K - 90 K (Lower temperature planned with HTS leads)
- $0 \leq H \leq 1.7$ T
- Up to 3.8-cm-long wires
- Fully automated data acquisition system

UNIQUE MEASUREMENT CAPABILITIES AVAILABLE TO INDUSTRY

SHORT SAMPLE MEASUREMENT SYSTEM:

- Angular dependence of J_c (T,H)
- Currents to 500 A pulsed, with highly-controlled pulse shape, 100 μs rise time
- 2.5-cm-long samples
- 17-T background field
- Fully variable temperature

LARGE VARIABLE TEMPERATURE CRYOSTATS

Description	Unit 1	Unit 2	Unit 3
Background magnet type	Cu	Cu	SC
Warm bore of background magnet, cm	15.2	28	38
Max. coil diameter, cm	7.5	24	34
H, Tesla	8	6	8
Field ramp rate, T/s	2	2	N/A
T (K)	4.2-100	4.2-100	4.2-100
Availability	Now	April 1994	Fall 1994

DC power supplies: 3 kA and 25 kA (solid state)
Motor/generator sets: 17 kA

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Technology Transfer

- **Mission**
  - *Contribute to the economic well-being and quality of life in the nation through the technology development, in partnership with U.S. industry, of high temperature superconductivity for electric utility and renewable energy applications*

Technology Transfer

- **Superconductivity Partnerships Program**
  - Program Manager: Robert McConnell (303-384-6419)
- **Superconductivity Partnership Initiative Technical Support and Applications Task**
  - Task Leader: Richard Blaugher (303-231-7298)
- **Superconducting Wires and Tapes Task**
  - Task Leader: David Ginley (303-231-7873)
    - » Philip Parilla
    - » Raghu Bhattacharya
    - » Douglas Schulz
    - » Jeff Alleman
    - » Anna Duda

Technology Transfer

- **General Electric: CRADA I ($100K/yr)**
  - Development of Thallium-Oxide Superconducing Materials for Electric Power Applications: 9/92-8/93
- **General Electric: CRADA II**
  - Pb and Sr-substituted Tl-1223 Thick Films: In final negotiations
- **Sierra Research: CRADA ($100K/yr)**
  - Development of High Temperature Superconducting Materials for Solid State Cooling Technologies: 9/93-9/95
- **Davis, Joseph & Negley: Work For Others**
  - Superconductor Oxide Plating by Metafuse Process: 7/93-7/94

Technology Transfer

- **Records of Invention**
  - Available for transfer to industry are three records of invention and one patent application resulting from NREL's electrodeposition process R&D
- **CRADA solicitation**
  - Using the Commerce Business Daily, NREL solicited industry interest in a CRADA focussing on the application of high temperature superconductivity
  - From an evaluation of 6 respondents, one was selected for negotiation
- **Conference on the Science and Technology of Superconducting Films: Breckenridge, CO**
  - May 31 - June 3, 1994 (Abstracts due March 1, 1994)

BNL – S. C. Properties
Characterization
Facilities

* $I_c(T, H, \theta)$ · T = 4.2, 27,

· H = 0–8 T $\frac{54\text{–}90\ K}{\text{Liq. } O_2}$

· –90° · θ · + 90°

· V ≥ 10^{-9} V

[at FSU
· T = 4.2 K, 27 K
· H = 0–20 T
· θ]

* I_c (ε, T, H)
· T = 4.2, 77 K
· H = 0–0.5 T
· Δ–4 T

* ac Losses (Magnetic)
· T = 65–77 K
· frequency · 15–250 Hz
· H < 15 [illegible] O_e

High-T_c Superconductivity at the National High Magnetic Field Laboratory

Justin Schwartz
S. W. Van Sciver
B. Brandt
Y. Hascicek
H. Weijers
J. Kessler
(numerous students)

OUTLINE

- User Facilities
- In-house Characterization
- Internal synthesis / processing / properties

Facilities

- The NHMFL is primarily a user's facility for measurements and experiments in large magnetic fields
- A 290,000 sq. ft. facility has been constructed with funding from the State of Florida and the NSF
- Magnet Facilities:

in operation: (serving users)	2	20T SCMs (50 mm)		
		20T resistive (50 mm)		
coming online:	2	20T resistive (50 mm)	Spring	'94
	3	27T resistive (33 mm)	December	'94
	1	45T hybrid (33 mm)	June	'95

- some probes will be available for users
- facilities personnel will work with the users to address their needs

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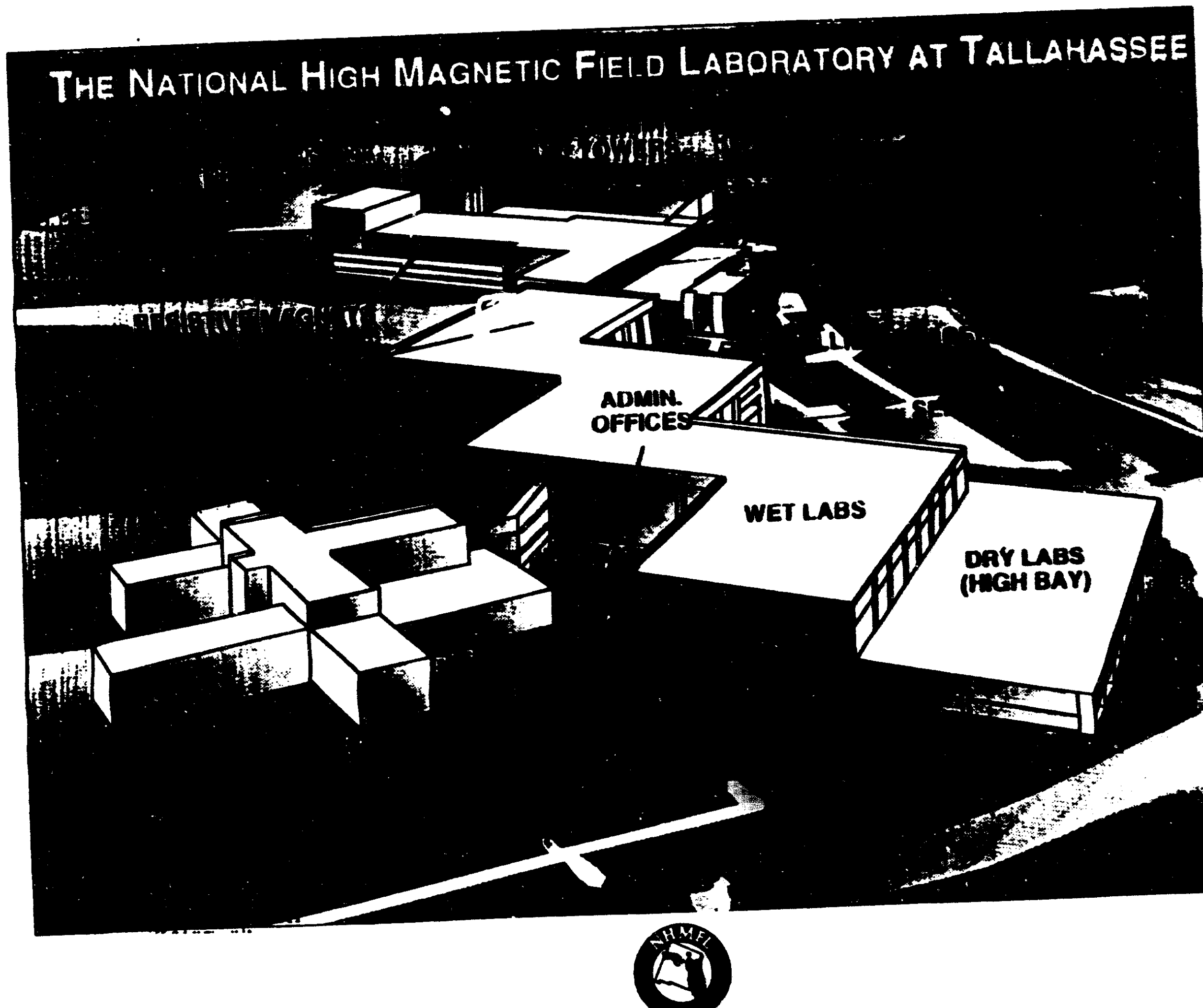


In-house Characterization

- short and long samples and small coils
- transport J_c (T, B, ε, σ)
- collaboration with industry, universities and labs
- additional collaborations are sought

Internal Materials Research

- wire processing seeded by NHMFL
  (wire drawing and rolling equipment plus post-doc)
- other funding via traditional "university mode"

tivities Include:

- strengthened sheaths for 2212
- dopants for improved high field flux pinning in 2212
- synthesis of Hg-based superconductors via conductor relevant approaches
- irradiation effects on Hg-based materials
- PIT and doctor blade tape casting

lustrial and DOE-lab interactions are sought

HIGH TEMPERATURE SUPERCONDUCTING
WIRE DEVELOPMENT WORKSHOP

INDUSTRIALIZATION OF NOVEL SUPERCONDUCTING MAGNET MANUFACTURING METHODS DEVELOPED AT THE SSC LABORATORY.

PRESENTED BY JOHN SKARITKA
SSC LABORATORY

FEBRUARY 17, 1994

This work performed under contract to the U.S. Department of Energy

INTRODUCTION

- The Superconducting SuperCollider was to be the largest Scientific Instrument in the world.
- A cascading series of accelerators, SSC was to provide pulsed beams of protons of up to 20 trillion electron volts to perform basic high energy physics research.
- Over 8000 superconducting dipoles and 2000 Quadrupoles would have been used to control the trajectory of counter rotating proton beams around an elongated arc over 54 miles in circumference. Over 120 miles of accelerator beam line were to be built.
- This paper is primary concerned with lesser known types of magnets used in the SSCL. All the superconducting corrector magnets used for the collider rings and high energy booster accelerator.
- These magnets were to provide adjustment and correction to magnetic optics of the accelerator.

UNIQUE REQUIREMENTS OF THE SSCL CORRECTOR MAGNETS

- Approximately 8000 superconductor corrector magnets were to be built.
- Various Corrector Magnets would be manufactured into custom assemblies.
- Axial, space was very limited, the correctors were sandwiched between the high profile main Dipoles and Quadrupoles.
- Radialy; support structures, cryogenic equipment, high current buss work and instrumentation limited magnet diameter.
- During production it would be unlikely that no two corrector magnet packages would be built in sequence.
- Over 2000 corrector magnet packages would be required.
- Field strength, field quality and magnetic alignment requirements exceeded those of magnets used in previous accelerator application.
- Extreme reliability would be necessary, only 1-2 failures would be permitted per year, over a 25 year machine life.

- Due to the cost of refrigeration, the cryogenic feed through and the thousands of current leads required minimum thermal loss. Maximum operating currents were chosen to be 100 amperes or less.

- The budget for development and production was definitely limited.

- The final requirements of the correctors might not be precisely know until after a series of production dipoles and quadrupoles were built and tested.

- Highly compact coils required the highest practical coil current density with the most efficient use of iron.

- The production method had to be extremely flexible, highly reliable and cost effective.

- No technology previously used in any Accelerator could meet all the requirements simultaneously, therefore new techniques had to be developed.

The following is the program that was adapted to address these unique requirements.

- Requirements formulated
- R & D at contracted labs and SSCL
- Technological options identified
- Phase I Industrialization
- Down selection and upgrade technological options
- Phase II Industrialization
- "Value Engineering" and design otimization
- Incorporation of final requirements derived from production main magnet.
- Preproduction
- Issue of fixed priced "Build to print production" contract.
- Low rate production
- Full rate production

DEVELOPMENTS THAT OCCURED DURING THE RESEARCH PHASE OF THE PROGRAM.

- Magnets developed at these laboratories were largely generic in nature, but most of the ideas first investigated during this period found their way into the industrialization prototypes.
- LBL developed potted, high density random wound cosine theta magnets.
- Potting caused more problems that it solved, since epoxy took up valuable space.
- High density could not adequately be impregnated to assure reliable performance.
- LBL confirmed that wrapped film insulation was critical to improve magnet performance.
- TAC found that super ferric magnets used less superconductor and incorporated an automated method for coil fabrication.
- The SSCL established it's first in-house corrector lab during this time period.

DEVELOPMENTS THAT OCCURED DURING THE RESEARCH PHASE OF THE PROGRAM.

The following items were incorporated into the conceptual design.

- 1. The superferric iron design was adopted for all magnet options.
- 2. Jelly role coil design was incorporate due to its potential for automation.
- 3. Wrapped kapton was adopted as the primary insulation system.

Three technologies were selected for Industrialization.

- 1. Ordered Wound Technology.

  A method similar to magnets used at the HERRA accelerator in Germany.

  It produces the highest density coil, but does not require potting and uses a unique wiring procedure developed at the SSC, that illuminates all crossovers in the ends of the magnet coil.

  This method is the most conventional in appearance but does represent a significant advancement in coil winding. It uses much of the development that took place at LBL.

- 2. Jelly Role Technology.

  A method similar to that used with RHIC corrector magnets developed at Brookhaven National Laboratory.

  This technique was advanced by TAC. It used an automated method to deposit insulated superconductor wire accurately in a coil pattern on a flat substrate. After wiring the substrate can be wrapped around a coil support mandrel to form a coil structure, resembling a jelly role like structure. Iron is then secured around the coil to form a super ferric magnet.

- 3. <u>Direct Wire Technology.</u>

This methods is similar to techniques employed to deposit superconductor on the beam tube magnet correctors used in the HERRA machine in Germany.

This technique was exclusively developed at the SSC Laboratory, and is an amalgamation of techniques 1 and 2.

This is the most automated method using a similar automated wire bonding technique used in Jelly role technology, but depositing wire directory onto a coil support mandrel to form a completed coil using no further processing or potting, hence the name "Direct Wire.

PHASE I INDUSTRIALIZATION.

- This phase was initiated to establish an experience base in U.S. Industry.

- Three contractors were selected by competitive bid and best technical proposal for cost plus fixed fee contracts.

- Each contractor would investigate a particular technical option. SSCL selected the technical options for the contractors based on the companies previous experience and capabilities.

- An in-house laboratory provided Technical support and training for the Industrial contractors. This Laboratory performed incoming inspection and testing of industrially built magnets.

- The Following Contractors were selected:

Contractors	**Technical Option**
Martin Marietta	Jelly Roll
Everson Electric Co.	Ordered Wound
Babcox and Wilcox	Direct Wire

Phase I Results:

- Jelly Roll Magnet Technology proved to be more expensive than previously expected. Industrially built jelly roll prototypes never achieved the levels of initial performance of earlier laboratory built prototypes.

- Industrially produced ordered wound prototypes appeared to have best performance for initial training behavior. Manufacturing problems continued to cause concerns for long term reliability and production costs.

- Initial results of the direct wire magnets showed poor initial training behavior, but excellent training memory. The process had few manufacturing problems. The direct wound magnets were built on schedule and within budget.

Phase II Industrialization

- The Phase II Industrialization Program was started as new cost plus fixed fee contract competency bid among the participants for Phase I.
- The goal of Phase II was to incorporate any new requirements or information obtained during Phase I into a magnet package composed of Dipole, Quadruple and Sextuple Corrector Magnets. These magnet packages were to achieve the operational requirements of production corrector magnets and would be used in preproduction spool pieces.
- The following contractors were selected:

Contractors	**Technical Option**
Martin Marietta	Ordered Wound
Everson Electric Co.	Ordered Wound
Babcox and Wilcox	Direct Wire

Technological lessons learned from the Corrector Development/Industrialization Program.

- 1. The Elastic modules of a coil has been proven to be an important criteria for improved initial and reproducible magnet performance. Compressive elastic modules of greater than 500,000 lbs/in^2 will give acceptable training behavior .

- 2. High prestress may not be necessary as long as coil modules and matrix material strength is adequate to prevent gross motion due to Lorentz loads in coil assemblies.

- 3. A wrapped insulation, specifically Kapton wrapped wire allowing a slip plane between wire and matrix does significantly improve coil performance.

- 4. As long as there is no extraneous space for conductors to move into and the wire matrix supports itself, coil performance is optimised.

- 5. Both ordered wound coil manufacture and direct wire coil manufacture have been shown to be very effective technologies for the fabrication of Superconducting magnets.

  - Ordered wound coil technology reduces possible wire motion in coil ends and maximizes winding density in coil straight sections.

    This technique can be used for fine wire and may have many other applications using larger Rectangular Conductors.

  - For wire diameters of .5 mm and less, the direct wire technology represents a significant advancement in the state of the art of Superconducting coil manufacture. This extremely flexible and cost effective method will almost certainly find many applications outside the SSC project.

5 of 6

Managerial lessons learned from the Corrector magnet Development/Industrialization Program

- Research and basic developmental activities have been shown to best remain generic to incorporate the widest possible range of ideas.
- Once basic technologies have been identified collaborations with industry for specific applications and close cooperation between contractors and in-house laboratory support staff, prove to be extremely cost effective and assure efficient technology transfer between the laboratory and the contractors.
- Once the technology is fully developed, build to being fixed prices production contracts can be issued to minimize production cost.
- The relationship of shared liability proved essential to incorporate rapid changes and new information so as to rapidly advance in industrialization activities.
- To transfer liability to sub-contractors or program integrators may seem prudent but in high profile politically charged projects such as in the case of the SSC, liability will always find its way back to the prime contractor. For future projects the concept of shared liability should be considered to substancially reduce costs and in hanse rapid development and successful industrialization.

Dynamic Magnetic Compaction and Pressing

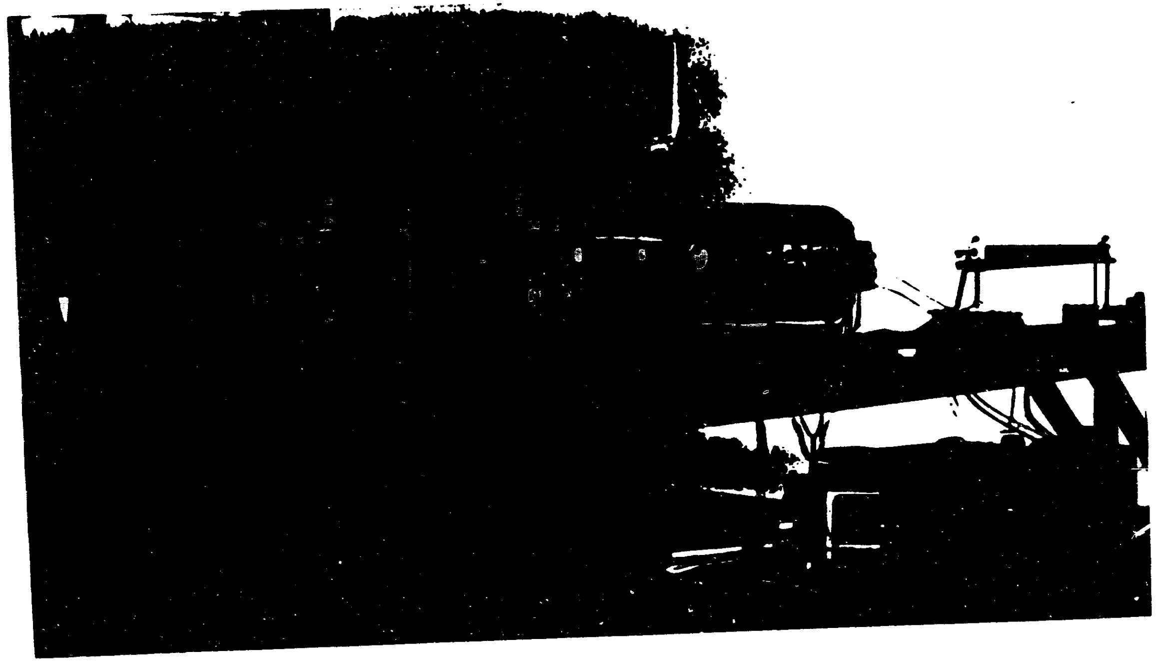
Densification Technology for HTS Fabrication

John P. Barber

IAP Research, Inc.
2763 Culver Avenue
Dayton, Ohio 45429-3723

IAP

DMC Densification System



- < 1 ms densification
- 50 ksi consolidation pressures (150 ton)
- up to 1000 °C consolidation
- air or inert gas atmosphere

DMC Technology is Ready for Application to HTS Conductor Fabrication.

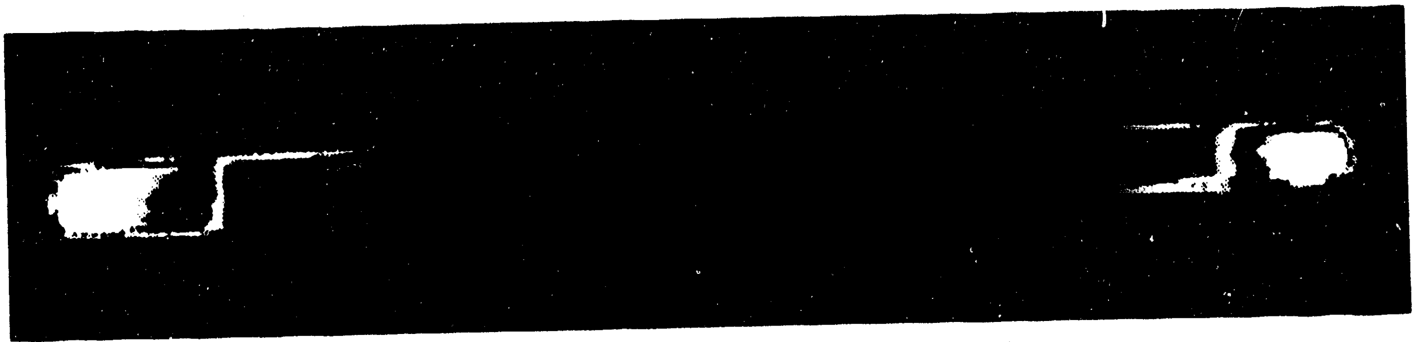
- Densification of PIT Preforms
  - high density (> 85% T.D.)
  - uniform pressure/density
  - eliminate drawing/easily rolled to tape
  - sheathed or unsheathed
  - enhanced properties

- Pressing of Long Tapes
  - ~ 5 ft. in a single press
  - up to 1 GPa (500 ton capacity)
  - uniform pressure

IAP

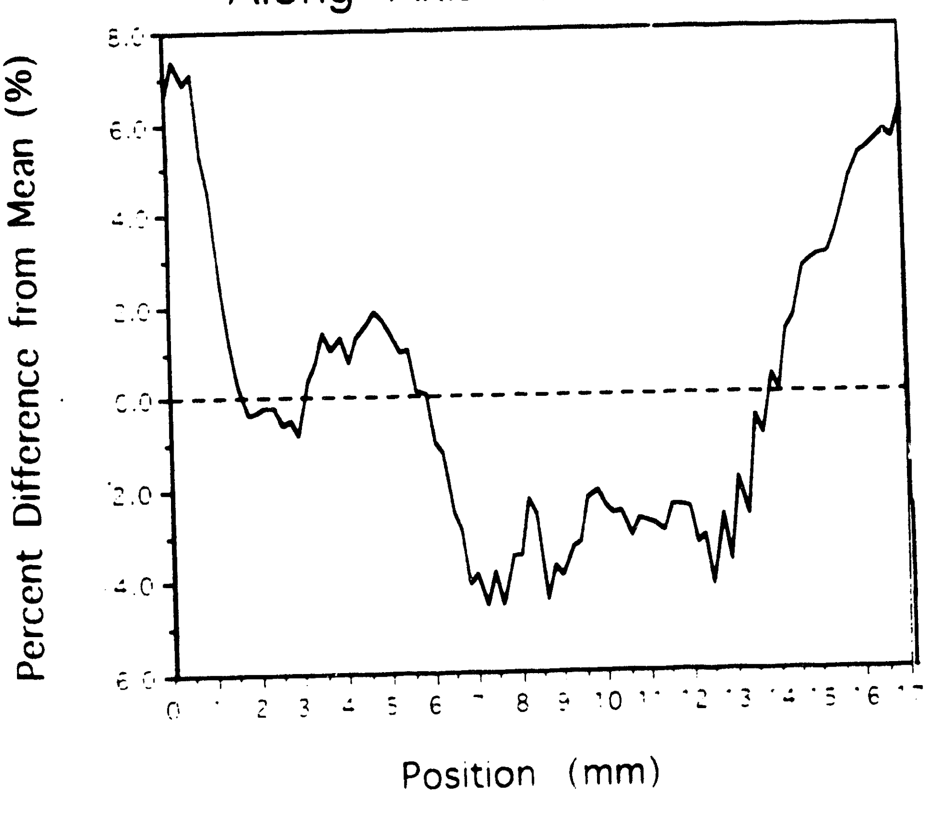
(19423)

CT Image Depicting Axial Variations in Density

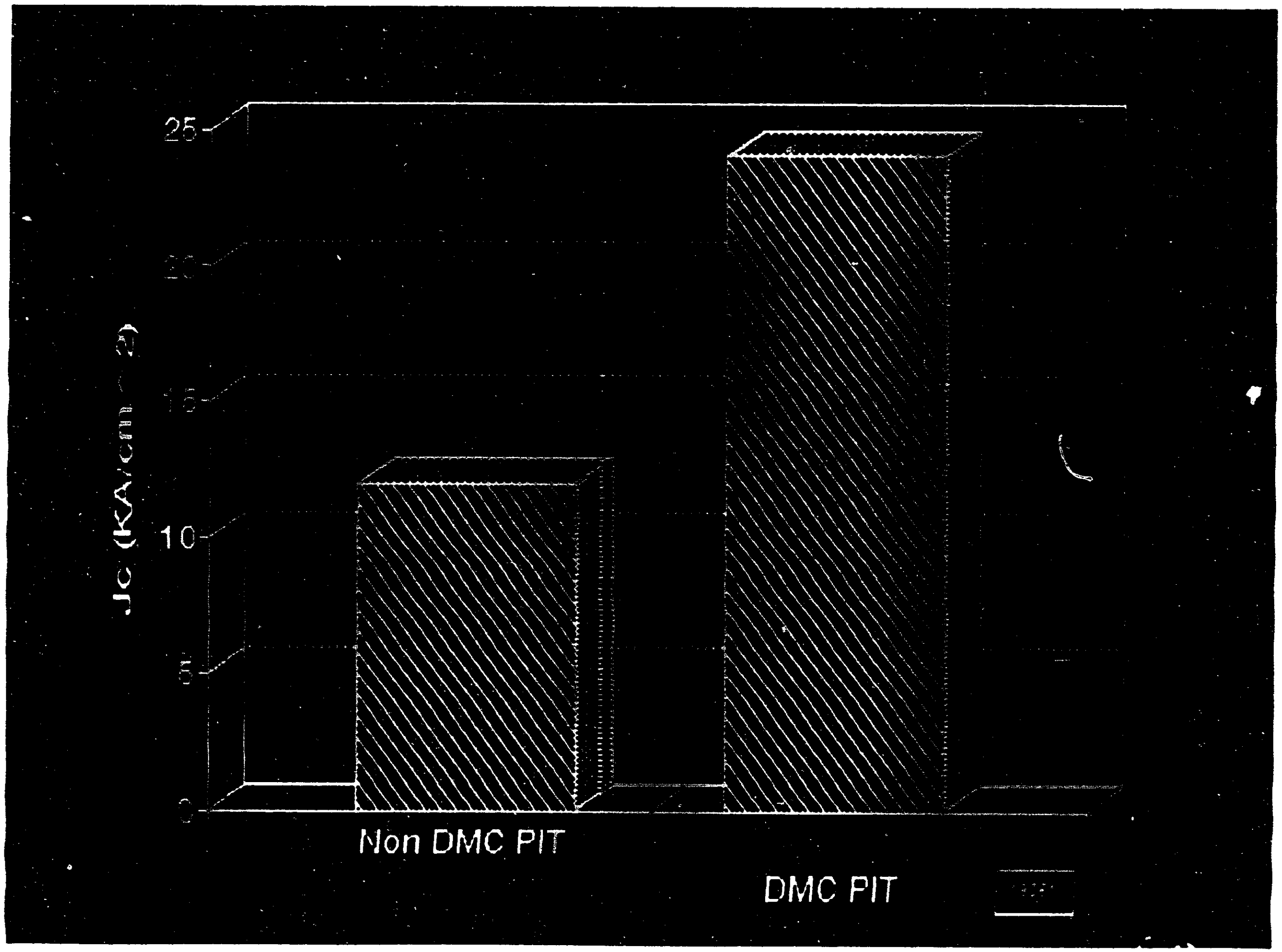


Color map in order of decreasing density:
White, red, yellow, green, light blue, dark blue

Normalized Density Variation Along Axial Cross-section



Performance Enhancement



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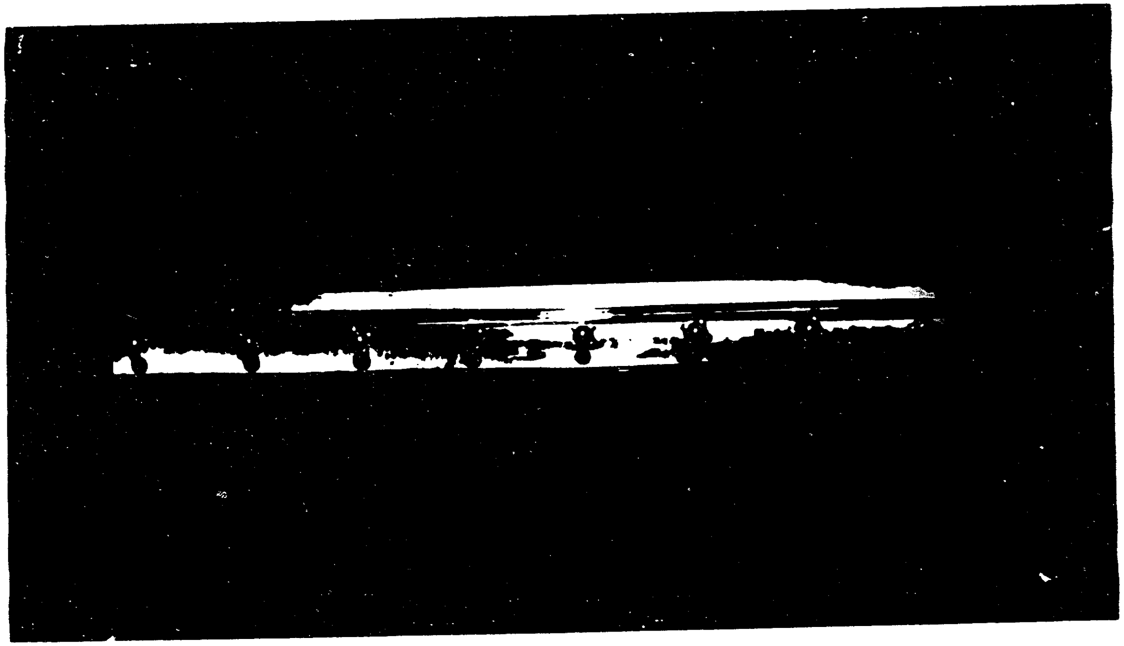
Flat Press for Pressing Long Tapes



- < 1 ms pressing time
- 60-130 ksi pressure on 5 ft long tapes (500 ton)
- commissioning underway

SUPERCONDUCTING COIL DEVELOPMENT & MOTOR DEMONSTRATION
BISMUTH CUPRATE CONDUCTORS

Objective: Development Industrial Capability to Manufacture Production Quantities of High Temperature Superconducting Wire with Quality Sufficient for Military and Commercial Applications.

Demonstrate Capability by operation of a 400 Horse Power Superconducting Motor Designed for Ship Propulsion using the High Temperature Superconducting Wire.

Approach: Contracts with US industries and National Manufacturing Center for production of Bismuth -Cuprate High Temperature Superconducting Coils for Retrofitting existing NAVY 400 HP Superconducting Motor.

Use Universities and NAVY Laboratories to Co-Develop Materials and Processing Techniques to Ensure Quality Production runs of Bismuth-Cuprate Conductors.

NAVY provides system design, system retrofitting, and Conducts Motor Demonstration

SUPERCONDUCTING COIL DEVELOPMENT & MOTOR DEMONSTRATION
BISMUTH CUPRATE CONDUCTORS

* Cooperative program between NAVY and ARPA

Funding:
NAVY: $1600 K
ARPA: $1400 K

Participants:

Navy:
Naval Research Laboratory (PI)
Naval Surface Warfare Center - Annapolis
National Center for Excellence in Metal Working Technology

Industry:
American Superconducting Corporation
Intermagnetics General Corporation
Transcience Corporation

University:
University of Wisconson (Applided Superconductivity Center)
State University of New York (New York Superconductivity Center)
Florida State University (National High Magnetic Field Laboratory)

SUPERCONDUCTING COIL DEVELOPMENT & MOTOR DEMONSTRATION
BISMUTH CUPRATE CONDUCTORS

ORGANIZATION CHART

Program Manager
Dr. D.U. Gubser
Naval Research Laboratory

LEAD ORGANIZATIONS (NAVY)

- Naval Research Laboratory
- Naval Surface Warfare Center-Annapolis
- National Center for Excellent in Metalworking Technology

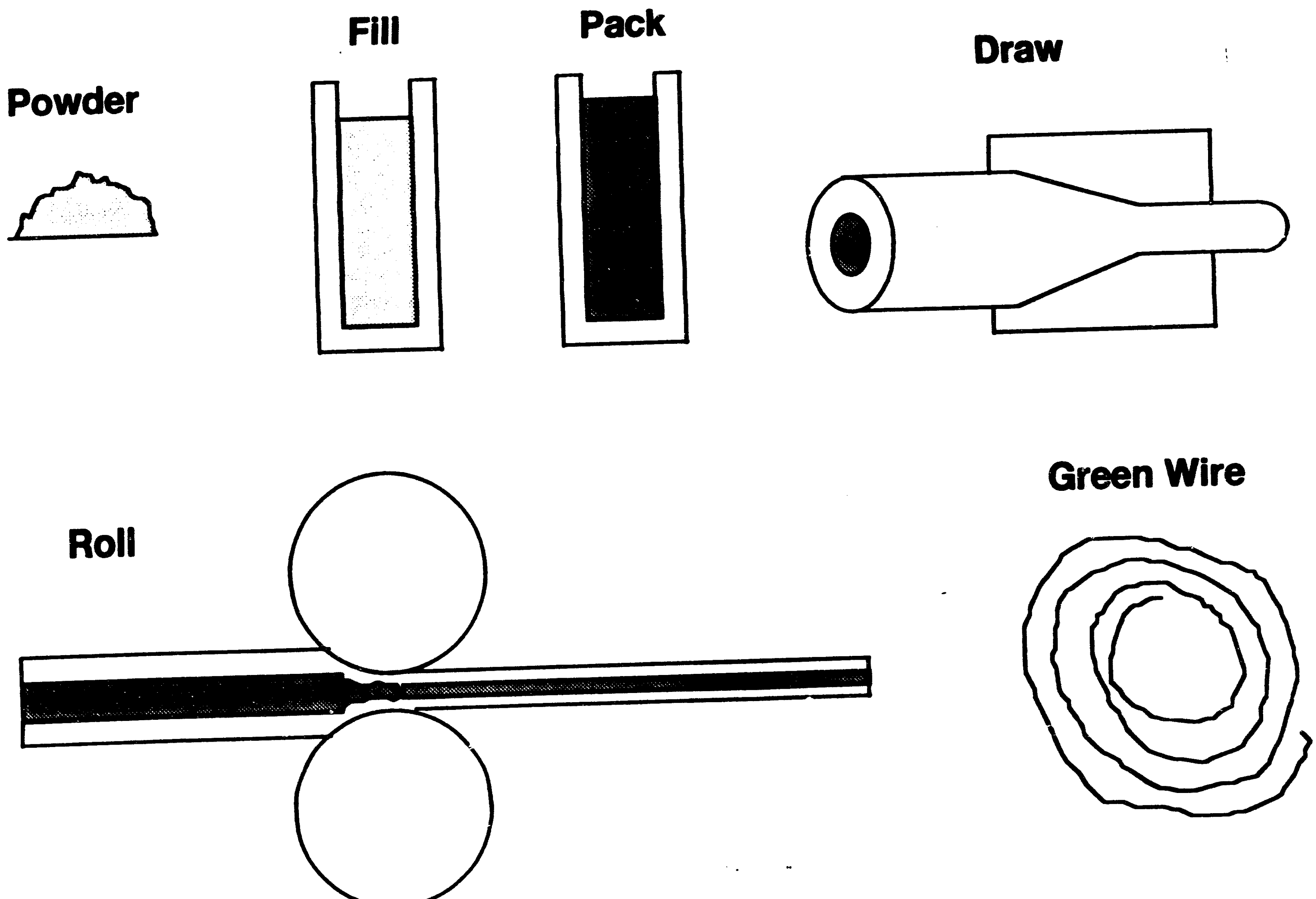
ASSOCIATE ORGANIZATIONS (ARPA)

- State University of New York-Buffalo
- University of Wisconson
- Florida State University
- Intermagnetics General Corporation
- American Superconductor Corporation
- Trans Science Corporation

CONTRIBUTING ORGANIZATIONS

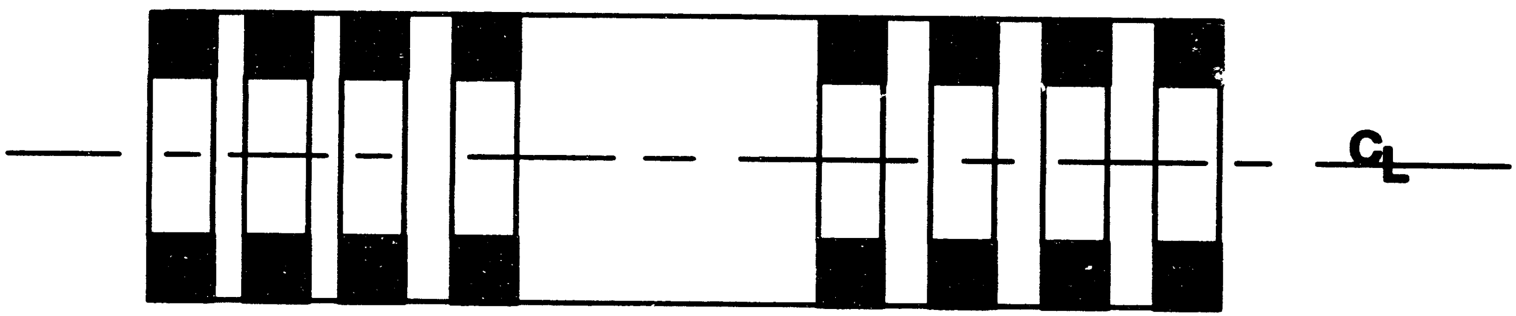
- Oxford Superconductor Corporation
- Air Force Propulsion Laboratory

SUPERCONDUCTING COIL DEVELOPMENT & MOTOR DEMONSTRATION
BISMUTH CUPRATE CONDUCTORS



SUPERCONDUCTING COIL DEVELOPMENT & MOTOR DEMONSTRATION
BISMUTH CUPRATE CONDUCTORS

Magnet System:



* 4 Coil Pairs (Six coil pairs delivered per industrial contractor)
* 100 - 125 Amperes per Coil
* Current Density, 10^4 Amp/cm^2
* Additional Coils supplied using NCEMT fabricated wire (IGC)
* One set of coils from Oxford Superconductor - No cost

Opportunities for Technology Development: Industry Perspective

Larry Masur
American Superconductor Corporation

American
Superconductor
CORPORATION

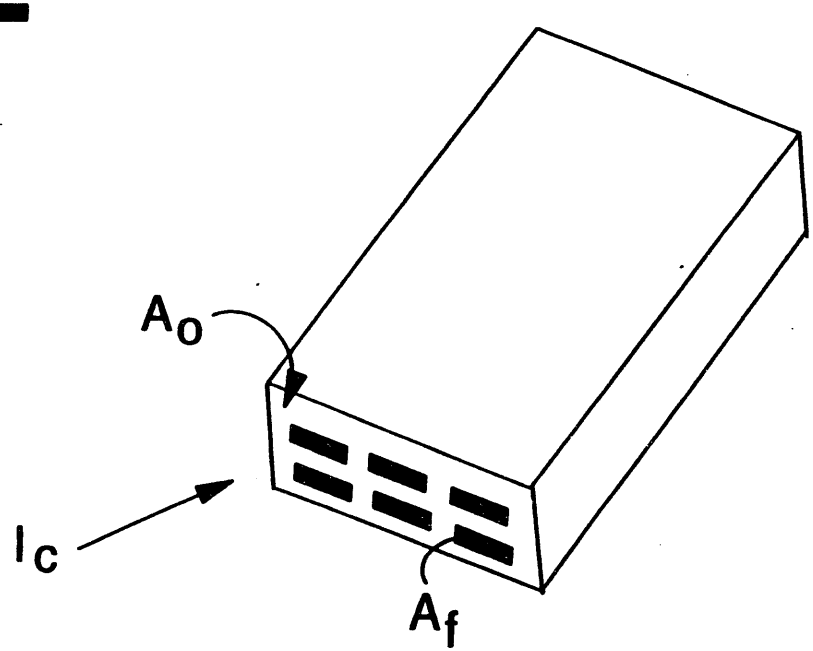
Outline

Conductor Development:
Achievements and Requirements

Systems Development:
Achievements and Requirements

American Superconductor CORPORATION

Critical Current Density



Filament Critical Current Density = $J_c = I_c / A_f$

Engineering Critical Current Density = $J_e = I_c / A_o$

fill factor = A_f / A_o

How high does Je need to be?

Coils and Magnets Applications:

10 - 25 kA/cm² at 20K and 5 Tesla

Power Transmission Applications:

> 10 kA/cm² at 77K and 0.1 Tesla

American Superconductor CORPORATION

Multifilamentary Composite Conductor Performance: Metallic Precursors (77K, self field)

Length (m)	Jc (A/cm²)	Je (A/cm²)
	($10^{-11}\Omega$–cm)	($10^{-11}\Omega$–cm)
.03	22,500*	4,050*
10	19,500	3,500
85	17,900	3,200

* 1μV/cm

American Superconductor CORPORATION

Multifilamentary Composite Conductor Performance: OPIT (77K, self field)

Length (m)	Jc (A/cm²)	Je (A/cm²)
	($10^{-11}\Omega$–cm)	($10^{-11}\Omega$–cm)
.03	22,100*	6,200*
60	17,800	5,000
280	10,900	2,500
650	7,000	1,600

* 1μV/cm

American Superconductor CORPORATION

Large Industrial Motors and Generators Achievements

- 2 hp motor demonstrated April 1993, 5 hp motor demonstrated January 1994 with EPRI and Reliance Electric

- SPI contract: develop and demonstrate 100 hp motor with Reliance Electric
- ATP contract: motor coil technology
- NRL/ARPA contract: motor and generator coils
- WPAFB contract: generator coils

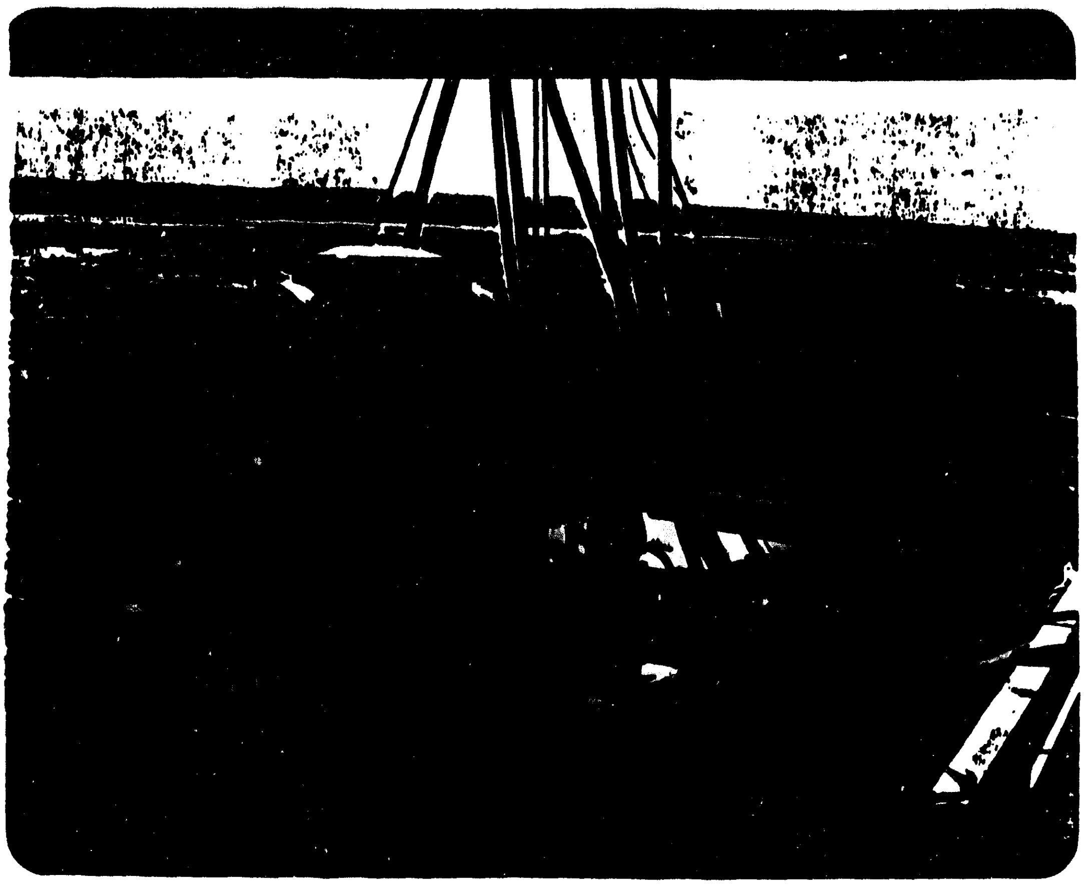
American Superconductor CORPORATION

Special Applications Achievements

- 500 amp prototype multistrand conductor demonstrated August 1992
- 2300 amp prototype multistrand conductor demonstrated November 1993
- Multistrand cable assembly design study completed by EPRI and Pirelli Cable Corporation
- Acoustic Transducer demonstrated June 1993 with US Navy

- SPI contract: develop and demonstrate fault current limiter with General Dynamics and Southern California Edison

American Superconductor CORPORATION



Critical Issues

- Conductor Je
- AC loss optimization
- Coil characterization
- Cooling technology

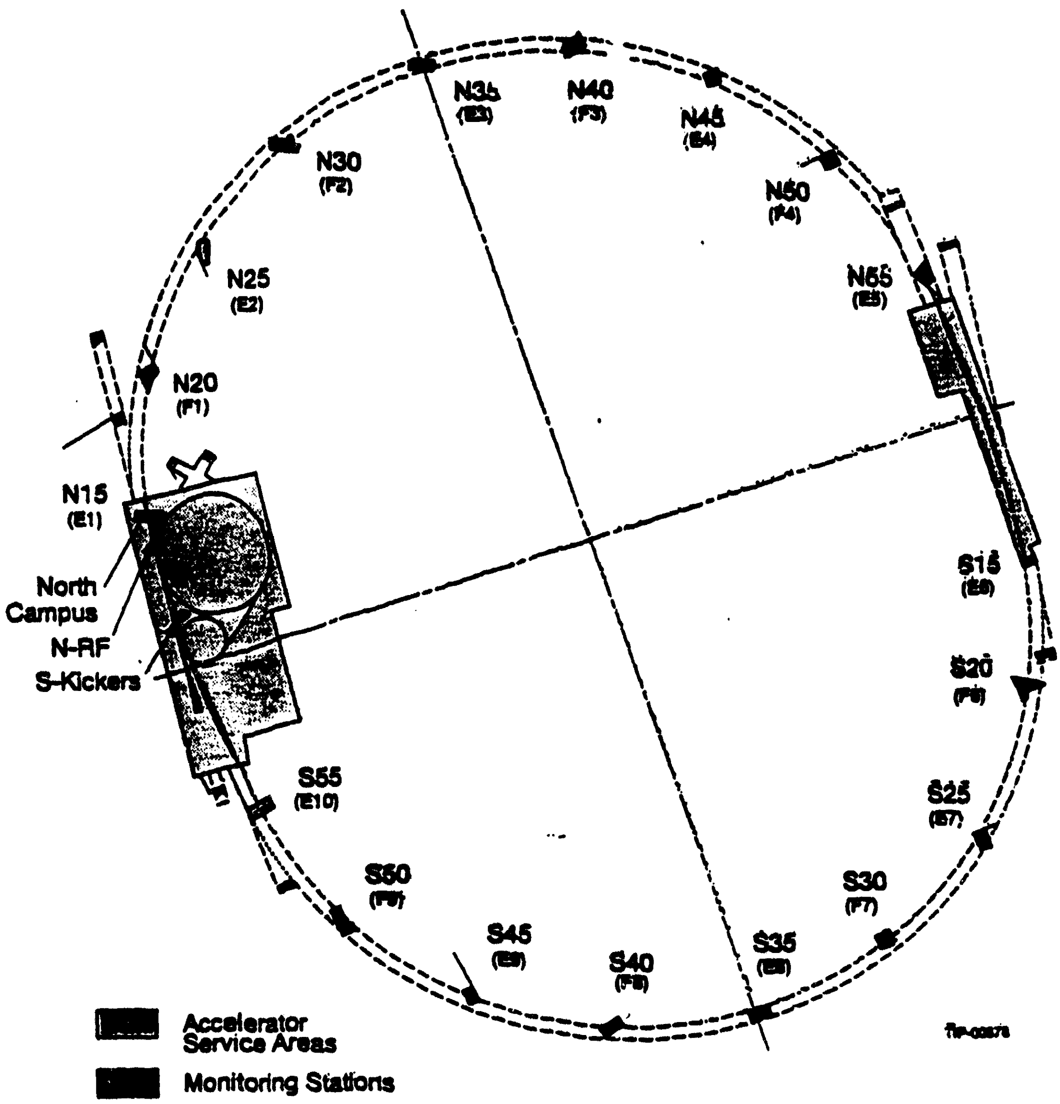
Summary

- The outlook for HTS components is very positive
- DOE has an important role in HTS technology development
  - DOE labs should continue to support critical path wire technology development:

    Je

    → understanding the current limiting mechanisms (microstructure-property relationships)
  - SPI-type programs are key to commercialization:

    systems integration


N35
(E3)
N40
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N30
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N50
(F4)
N25
(E2)
N55
(E5)
N20
(F1)
N15
(E1)
North
Campus
N-RF
S-Kickers
S15
(E6)
S20
S55
(E10)
S25
(E7)
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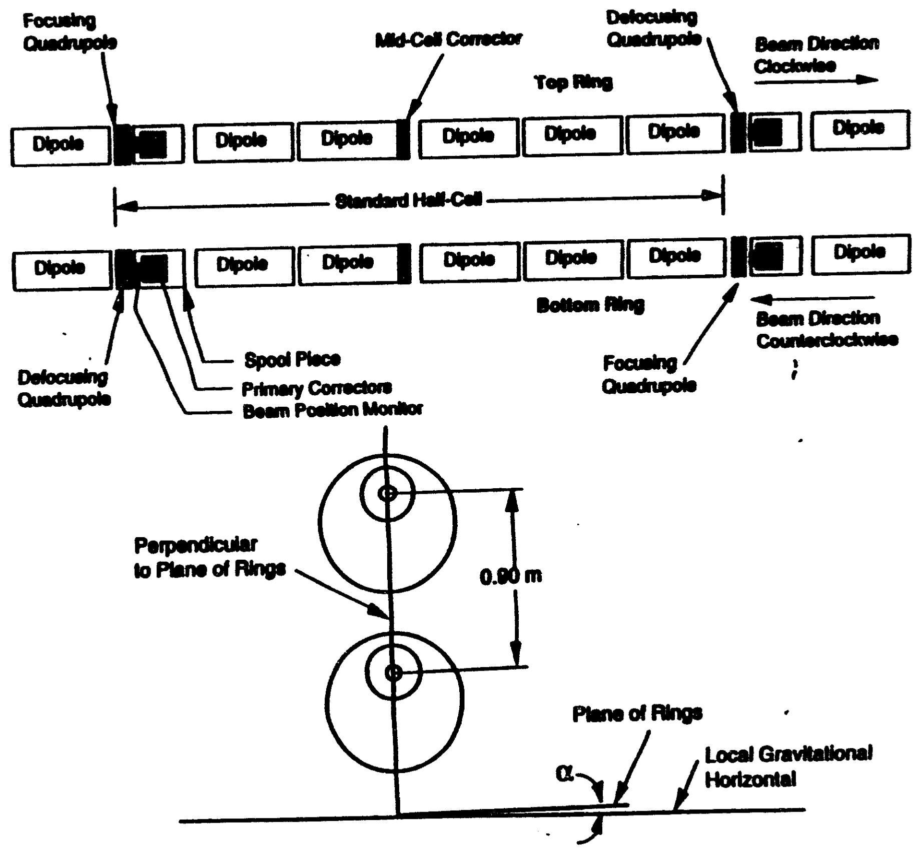
S50
S45
S40
S35
Accelerator
Service Areas
Monitoring Stations

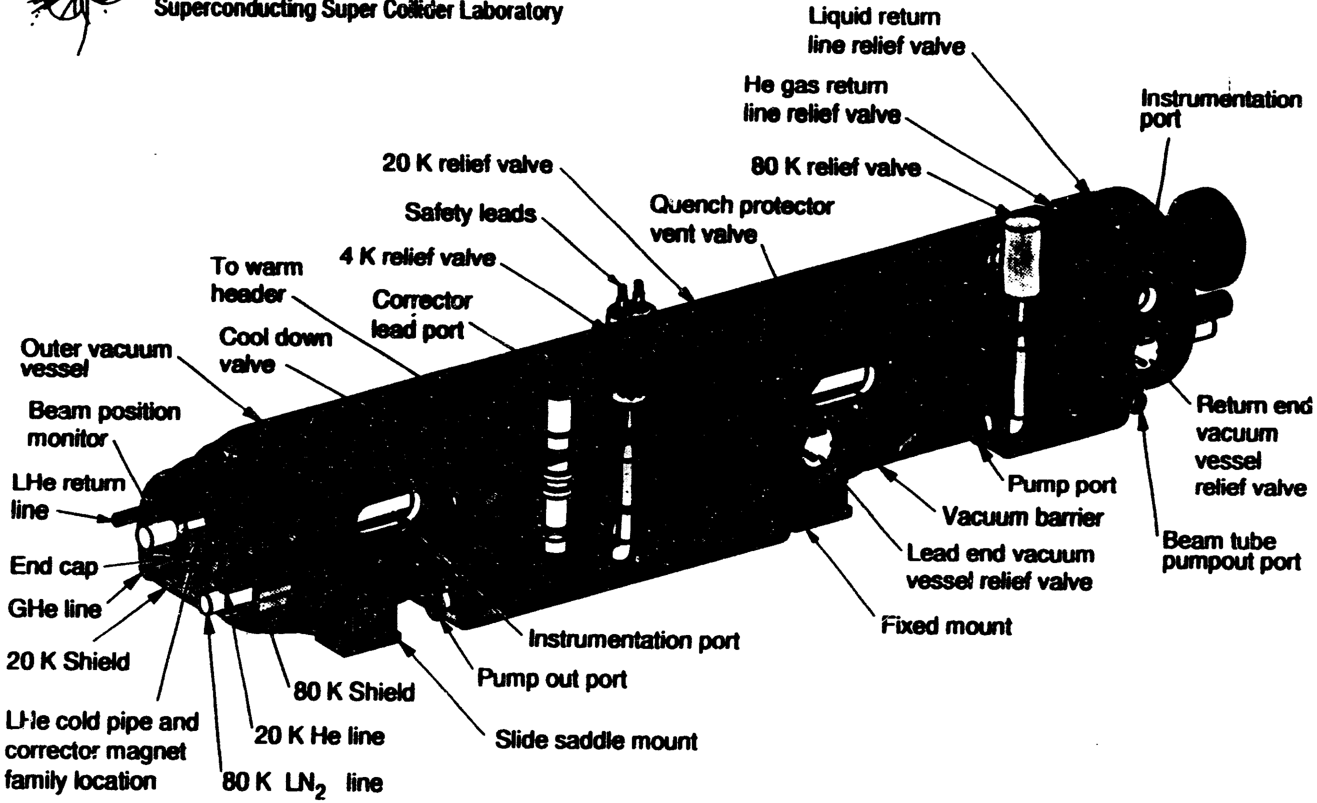
COMPONENT SEQUENCE FOR RINGS IN ARCS



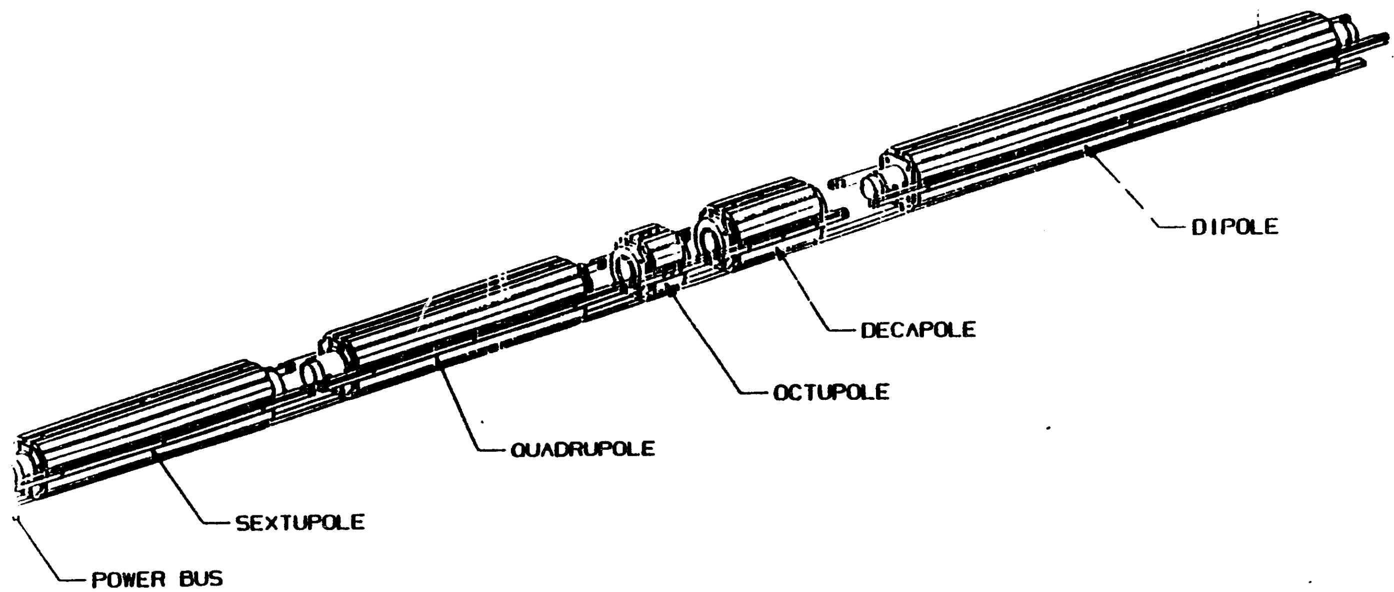
Note: The angle α varies from location to location in the tunnel.

Standard Spool Configuration

Superconducting Super Collider Laboratory

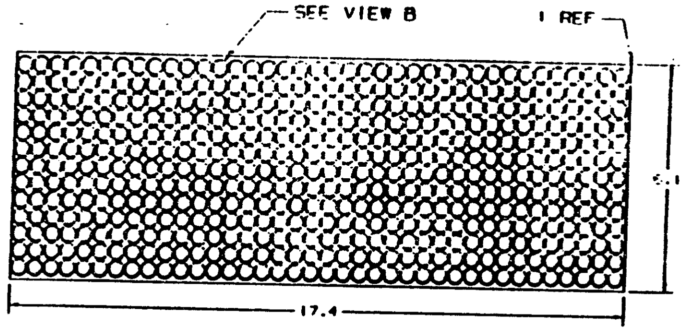


TIP-01521



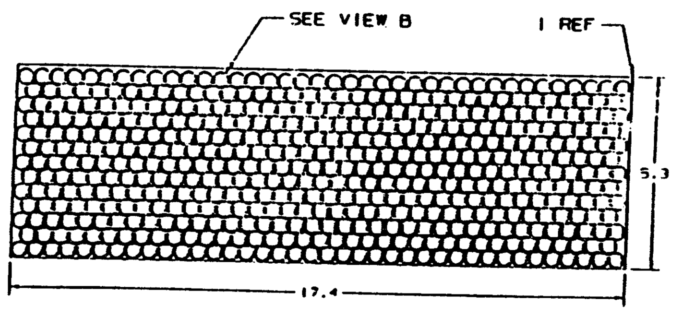
CORRECTOR SPOOL

TYPICAL ORDERED WOUND COIL CROSS SECTION



13 × 38 : 494

SQUARE CONDUCTOR ARRANGEMENT

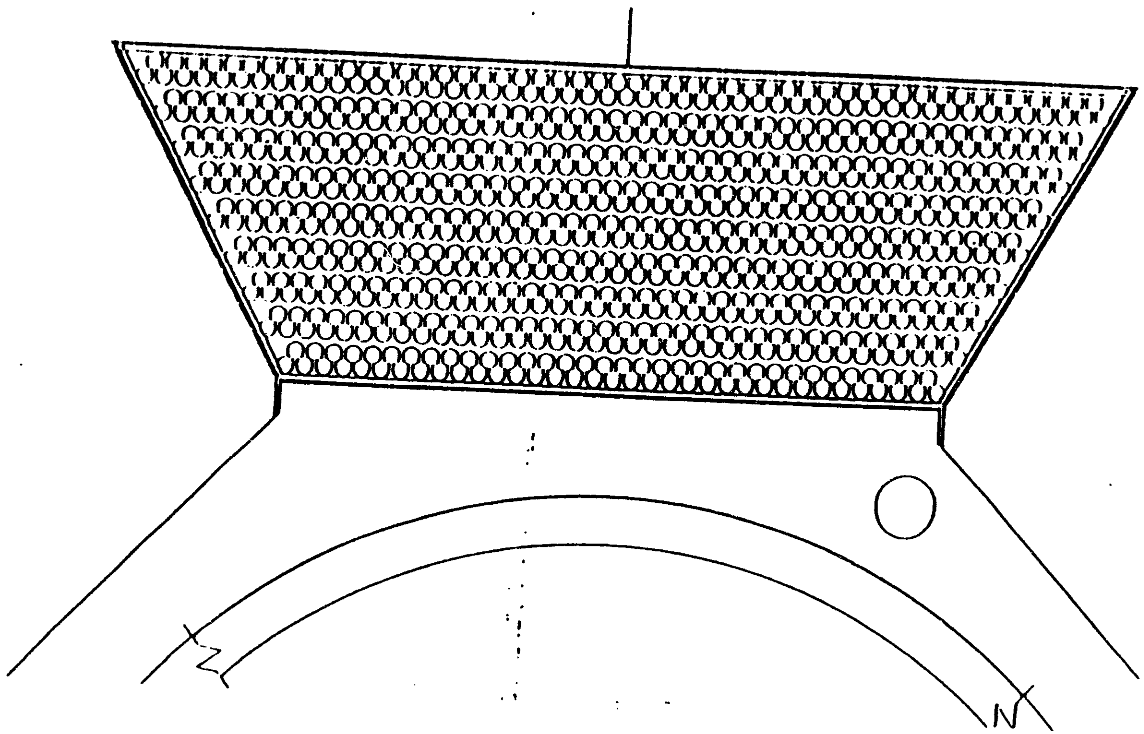


7 × 38 : 256
6 × 38 : 222
TOTAL : 488

HEXAGONAL CONDUCTOR ARRANGEMENT

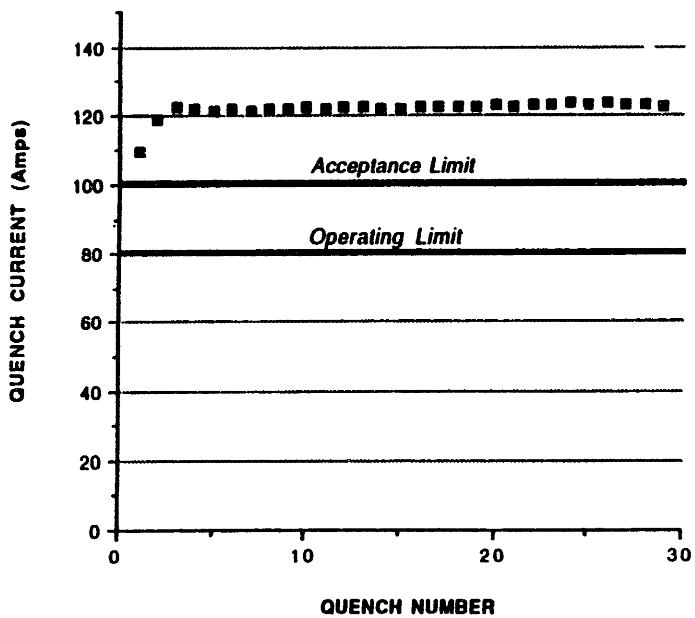

RANSOME

TYPICAL CROSS SECTION OF JELLY ROLL COIL

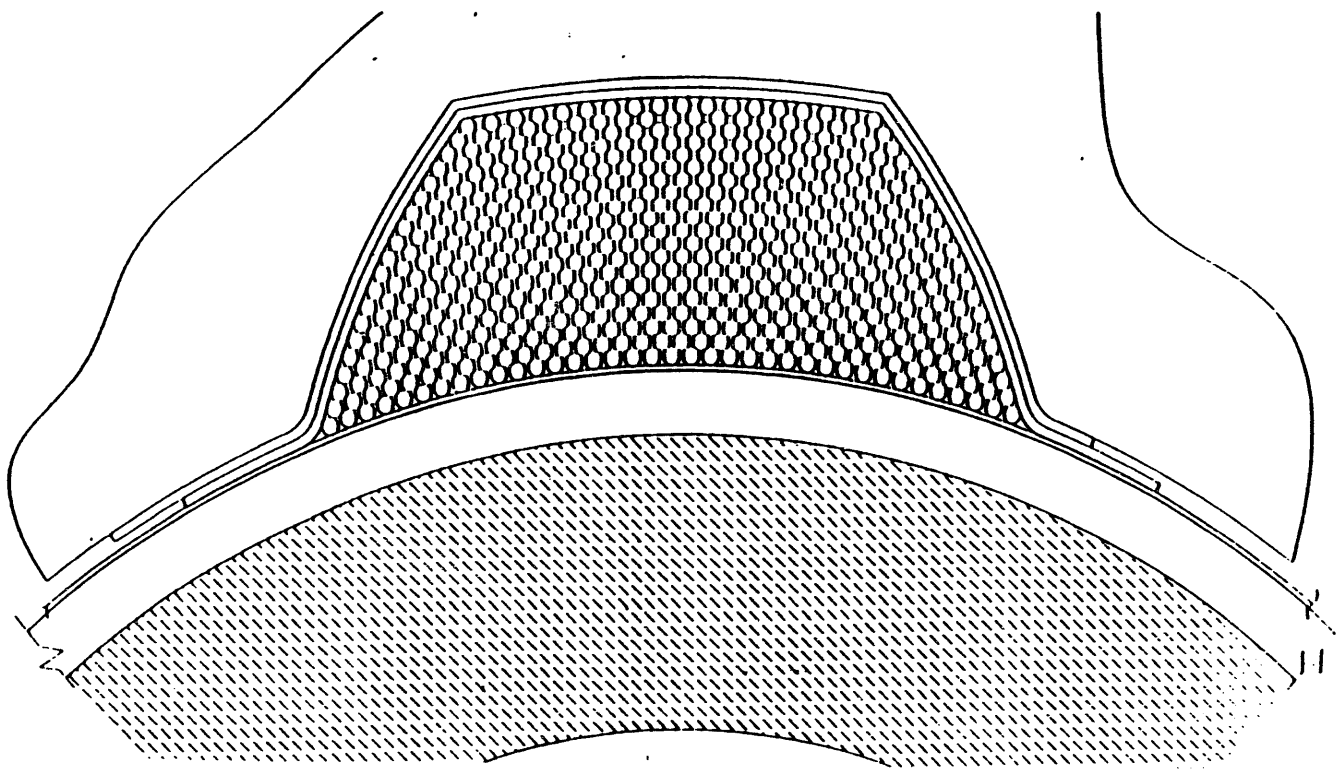


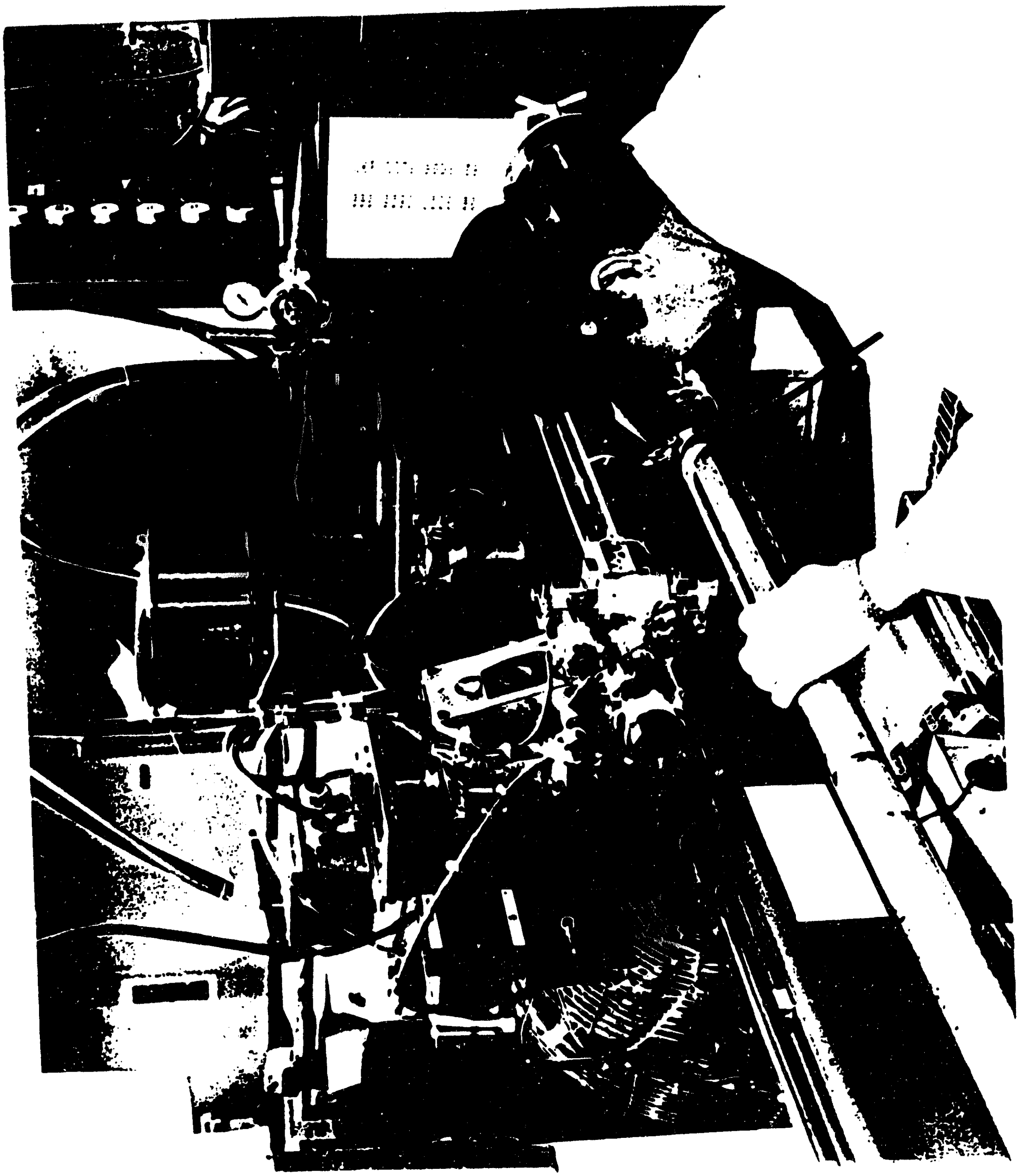
SUPERCONDUCTING SUPER COLLIDER LABORATORY
COLLIDER ARC CORRECTION MAGNETS
Preliminary Design Requirements Review
25 September 1992

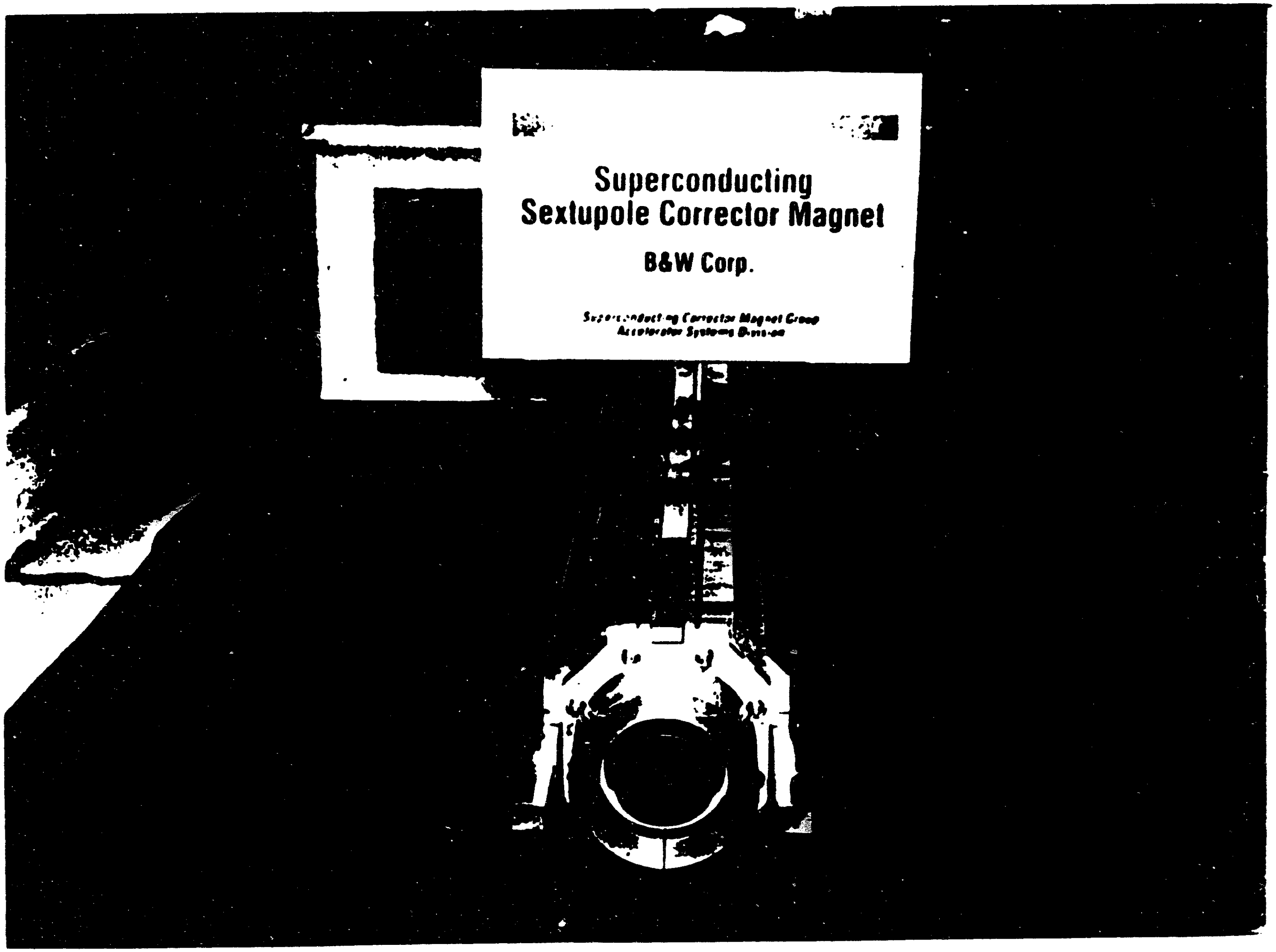
MMJb1.3
Series 2



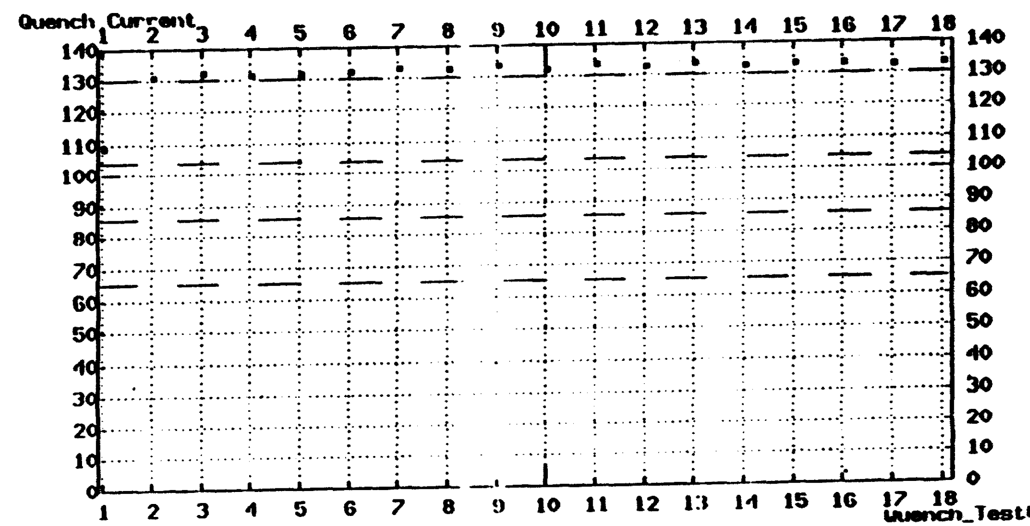
TYPICAL DIRECT WIRE COIL CROSS SECTION






Superconducting
Sextupole Corrector Magnet
B&W Corp.
Superconducting Corrector Magnet Group
Accelerator Systems Division

MAGNET: supmagnets/BCDb2/12 SERIES: 2 DATE: 09/14/93 I(C): 130.000000

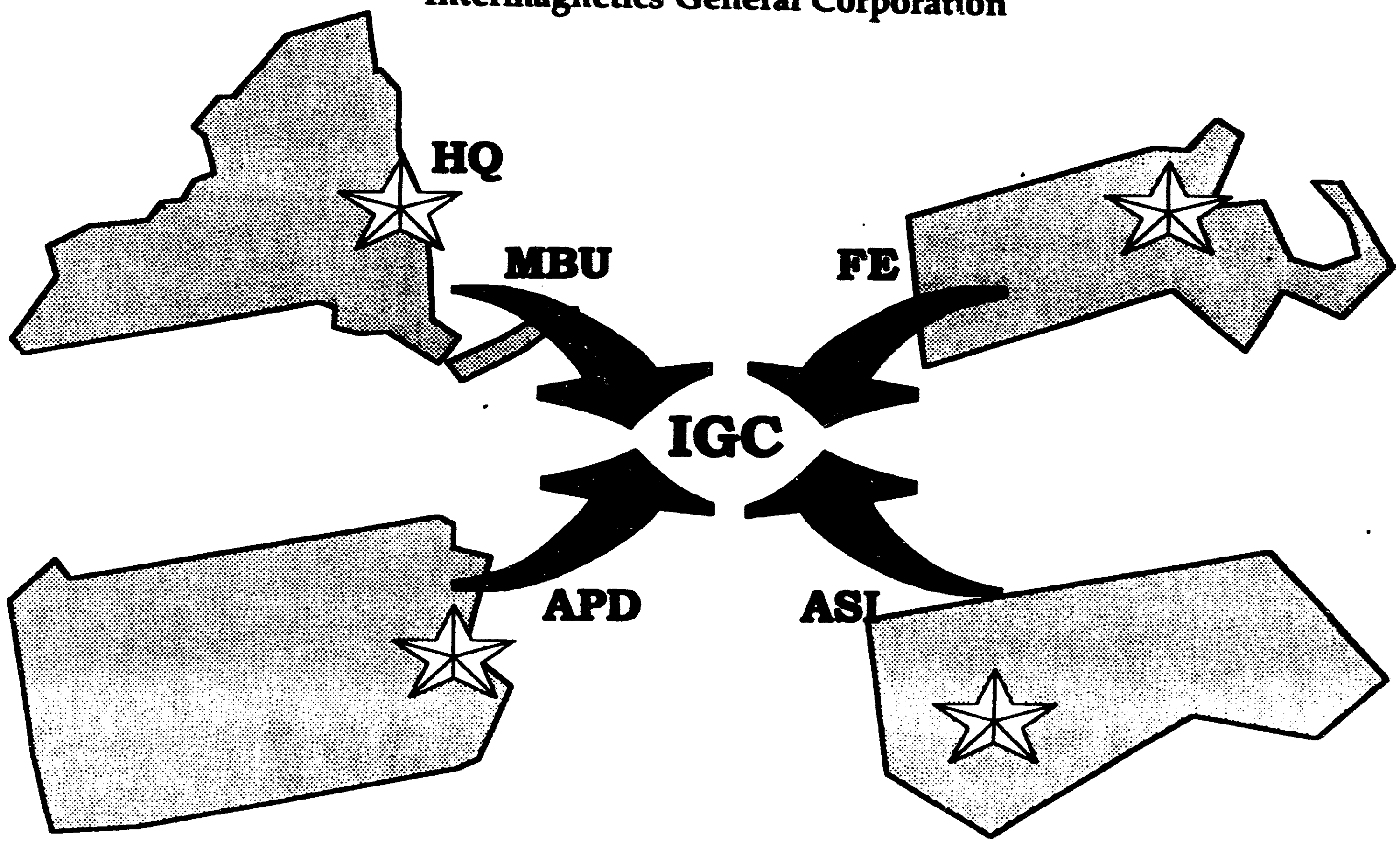


1	109.41	0.50	2	131.56	0.50	3	132.57	1.00
4	131.78	1.00	5	132.52	1.00	6	132.98	1.00
7	133.54	1.00	8	133.11	1.00	9	134.21	1.00
10	132.84	1.00	11	134.37	1.00	12	133.09	1.00
13	134.13	2.00	14	133.45	2.00	15	133.70	5.00
16	133.93	5.00	17	133.36	10.00	18	133.51	10.00

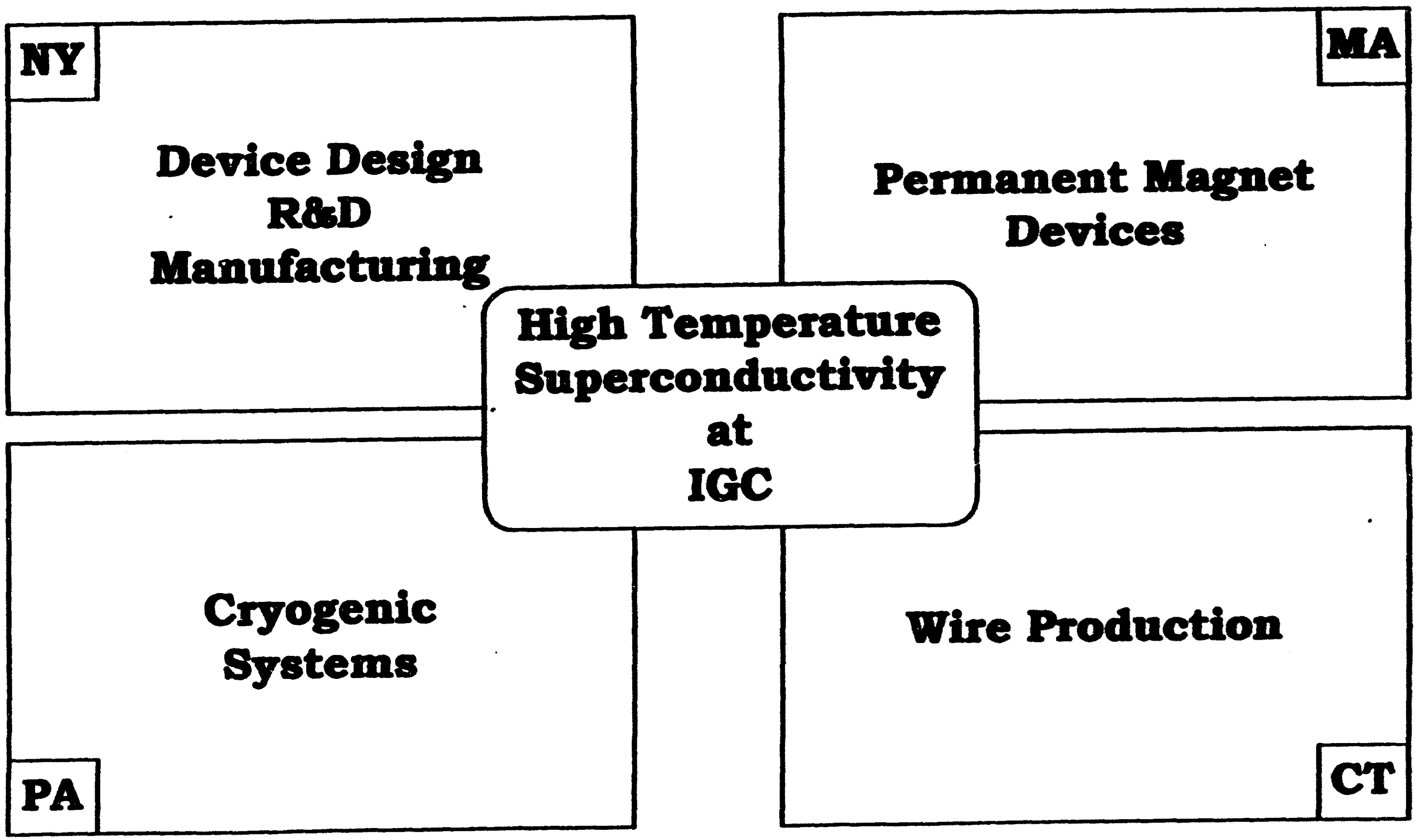
INDUSTRIAL OPPORTUNITIES

Two Decades of Growth

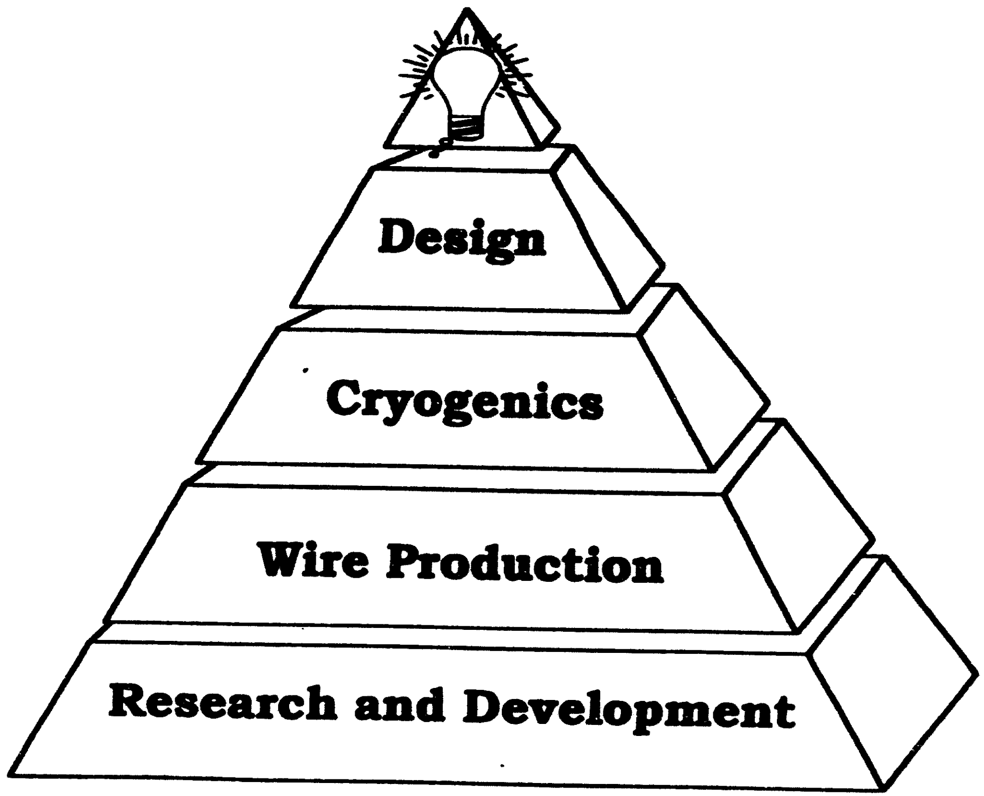
Robert S. Sokolowski
Intermagnetics General Corporation



Focus and Synergy

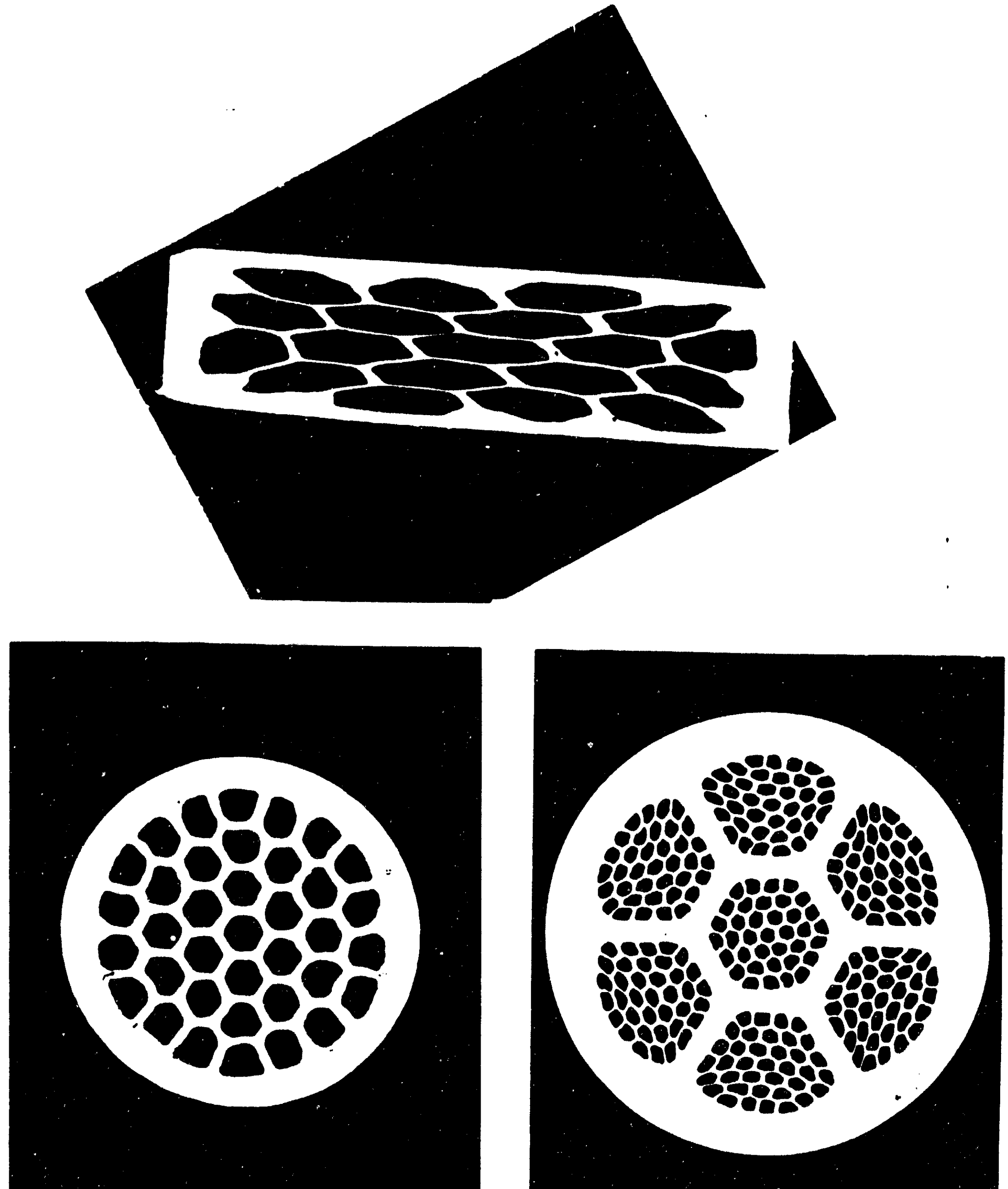


IGC-HTS : the Total Solution



IGC Collaborations with DOE Laboratories

•	1991	initial contact in February
•	1992	ANL......wire
		ORNL...coils
		BNL......characterization
•	1993	LBL...visiting scientist from IGC
		all labs...thallium working group
•	1994	LANL/SNL...thallium wire



HIGH TEMPERATURE SUPERCONDUCTING WIRE

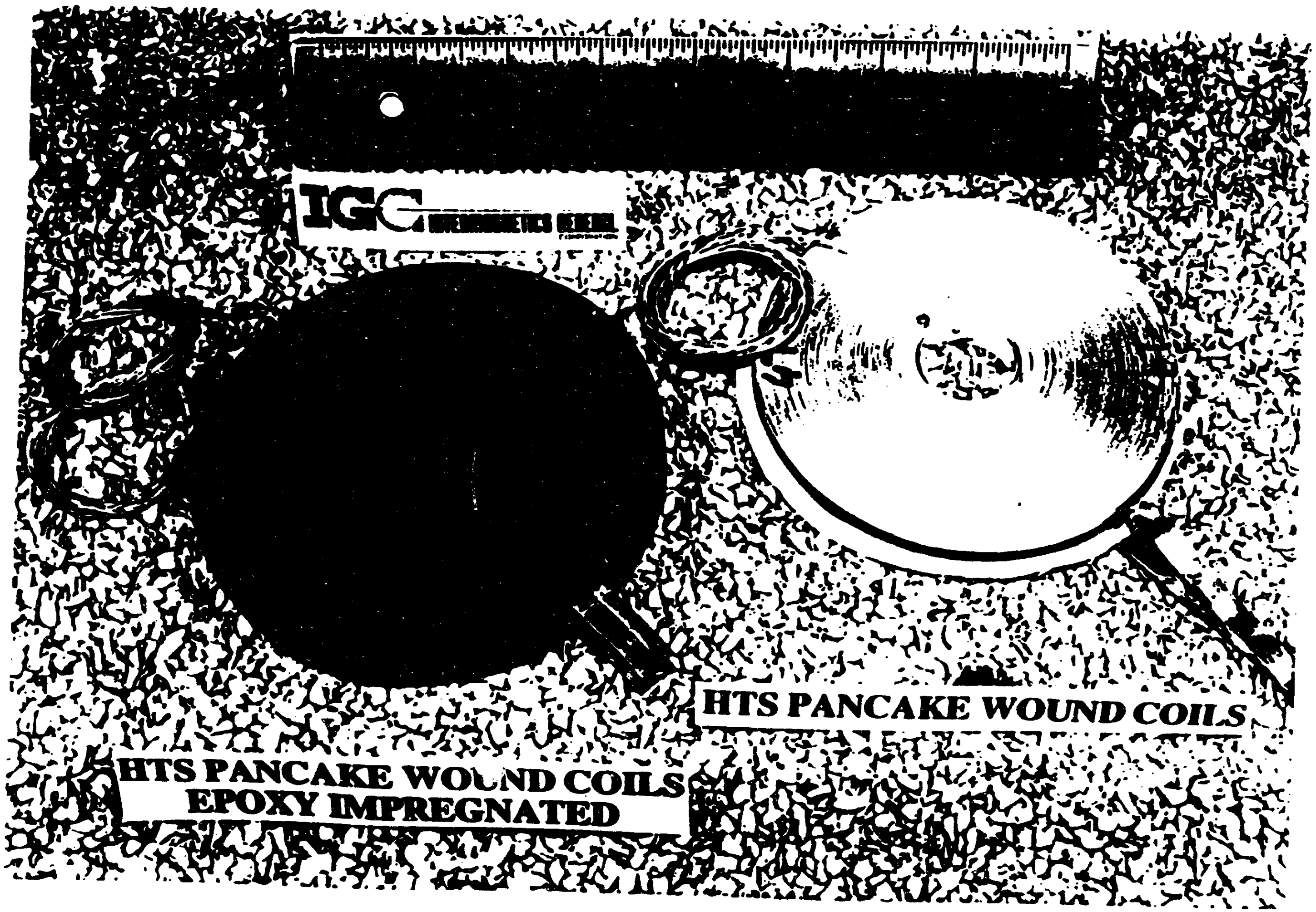
(All values typical as of revision date)

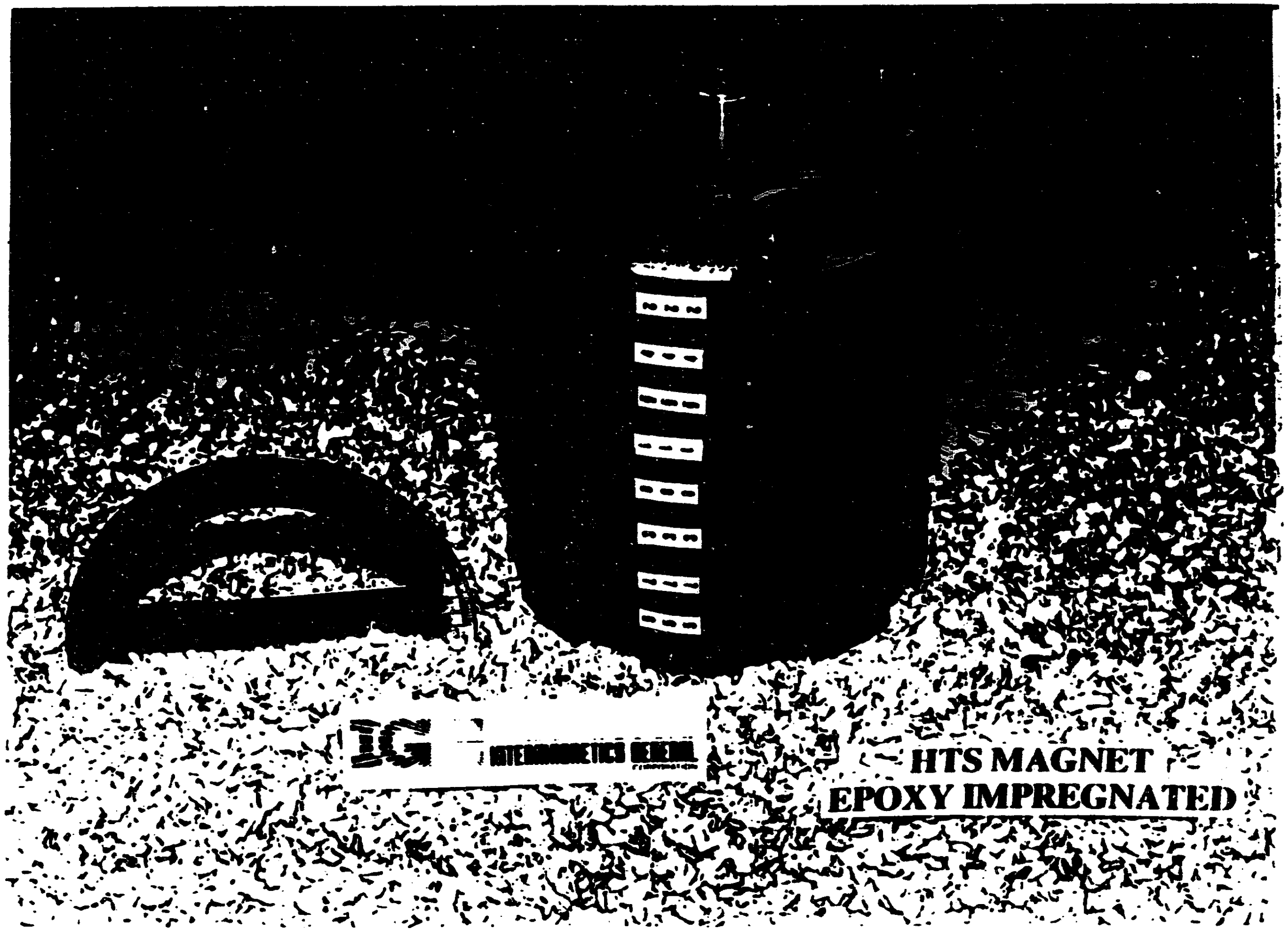
Bi-2223

Configuration:	Silver-Sheathed Monocore
% Superconductor:	20 - 30
Thickness:	0.15 mm
Width:	5.5 mm

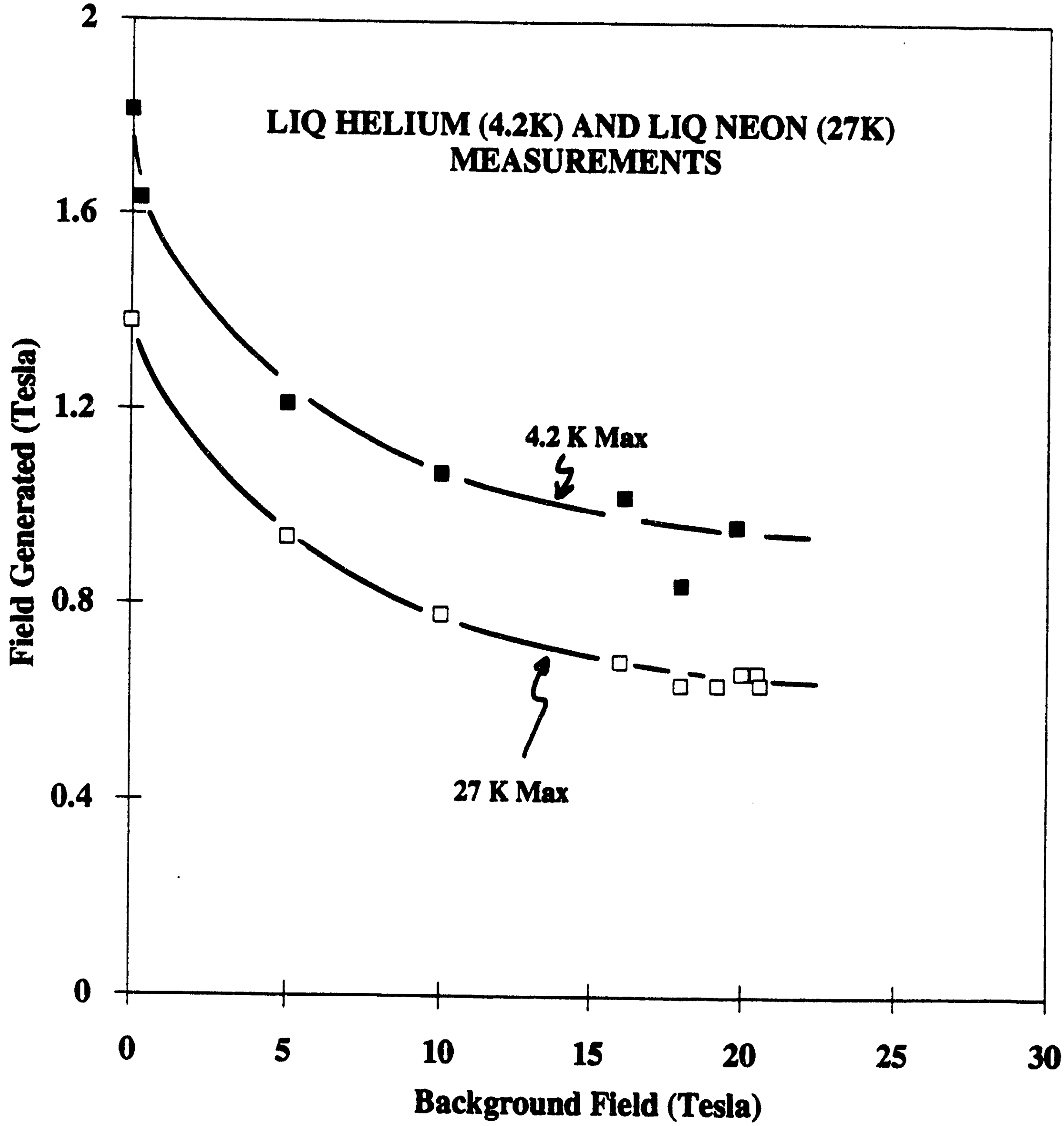
CRITICAL CURRENT
(1µV/cm criterion)

Piece Length	**4.2K**	**27K**	**77K**
< 30 m	150 A	100 A	20 A
< 70 m	110 A	75 A	15 A
> 100 m	75 A	50 A	10 A


IGC
HTS PANCAKE WOUND COILS
HTS PANCAKE WOUND COILS
EPOXY IMPREGNATED


HTS MAGNET
EPOXY IMPREGNATED

MIT DATA



PRADEEP HALDAR

IGC MAGNET 2/10/94

IGC
H T S

Summary

- Real products with high performance are being offered for sale at reasonable prices

- IGC is eager to meet aggressive partners, innovative collaborators, and confident investors

- IGC is interested in licensing technology and pursuing new business opportunities

SSC Technical Assets

As a World Class Laboratory the SSC has Built up Many Unique Technical Facilities:

- Superconducting Magnets
- Cryogenics Facilities
- Various Lab Facilities
- Computing Facilities
- Accelerator Design and Simulation
- Beam Induced Energy Deposition
- Development of EPICS
- Survey / Alignment
- Photodesorption Experiments

Magnet Development, Production and Testing

- **N15 Facilities MDL, MTL and ASST:**
  - State of the art equipment for development, production and testing of superconducting magnets
  - Integrated design and analysis codes
  - cabling, cable wrapping
  - Magnet System Test Facility (ASST)
  - Cable testing (mechanical, supercond. short sample testing)
  - Pick-up coil (Mole) production and calibration
  - Strain gauge calibration
  - Horizontal and vertical test stands
  - Power supplies (8000 A) and data acquisition system
  - Tooling for development and fabrication of correction coils

No other facility in the world has comparable set of equipment.

Correction Coil Development

Two techniques for superconductiong correction magnets have been developed and gone through an extensive industrialization program:

- Ordered Wind Technology (also used for RHIC)
  - Many different multipole coils have been produced inhouse.
- Direct Wind
  - Machine developed at SSC for fully automatic winding of various correction coils. The technology has the potential of very cost effective production of correction magnets.
- Complete testlab with vertical cryostats and measuring equipment for field quality and alignment.

Cryogenics Facilities

3 large Refrigerators are existing at the N15 site (ASST, MTL, N15B):

- **Power: ~ 4.4 kW at 4.2 K, max liquifaction 45 g/s**
- **The ASST Refrigerator is running successfully.**
- **MTL Refrigerator has been commissioned**
- **The N15B refrigerator is ready for electrical checkout.**

Various Lab Facilities

- **Resistive Magnet Lab**
  - Two 8000 A Power Supplies
  - Commercial test stands for field quality measurements
- **Vacuum Lab**
  - Various pumps and leak detection equipment
- **Electrodesorption Test Lab**
  - Unique test stand developed in collaboration with UT/A
  - Surface Physics experiments performed with that equipment have produced significant results.
- **Spool Piece Test stands**
  - Two test stands for cryogenic performance test of spool pieces are almost complete.

Various Lab Facilities

Large Machine Shop:

- Weld Shop with variety of equipment to perform welding, soldering, brazing and burning. Welding of dissimilar materials
- Sheet Metal Capability for fabricating components from all common materials including cold rolled steel, stainless steel, aluminum, copper, and brass
- Different CNC turning/milling machines (incl. 5 axes)
- CNC wire EDM
- Measuring Capabilities for highest levels of quality and consistency. Computerized measuring systems and full spectrum of standard measuring equipment.
- CAD/CAM system allows downloading of data from CAD system to machine shop.

Computing Facilities at the SSC

Hardware:

- Compute Engines
  - Hypercube (1.8 Gflop Parallel Processor)
  - PDSF (1.2 Gflop RISC Farm)
  - UNIX Network with 700 Workstations and 27 File Servers
- CAD Equipment
  - 125 UNIX Seats
  - 8 Data Servers
  - Automated Optical Disc Storage
- Graphics Processors
  - 10 Silicon Graphics Workstations including 1 Crimson

Accelerator Design and Simulation Capabilities at the SSC

- **Modeling Software**
  - TEAPOT: Operational Correction and Tracking Code Suite
  - Graphic Post-Processor for TEAPOT
  - VECTRAK: Optimized Tracking Kernel for Hypercube
  - ZLIB: Differential Algebra Library
  - ZMAP: Map Extraction CODE
  - Space Charge Simulation
  - Database Browsing Tools
- **Operational Simulation Software**
  - Interactive High Level Control Simulator
  - Cryogenic Simulation Codes, e.g. cool down & warm up
  - Energy Deposition Simulation
- **Commercial and Collaboration Software**
  - MAD, DIMAD, ISTK, SYNCH, MAGIC, TRANSPOT,MAFIA, POISSON, EPICS, MARS-12, STRUCT

Beam Induced Energy Deposition

- Unique Software and Expertise
- Beam Collimation System
- Accelerator/Experiment Interface
- Beam Failure Modes
- Beam Abort system

Scraper/Collimator System

- **Scraping Efficiency:**
  - Quench Limit, Background in IR's
  - Target and Scraper Material Integrity
  - Alignment and Movement Requirements
  - Cooling System
  - Instrumentation
  - Local Bump Scheme
  - Shielding and Residual Radioactivity
- **Collimator Optimization:**
  - Kicker Mis/Prefire, SC Magnet Protection and Background

“Full Scale” Monte Carlo Simulation

DTU + MARS12 + STRUCT Package

Coupled with

ANSYS: Thermal Analysis of Scrapers and Beam Backstop

MESA/SPA: Hydrodynamic Calculations of Accidental Beam Loss

For the Energy Densities of Future Hadron Colliders Energy Deposition Using Constant Equations of State Is No Longer Sufficient.

--> Hydrodynamic Calculations (see Figs.)

“Full Scale”: Detailed 3D Representation of All Components

Magnetic Fields Included

"Full Scale" Monte Carlo Simulation

Intensive Studies Performed for Collider:

- pp-Collisions in IR's & Final Focus Quadrupole Protection
- Beam-Gas Collisions
- Background in IR Detectors
- Interaction with Beam Scrapers & Beam Collimators
- Timing Errors, Unsynchronized Injection and Abort
- Abort Kicker Misfire & Prefire
- Beam Abort System
- Radiation Shielding Design for Complete Complex

Accelerator Design and Simulation Capabilities at the SSC

- **Accelerator Design**
  - Linear and Higher Order Lattice Design and Optimization Programs
  - Correction System Design Codes for Local, Global< Resonance and Multipole Correction.
- **Accelerator Performance Prediction**
  - Linear and Dynamic Aperture
  - Tune Scans
  - Luminosity Lifetime
- **Operational Simulation**
  - Interactive High Level Control Simulation
  - Hardware Failure Simulations
  - Commissioning Simulations
  - Quench Propagation Simulations
  - 3D Access Modeling
  - Energy Deposition Calculations (see below)

EPICS Development

Rationale:

- Long history in controls community of trying to find common approach.
- DoE Order to seek common software solutions for economy. Controls are called out explicitly.
- Effort has begun with EPICS collaboration. Interested organizations: (ANL, LANL, LBL, European labs, Universities, other labs, Fusion)
- SSC was playing a major role in that collaboration.

Proposal:

- Establish a small group that provides and maintains a common set of control system tools, that can be used by all DoE Labs and available to all interested parties.
- Initial toolkit would be based on EPICS hardware and software

EPICS Development

Prerequisites:

- Some facility is needed to which the control system could be applied. Ideally this would be an accelerator, but other systems, (e.g. ASST or cryo plant) might suffice.
- All necessary equipment exists at the SSC.

Survey/Alignment Equipment

Survey / Alignment Equipment existing at the SSC:

- 5 Gyro-Theodolites ~ 75 K$ each
- 2 LaserTrackers ~160 K$ each
- 2 Laser Distance Measuring Devices ~ 90 K$ each
- 6 GPS Receivers ~ 60 K$ each
- Large Set of Standard Survey Equipment
- Series of Optical Tooling
- Electronic Data Collectors running special software

Estimated value of all equipment ~ 2.5 M$

Photodesorption Experiments

Photodesorption experiments have been performed under an Interlaboratory Collaborative Agreement at the Novosibirsk Synchrotron Light Source.

- Experimental techniques have been developed that allow to simulate next generation proton collider vacuum conditions.
- A simple liner, i.e. coaxial perforated tube in thermal contact with beam tube, has been shown to successfully shield physiosorbed molecules from synchrotron radiation. If equipped with cryosorber this liner would meet the beam tube vacuum requirements
- First experiment with direct measurement of gas density in cryosorbing tube underway.

Summary

The world class facilities built up at the SSC could be beneficial for many science and R&D projects.

Development of superconducting magnets which is presently done by small groups in several National Laboratories would be more efficient and competitive if concentrated at the SSC.

A collaboration with Europe for the construction of LHC (Large Hadron Collider) would keep the US in the forefront of high energy physics. Using the existing SSC facilities would be the most cost effective approach.

Without rapid decisions enormous investments will be wasted.

SUPERCONDUCTIVE

Components, Inc.

J. R. Gaines

Quality Means ... What the Customer Wants !

BSCCO Powders via ORNL AEROSOL Process

Now Available from Superconductive Components, Inc.

TOLL FREE TEL (800)346-6567 FAX(800)292-8654

1145 Chesapeake Avenue, Columbus, Ohio 43212 tel(614)486-0261 fax (614)486-0912

I. <u>BSCCO POWDERS NOW AVAILABLE FOR SALE via Tech Transfer of AEROSOL PROCESS FROM ORNL:</u>

A. **The Advantages:**

1. *These Exceptionally Homogeneous particles, each containing the correct stoichiometric ratio of cations, provide rapid transformation to 2-2-2-3 phase during wire fabrication. This can substantially reduce wire fabrication time (vs Solid State Process Powders).*
2. *Low carbon content can enhance proper phase formation and improve grain boundary performance.*
3. *The particle morphology is well suited for mechanical deformation and, with no large, hard agglomerates, this powder is particularly useful for multifilamentary structures.*
4. *We can accurately tailor stoichiometries to fit client's requirements.*

B. **The Fabrication set-up at SCI/TMI:**

1. *Furnace w/temperature controllers and solutions*
2. *Nebulizer and input to furnace tube, extra port for additional nebulizer*
3. *Catch filter on exit side of furnace tube*

C. **The end product:**

1. *S.E.M. shot of powders showing particle size and shperical morphology*
2. *X-ray of 2-2-1-2 sample showing predominent 2-2-1-2 phase*
3. *Chemical Certificate of nominal 99.9%*
4. *This information is summarized in our Data Sheet*

D. **Buy our BSCCO Powders:**

1. *Looking for collaborative relationships with commercial and government organizations - on stoichiometries chosen by the client.*
2. *Research size samples available presently, with scale-up to happen over next 3 months to achieve kilo size lots.*
3. *Powders sold based on a nominal set-up fee then $$$ per gram, based on client's desired properties.*

E. **The Next Step = SCALE-UP and OPTIMIZATION:**

1. *ORNL working on the SCALE UP process now, expect results within the next 3 months that will increase through put by a factor of 50.*
2. *We are working to further reduce the carbon content and improve internal handling practice.*

DATA SHEET

BSCCO

+ PbBSCCO

$Bi_2Sr_2Ca_1Cu_2O_{8x}$, 99.9% purity, Precursor Powders

SCOPE:
This product data sheet characterizes BSCCO precursor powders produced by Superconductive Components, Inc. (SCI). The following information is not a specification; however, it may prove useful to the customer in developing a formal product specification.

GENERAL APPLICATION'S:
SCI's BSCCO precursor powders are composed of individual particles containing the correct stoichiometric ratio of metal cations which allows rapid transformation into the superconductive state. The powders can be fabricated into many typical shapes such as wires, tapes, and bulk geometries (i.e., sputtering targets), etc. They can also be incorporated in thick films. Research samples are currently available and can be shipped approximately 10 days after receipt of order.

GENERAL DESCRIPTION:
SCI's typical compositions for BSCCO are $Bi_2Sr_2Ca_1Cu_2O_{8-x}$, $Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_{10-x}$. Custom dopants can be added and various stoichiometries are available upon request. SCI's BSCCO precursor powders are characterized as containing small highly homogeneous particles which are low in Carbon and have good spherical shape. The powder contains no hard agglomerates.

PHYSICAL:

Avg. Particle Size	1.5 microns
Particle Size Distribution	D90<6.0 microns D50<1.5 microns D10<1.0 micron
BSCCO Theoretical Density	6.45 gm/cc
Color	Brown/Black

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CHEMICAL:

Typical Purity 99.9%

Major alloy or compound +/- 1% atomic

Typical Impurities:

Element	Avg. PPMw
C	<800.0
Na	<22.0
Mg	<24.0
Si	7.0
Cl	7.0
Mn	3.0
Fe	<150.0
Sn	2.0
Sb	<12.0
Pb	<60.0

PACKAGING:

The precursor powders are double sealed in an Argon filled Nalgene® container and sealed in an Argon filled glass container and securely fit into a shipping container.

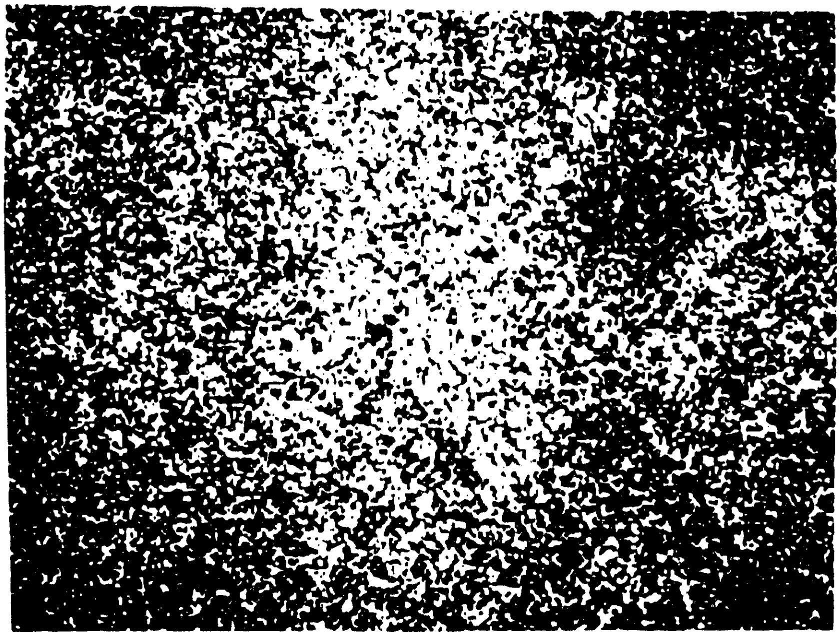
DOCUMENTATION:

A Certificate of Analysis and Compliance (COAC), Material Safety Data Sheet (MSDS), and appropriate labeling are included.

COAC: Includes material composition, sales order number, part number, lot number, product description, statement of conformance, purity, list of impurities, and date of manufacture. Actual analysis data for impurities can be provided at extra charge.

MSDS: Includes all required information.

Label: Includes material composition, part number, and lot number.



SEM EDAX

Map of typical homogeneity of BSCCO precursor powders produced by SCI's proprietary process.

SEM EDAX

Map showing carbon distribution in BSCCO precursor powders produced by SCI's proprietary process.

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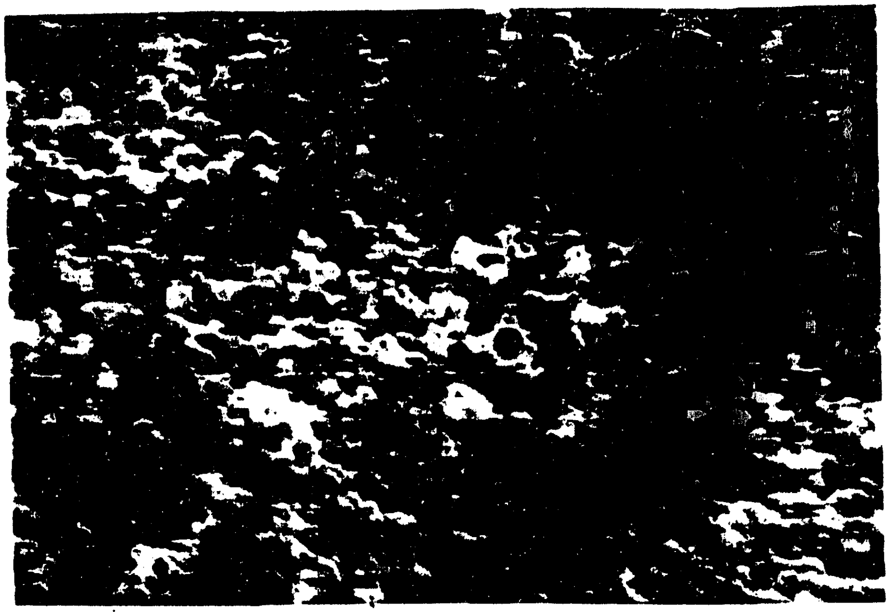
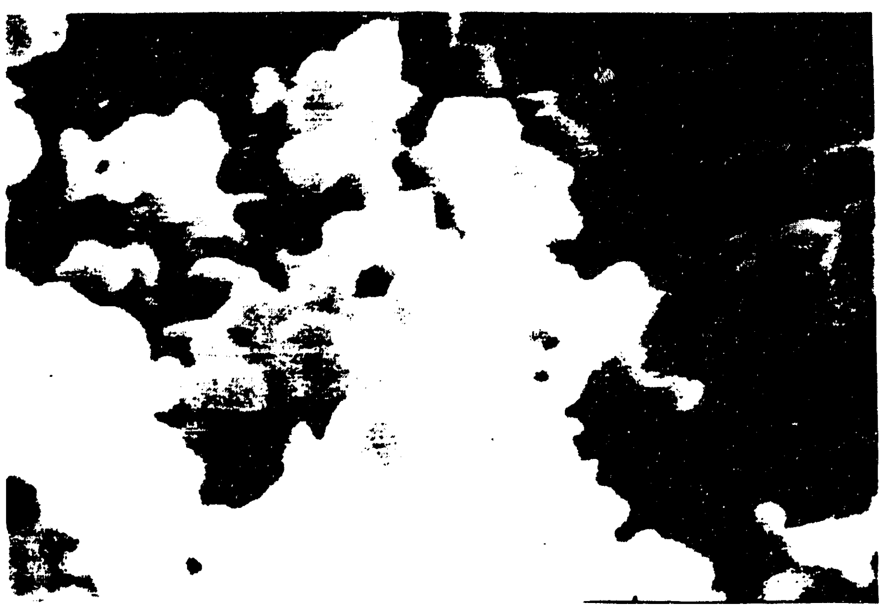


2000x SEM

Typical morphology of BSCCO precursor powders produced by SCI's proprietary process.



5000x SEM

Typical morphology of BSCCO precursor powders produced by SCI's proprietary process.

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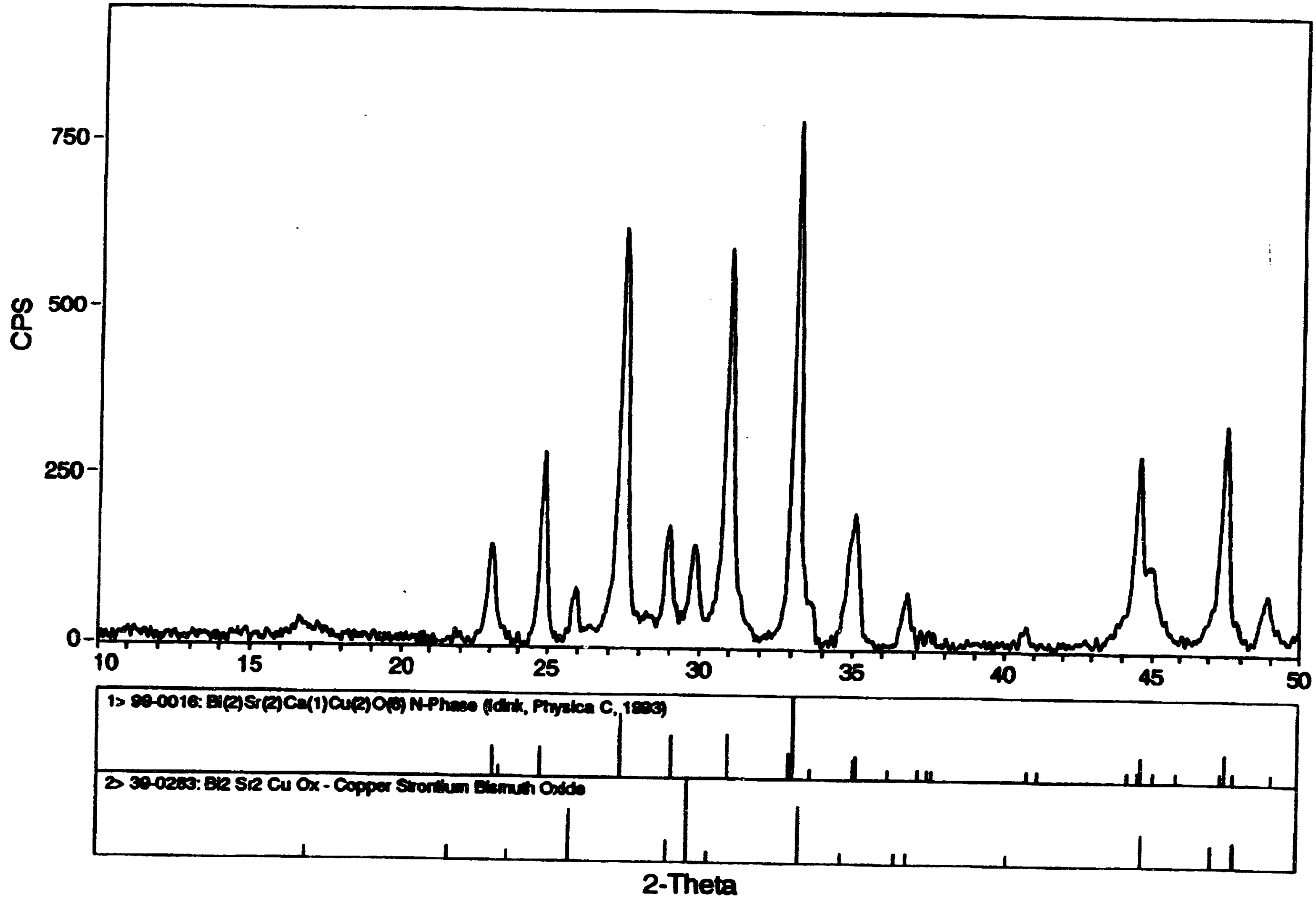

X-Ray diffraction of BSCCO precursor powders produced by SCI.

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CERTIFICATE OF ANALYSIS AND COMPLIANCE

MATERIAL COMPOSITION: $Bi_2Sr_2CaCu_2O_x$ S.O.: ____________

PART # ______________________ LOT # ____________

CONFORMS TO SCI/TMI Spec # P00C000XXXXX30/02.15.94

( ) actual (X) typical

CHEMICAL		IMPURITY
Na	..less than..	22
Mg	..less than..	24
Si	....	7
Cl	....	7
Mn	....	3
Fe	..less than..	150
Sn	....	2
Sb	..less than..	12
Pb	..less than..	60
C	....	778

SUMMARIZED CHEMICAL PURITY: 99.9%

((ABOVE DATA IS IN PPM BY WEIGHT))

This is to certify that all work done, materials and/or processes furnished or performed are in accordance with our normal process controls.

Date: 15 February 1994

Sartono Bambang

Q.A. Manager

SUPERCONDUCTIVE components, inc.

1145 Chesapeake Avenue Columbus, Ohio 43212
(614) 486-0261 FAX (614) 486-0912

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Target Materials, Inc.
a Division of Superconductive Components, Inc.

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ATTN: PLANT MANAGER/SAFETY DIRECTOR/PURCHASING AGENT

SUBJECT : FEDERAL HAZARD COMMUNICATION STANDARD
MATERIAL SAFETY DATA SHEET (MSDS)

FEDERAL HAZARD COMMUNICATION STANDARD 1910.1200 REQUIRES MANUFACTURERS OR DISTRIBUTORS TO PUBLISH AND DISTRIBUTE MATERIAL SAFETY DATA SHEETS.

THIS STANDARD ADDITIONALLY REQUIRES MANUFACTURERS/DISTRIBUTORS TO FURNISH A COPY OF THE MATERIAL SAFETY DATA SHEET FOR USERS OF THEIR PRODUCTS. ACCORDINGLY, A MSDS IS ENCLOSED FOR YOUR USAGE.

SUPERCONDUCTIVE COMPONENTS, INC., IS SUPPLYING THIS INFORMATION IN COMPLIANCE WITH THE OSHA HAZARD REGULATION 1910.1200.

WE SUGGEST THAT YOU MAKE THIS INFORMATION AVAILABLE TO YOUR HEALTH AND SAFETY PERSONNEL. HAZARDOUS SITUATIONS MAY ARISE IN VARIOUS FABRICATION PROCESSES. THESE INCLUDE BURNING, WELDING, MACHINING, CUTTING, GRINDING AND PICKLING. IN ADDITION, CERTAIN COMBINATIONS OF UNUSUAL AND OR EXTREME CHEMICAL AND PHYSICAL ENVIRONMENTS MAY PERMIT POTENTIALLY HAZARDOUS SITUATIONS TO DEVELOP.

SHOULD YOU HAVE ANY QUESTIONS REGARDING THE ABOVE COMMUNICATION PLEASE WRITE OR CALL US.

SINCERELY YOURS,

SUPERCONDUCTIVE COMPONENTS, Inc.

TARGET MATERIALS, INC.
A Division of Superconductive Components, Inc.

(614) 486-0261 • 1145 Chesapeake Avenue • Columbus, Ohio 43212 • FAX (614) 486-0912

MATERIAL SAFETY DATA SHEET

Emergency Contact: CHEMTREC 1-800-424-9300

Product Identification

NAME: Bismuth Oxide syn. Bismuth Trioxide
CHEMICAL FORMULA: Bi_2O_3
CAS NO: 1304-76-3
CHEMICAL FAMILY: Metal Oxide

TSCA

Listed on the TSCA inventory.

Physical Properties

Appearance and Odor: Rhombic yellow crystals.
Melting Point: 820°C Boiling Point: 1890°C
Specific Gravity: 8.9
Solubility in Water: Nearly insoluble in water, soluble in HCL and HNO_3.

Physical Hazards

Conditions to Avoid: When heated to decomposition emits toxic fumes of Bi.

Health Hazards

TLV/PEL: Not set
TWA for Bi_2Te_3: 10 mg/m^3
Not listed as a carcinogen by NTP, IARC. Routes of entry: ingestion, injection. There are no reports of industrial Bi poisoning. All accounts of Bi poisoning are from the soluble compounds used in therapeutics. Intramuscular or intravenous injections of soluble compounds have resulted in fatalities and near-fatalities. Principal organs affected by poisoning are kidneys and liver. Liver and kidney function should be followed if large amounts of Bi salts are ingested.

Emergency First Aid

Skin: Wash thoroughly with soap and water.
Eyes: Flush thoroughly
Ingestion or Injection: CALL PHYSICIAN OR POISON CONTROL CENTER.
Inhalation: Remove to fresh air.

Handling Procedures

Wear gloves, safety glasses, protective clothing. Use air-purifying respirator if exposed to dust or fumes. Store in tightly closed container.

Spill/Leak Procedures

Scoop or sweep up, dispose of in approved landfill. Avoid breathing dust.

Date of Last Revision 3/10/93

TARGET MATERIALS, INC.

A Division of Superconductive Components, Inc.

(614) 486-0261 • 1145 Chesapeake Avenue • Columbus, Ohio 43212 • FAX (614) 486-0912

MATERIAL SAFETY DATA SHEET

EMERGENCY CALL CHEMTREC 800-424-9300

****

SECTION 1-IDENTIFICATION

****

Product Code: 12495 **Revision Date:** 3/13/91
Product Name: Strontium oxide
Synonyms: Strontium monoxide
Strontia
Chemical Family: Alkaline earth metal oxide
CAS#: 1314-11-0
Molecular Formula: SrO

****

SECTION 2-INGREDIENTS

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Chemical: Strontium oxide

CAS#	%	PEL	TLV
1314-11-0	100	Not established	Not established

****

SECTION 3- PHYSICAL DATA

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Boiling Point: Approx. 3000oC
% Volatiles: 0
Solubility in Water : 0.69%
Specific Gravity (H2O=1): 4.7
Freezing/Melting Point: 2430oC
Evaporation Rate (butyl acetate=1): 0
Vapor Density (air=1): Not applicable
Vapor Pressure : 40mm @ 2410oC
Appearance and Odor: Grey-white powder, odorless
Other: No data

****

SECTION 4-FIRE AND EXPLOSION HAZARD DATA

****

Flash Point:(oF) Not applicable
Flammable Limits in Air, % by volume: Lower Not applicable
Upper Not applicable

Autoignition Temperature: No data
Extinguishing Media: If involved in a fire, use dry chemical extinguishing agents, dry sand, dry ground dolomite.
Special Fire Fighting Procedures: Do not use water or carbon dioxide unless fire is massive or advanced. See section 6. No special

firefighting procedures needed, use normal procedures which include wearing NIOSH\MSHA approved self-contained breathing apparatus flame and chemical resistant clothing; hats, bots and gloves. If without risk, remove material from fire area.

****

SECTION 5-HEALTH DATA

****

OSHA (PEL): Not established
ACGIH (TLV): Not established

A. ANIMAL TOXICITY

LD50: No data
LC50: No data
Other: No data

B. EFFECTS OF EXPOSURE

ACUTE EFFECTS

Ingestion: Causes irritation or burns of the mouth, throat and gastro-intestinal tract.
Skin Contact: Causes irritation or burns
Eye Contact: Causes irritation or burns
Inhalation: Causes irritation or burns
Medical Conditions, if any, Aggravated by the Chemical: None known
Other Health Hazards: None known
Most Likely Routes of Entry: Ingestion

CHRONIC EFFECTS

Ingestion: None known
Skin Contact: None known
Eye Contact: None known
Inhalation: None known
Other: None known

C. EMERGENCY AND FIRST AID PROCEDURES

Ingestion: No data available but one should obtain medical attention.
Skin Contact: Remove contaminated clothing, flood skin with large amounts of water. If irritation persists seek medical attention.
Eye Contact: Immediately flush eyes, including under eyelids, with large amounts of water for at least 15 minutes. Call a physician.
Inhalation: No specific information available, one should obtain medical attention.

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SECTION 6-REACTIVITY

****

Incompatibility: acids, CO2, Al, Mg, H2O
Hazardous Decomposition Products: Sr(OH)2
Conditions to Avoid: Thermal decomposition, imcompatibles
Stability: Stable
Hazardous Polymerization: Will not occur

Other: In the presence of water or large amounts of moisture, this material may evolve enough heat to ignite easily combustible materials. May evolve hydrogen if wet and in contact with metals like aluminum and magnesium.

****

SECTION 7-ENVIRONMENTAL INFORMATION

****

RCRA Code: None
TSCA Registered: Yes
Spill and Leak Procedures: Wearing full protective equipment, cover spill with dry sand or vermiculite. Mix well and carefully transfer to a container.
Waste Disposal: Consult state, local or federal EPA regulations for proper disposal.

****

SECTION 8-PROTECTION INFORMATION

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Ventilation Requirements: Glove bag or box with dry inert atmosphere.
Respiratory Protection: High efficiency particle respirator
Protective Gloves: Rubber
Eye/Face Protection: ANSI approved safety goggles

****

SECTION 9-SPECIAL PRECAUTIONS

****

Handling and Storage: Keep container tightly closed. Store in a cool, dry, well-ventilated area. Wash thoroughly after use.
Other Precautions: Lab coat and apron, flame and chemical resistant coveralls, eyewash capable of sustained flushing, safety drench shower and hygienic facilities for washing.

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SECTION 10-TRANSPORTATION INFORMATION-U.S. D.O.T.

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Per 49CFR 172.101
Proper Shipping Name: ORM-B n.o.s.
Hazard Classification: ORM-B
UN #: NA1760

****

SECTION 11-COMMENTS

****

Warning: Burns skin, eyes, nose and throat

TARGET MATERIALS, INC.
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MATERIAL SAFETY DATA SHEET

Emergency Contact: CHEMTREC 1-800-424-9300

Product Identification

NAME: Calcium Oxide
CHEMICAL FORMULA: CaO
CAS NO: 1305-78-8
CHEMICAL FAMILY: Inorganic Salt

TSCA

Listed on the TSCA inventory.

Physical Properties

Appearance and Odor: White or greyish-white granular powder.
Density: 3.37.
Melting Point: 2580°C Boiling Point: 2850°C
Solubility in H_2O: Soluble in water and acid.

Physical Hazards

Conditions to Avoid: Disaster Hazard: Violent reaction with $(B_2O_3 + CaCl)_2$, BF_3, ClF_3, F_3, HF, P_2O_5, water. Incompatible with hydrogen fluoride, interhalogens; phosphorus (V) oxide, water.

Health Hazards

TLV: AIR: 2 mg/m^3.
Routes of entry: Inhalation of dust. Points of attack: respiratory system, skin and eyes. CaO is irritating and may be caustic to the skin, conjuctiva, cornea and mucous membranes of upper respiratory tract, may produce burns or dermatitis with desquamation and vesicular rash, lacrimation, spasmodic blinking, ulceration, and ocular perforation, ulceration and inflammation of the respiratory passages, ulceration of nasal and buccal mucosam and perforation of and nasal septum. Bronchitis and pneumonia may occur from inhalation of dust.

Emergency First Aid

Skin: Wash thoroughly with soap and water.
Eyes: Flush with water for at least 15 minutes.
Ingestion: Call physician or poison control center.
Inhalation: Remove to fresh air. Call physician.

Handling Procedures

Wear gloves, safety glasses, protective clothing. Use air-purifying respirator if exposed to dust or fumes. Store in tightly closed container.

Spill/Leak Procedures

Scoop or sweep up, dispose of in approved landfill. Avoid breathing dust.

Date of Last Revision 3/10/93

TARGET MATERIALS, INC.

A Division of Superconductive Components, Inc.

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MATERIAL SAFETY DATA SHEET

EMERGENCY CALL CHEMTREC 800-424-9300

SECTION 1-IDENTIFICATION

Product Code: 10700 **Revision Date:** 6\15\88
Product Name: Copper (II) oxide, black
Synonyms: Cupric oxide
Copper monoxide
Chemical Family: Metal oxide
CAS#: 1317-38-0
Molecular Formula: CuO

SECTION 2-INGREDIENTS

Chemical: Copper (II) oxide

CAS#	%	PEL	TLV
1317-38-0	100	Not established	Not established

SECTION 3- PHYSICAL DATA

Boiling Point: Decomposes
% Volatiles: 0
Solubility in Water : Insoluble
Specific Gravity (H2O=1): 6.32
Freezing/Melting Point: 1062oC
Evaporation Rate (butyl acetate=1): 0
Vapor Density (air=1): Not applicable
Vapor Pressure : Essentially 0
Appearance and Odor: Black powder, odorless
Other: No data

SECTION 4-FIRE AND EXPLOSION HAZARD DATA

Flash Point:(oF) Not applicable
Flammable Limits in Air, % by volume: Lower Not applicable
Upper Not applicable
Autoignition Temperature: No data
Extinguishing Media: Noncombustible. Use extinguishing media appropriate to surrounding fire condition.
Special Fire Fighting Procedures: No special firefighting procedures needed. Use normal procedures which include wearing

NIOSH/MSHA approved self-contained breathing apparatus, flame and chemical resistant clothing, hats, boots and gloves. If without risk, remove material from fire area. Cool container with water from maximum distance.

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SECTION 5-HEALTH DATA
****

OSHA (PEL): Not established
ACGIH (TLV): Not established

A. ANIMAL TOXICITY

LD50: No data
LC50: No data
Other: No data

B. EFFECTS OF EXPOSURE

ACUTE EFFECTS

Ingestion: May cause nausea, vomiting, abdominal pain, metallic taste and diarrhea. Copper oxide is less toxic than soluble copper salts.
Skin Contact: May cause irritation, redness and pain
Eye Contact: May cause irritation, redness and pain, discoloration and damage
Inhalation: May cause irritation. May cause symptoms similar to those of the common cold including chills and stuffiness of the head.
Medical Conditions, if any, Aggravated by the Chemical: None known
Other Health Hazards: Poisoning by soluble copper salts is characterized by hemolysis, jaundice, anemia, hypotension and convulsions.
Most Likely Routes of Entry: Ingestion

CHRONIC EFFECTS

Ingestion: May cause renal damage
Skin Contact: Prolonged skin contact may produce sensitization, dermatitis. Chronic skin contact with copper solutions will cause arythema and other skin reactions in some individuals
Eye Contact: None known
Inhalation: May cause atrophic changes and irritation of mucous membranes, renal damage
Other: None known

C. EMERGENCY AND FIRST AID PROCEDURES

Ingestion: No data available but one should obtain medical attention.
Skin Contact: Remove contaminated clothing, flood skin with large amounts of water. If irritation persists seek medical attention.
Eye Contact: Immediately flush eyes, including under eyelids, with large amounts of water for at least 15 minutes. Call a physician.
Inhalation: No specific information available, one should obtain medical attention.

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SECTION 6-REACTIVITY

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Incompatibility: Aluminum, boron, cesium, hydrazine, magnesium, phosphorus, potassium, rubidium, acetylene, sodium, titanium, zirconium, hydrogen, phthalic anhydride
Hazardous Decomposition Products: Copper fumes
Conditions to Avoid: Thermal decomposition, incompatibles
Stability: Stable
Hazardous Polymerization: Will not occur
Other: Reactions with incompatibles may pose an explosion hazard. Large masses exposed to moist air at over 100oC can result in spontaneous combustion.

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SECTION 7--ENVIRONMENTAL INFORMATION

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RCRA Code: None
TSCA Registered: Yes
Spill and Leak Procedures: Wearing full protective equipment, cover spill with dry sand or vermiculite. Mix well and carefully transfer to a container.
Waste Disposal: Consult state, local or federal EPA regulations for proper disposal.

****

SECTION 8-PROTECTION INFORMATION

****

Ventilation Requirements: Laboratory fume hood
Respiratory Protection: High efficiency particle respirator
Protective Gloves: Rubber
Eye/Face Protection: ANSI approved safety goggles

****

SECTION 9-SPECIAL PRECAUTIONS

****

Handling and Storage: Keep container tightly closed. Store in a cool, dry, well-ventilated area. Wash thoroughly after use.
Other Precautions: Lab coat and apron, flame and chemical resistant coveralls, eyewash capable of sustained flushing, safety drench shower and hygienic facilities for washing.

****

SECTION 10-TRANSPORTATION INFORMATION-U.S. D.O.T.

****

Per 49CFR 172.101
Proper Shipping Name: Not regulated
Hazard Classification: None
UN #: None

****

SECTION 11-COMMENTS

****

Warning! Irritates eyes, nose and lungs

Employers should use this information only as a supplement to other information gathered by them, and should make independent judgement of suitability of this information to ensure proper use and protect the health and safety of employees. This information is furnished without warranty, and any use of the product not in conformance with this Material Safety Data Sheet, or in combination with any other product or process, is the responsibility of the user.

SECTION X

SUMMARY SESSION - REPORTS FROM WORKING GROUP CHAIRPERSONS

Reports from Working Group Chairpersons

I. WIRE CHARACTERIZATION: ISSUES AND NEEDS - SUMMARY

The wire characterization session was designed to address important issues concerning the characterization of physical, microstructural, chemical and mechanical properties of materials and processing variables that are important for the production of superconducting wires and tapes with good properties. The formal session featured 10-minutes talks by 5 individual speakers, who discussed a variety of characterization topics, which will be briefly summarized below. The following "breakout" session attempted to identify the most critical characterization issues in the opinions of the participants. A summary of this deliberation also appears below.

1. Victor Maroni, Argonne National Laboratory, concentrated his presentation on the importance of characterizing both the stoichiometry of starting materials and the subsequent heat treatment schedules. Using the Argonne two-powder process as an example, he indicated the extreme sensitivity to the composition of the starting powders, particularly to the Pb content of the Bi-2212. He stressed the importance of the subsequent heat treatment schedule parameters: time, temperature, and O_2 partial pressure. Much of the sensitivity to the details of the heat treatment schedule appear to come from the formation of liquid phases and their effect upon reaction kinetics and microstructure. Because liquid phase formation is so sensitive to the reaction temperature and its control so important to the final J_C, he felt hat an in situ technique for its detection was essential. He showed some results from an acoustic velocity measurement apparatus under development at ANL that clearly showed the onset of liquid formation in a thallium based superconductor.

A separate characterization issue introduced by Maroni was that of determining the actual current carrying profiles in the finished conductor. Some results from a magneto optical imaging technique developed at ANL showed large regions of a Bi-tape conductor that carry little or no current.

2. Rudy Wenk, U.C. Berkely, discussed problems involved with the determination of texture in ceramic superconductors. With a brief tutorial on definition of textures and determination by x-ray pole figure analysis, he pointed out the difficulties presented by perovskite-related structures because angular resolution is not adequate to resolve closely spaced diffraction peaks. Neuton diffraction results on YBCO polycrystalline samples showing texturing produced by high-temperature high-pressure deformation indicated the power of this technique, but high cost prevents its wide-spread use. An improved methodology for analyzing x-ray data was shown to give good results on cold pressed Bi-2223 powders. This study showed a resulting high degree of texturing in agreement with a model of homogeneous reorientation of rigid particles during compression.

3. Mas Suenaga, Brookhaven National Laboratory, discussed issues related to mechanical strain tolerance of Bi-2223 tape conductors and its determination. He described an apparatus

developed at BNL that allows in situ measurement of J_c in magnetic fields to 0.5T in an extensometer that simultaneously measures stress-strain. Measurements of Young's modulus on four monocore tapes showed a bimodal distribution with 2 @ 35GPa and 2 @ 75GPa. The I_c under strain measurements showed irreversible degradation in all tapes at strain levels near 0.1%.

4. Jeff Willis, Los Alamos National Laboratory, discussed issues related to the determination of J_c, primarily from transport measurements of the I-V curves of BSCCO tape conductors. He pointed out the uncertainties related to determination of core cross-sections due to variations along the length and other problems, and he made a strong case for reporting an "engineering J_c" (I_c divided by the overall cross-section, sheath plus core) as being more relevant for applications. He then discussed the difference in criteria for J_c, electric field versus resistivity, and showed from modeled power-law I-V curves that the different criteria could result in large differences in inferred J_c particularly for small n-values. The resistivity criterion appears to give the most useful information for long tapes. The relation of power-law n-values to flux creep models was shown to predict decreasing n-values and increasing sensitivity to criteria levels as field and temperature increase, in agreement with experimental results. He also discussed issues related to conductor damage caused by application of contacts and by thermal cycling.

5. Amit Goyal, Oak Ridge National Laboratory, discussed mechanical properties measurement using an nanoindenter as a local probe. A survey of available information on elastic modulus and hardness showed no good data on Bi-2223 and a wide variation of Bi-2212 depending on sample type, oxygen stoichiometry and Pb content. He discussed the utility of the nanoindenter and the method of extracting hardness and the elastic modulii from the unloading curve. The results of his measurements show that Y-123, Bi-2223 and Bi-2212 exhibit highly anisotropic mechanical properties (ratios ranging from 1.3 to 1.9) and that, compared to Y-123, the BSCCO phases are much softer and less stiff.

Breakout Session Discussion Summary

1. In situ monitoring of liquid phase formation during processing. Members of the panel felt that this was an important issue owing to the sensitivity of the final microstructure and resulting J_c on control of liquid formation and the requirements this places on temperature control. Particularly for long tape processing, real time detection of liquid phase formation can avoid irreversible damage of the conductor. The ANL acoustic velocity technique was cited as an example of a technique that should be further developed and more widely employed.

2. Studies of local texture in superconductors. Many techniques, e.g. x-ray pole figures, determine average or global texture, whereas it is clear that local grain to grain orientation is more important for strong intergranular coupling. Recent discovery of the importance of colonies for current transport in Tl-based conductors was cited as an example. The electron backscattering technique should be useful for this purpose and more studies are desirable. The relation of texture to J_c remains unclear, particularly in the case of round Bi-2212 wires with high J_c and no apparent texture.

3. Determination of local current and flux distributions in conductors. It is now clear that, even in the best bulk conductors, current flow is very inhomogenous and likely resistricted to a small fraction of the cross-section. We need a local probe of current and flux profiles in order to correlate strong pathways with local microstructure. The magneto-optic and micro-Hall-probe techniques were cited as useful for this purpose.

4. High magnetic field measurements. Development of conductors and solenoids from HTS materials for high magnetic field applications requires testing at high field facilities with the following capabilities cited as useful: a. High current, 100-200A, in baths of liquid helium and liquid neon. Pulsed high currents may be required for measurements performed at intermediate temperatures in a flow cryostat. b. Large bore, high-field magnets for providing a background field for HTS coils.

5. AC loss measurements were cited as important for transmission line and pulsed magnet applications.

6. Improved standardization of J_c determination was cited as important. Issues included: voltage or resistivity criteria, examination of longitudinal cross-sections for sausaging.

II. TECHNOLOGY FOR OVERCOMING BARRIERS: WEAK LINKS AND FLUX PINNING - SUMMARY

A number of issues were presented and discussed. While many of them have a strong overlap with those discussed by other working-group panels, this may be a healthy sign that the field is narrowing down its scope. Several key issues were identified: these seem to be universal and will be discussed in some detail below. Critical development issues, new and/or different areas of emphasis and facility and/or resource needs will be included. In other cases, the panel noted important development issues which need to be addressed by the individual groups working in these areas: the research areas and key questions are given below. Finally, a proposal to "Develop Standardization of Measurement Procedures and Interpretation for Critical Currents" was presented and discussed. The results of those discussions and the panel recommendations will be described.

Major Issues for Flux Pinning and Weak Links

Flux Pinning. Flux pinning is intimately related to the irreversibility behavior in a magnetic field. The low temperature J_c can be enhanced up to a factor 3-4 by introducing ion-track damage, which produces pinning centers of an almost ideal diameter in each and every Cu-O bilayer. However, the value of such performance enhancements may not overcome the practical processing difficulties for applications at low temperatures. Ion tracks are so ideally suited to flux pinning in the highly-anisotropic HTS, that is hard to imagine other methods of attaining such a perfect microstructure. Nonetheless, since such enhancements play a much larger, enabling role at higher temperatures, methods of attaining this should be explored. An important issue is operation at 65-77 K in fields of ~4 T (e.g., for motors in liquid nitrogen). Pinning in the single Tl or Hg layer compounds (e.g., Tl-1223) without ion tracks is close to those operating conditions, but the high T_c of Hg-1223 or the Bi- and Sr-substituted Tl-1223 may be crucial. The general feeling is that for these applications, the encouraging results for thick deposits of Tl-1223 is a good start, but that Y-123 (which does not need ion track damage for sufficient pinning) and Hg-1223 are deserving of further parallel studies.

Weak Links. Here the issue is that powder-in-tube and thick deposits are typically polycrystalline materials and the evidence is that only a small fraction of the actual cross-sectional area is used to transport current. In some cases, with a high degree of c-axis orientation and in-plane texture, strongly-linked current paths are found, apparently with the transport mostly dependent on the limitations of flux pinning. However, the effects of any weak-link along these paths needs to be understood. In most cases, which often lack texture, the current transport is clearly dominated by weak links. While many agreed that bi-axial texture is sufficient to solve the problem, it was noted that the Siemens BSCCO PIT did not exhibit such texture and still exhibited a high J_c. Even for samples with a high degree of texture, there is the potential for segregation of impurities to grain boundaries with small misorientation angles or with a pile-up of dislocations which would lead to poor current transport: this is evidenced in the multifilamentary wires of Y-124.

There are several ways to overcome these problems, each of which should be pursued in parallel: (1) concentrate on finding ways to achieve excellent texture with clean gain boundaries; (2)

continue the approach of modifying composition and processing to improve J_c; and (3) seek to determine the reasons that only a small cross-sectional areas is active in practical conductors and feed back that information into the processing in (2). Two approaches were identified for (3). The most relevant property is current transport, so the first and most powerful approach would be to visualize the *actual* current flow in a polycrystalline sample and then to correlate it with standard microstructural analyses on the same sample. Since this is admittedly difficult, especially for three-dimensional samples like PIT, a second approach is to make careful measurements of the current-voltage characteristics, I(V), and correlate them to the microstructure by modeling with known or measured I(V) for individual gain boundaries and intragranular flux motion.

Achieving High Degree of Texture. There are three examples of this: BSCCO PIT processing; deposition onto flat substrates and multifilamentary wires of Y-124. Whilst the weak-link behavior seems missing for the first two, there are significant questions about the effective use of cross-sectional area. Transport in the third case is dominated by weak-link effects. Feedback from microstructural analysis, such as suggested in (3) could be very valuable here.

Composition and Processing Modifications. Without using feedback from the microstructural analysis, such as suggested in (3), this is an Edisonian approach. It stands a better chance of significant progress in cases exhibiting a high degree of microscopic homogeneity, e.g., Tl-1223 thick deposits or BSCCO PIT. However, in other cases, including BSCCO PIT, significant feedback is likely necessary to improve the efficient use of the whole cross-sectional area.

Determine Microstructure-Properties Relationship through Visualization of J. A number of probes offer potential to visualize the current flow: magnetooptical films; magnetic force microscopy; and Hall or magneto-resistance microprobes. Although these cannot probe the third dimension, they should be adequate for Tl-1223 thick deposits and of some value to sliced and polished PIT if they can be correlated with the microstructure at the surface of the slice. Another issue is whether the field sensitivity is adequate to visualize current flows on an individual grain basis.

Determine Microstructure-Properties Relationship through I(V). In this case the properties measurements are very straightforward, and success will depend on the ability to model the current flow in such a way to distinguish between flux motion and grain boundary dissipation. Samples with simple structures (e.g., thick deposits on flat substrates and multifilamentary wires of Y-124) will minimize the number of modeling parameters to allow testing of the overall procedure. Another very promising approach is to individually measure sections of PIT (e.g., by laser cutting). Although more rapid progress can be expected here, it is unlikely to be as insightful as the above visualization of current flow.

Issues Requiring Further Development

Assuming that sufficient pinning can be included through ion irradiation (or a more commercially promising processing technique), is BSCCO-2223 potentially usable at 65-77 K in a 1-4 T field? The ion irradiated damage is so ideally suited to flux pinning in the highly-anisotropic HTS, with pinning centers in each and every layer of an almost ideal diameter, that it is hard to imagine other methods of attaining such a perfect microstructure.

Will the non-uniform current flow in thick deposits of Tl-1223 be solved through biaxial grain alignment?

Can the encouraging results on metallic precursors for multifilamentary Y-124 be improved at high fields and temperatures? Is there any hope of using the technique for other materials (e.g., Y-123, Tl-1223).

Can the biaxially aligned Y-123 deposits on metallic substrates be made into a practical conductor (i.e., increased thickness)?

Three-dimensional techniques were suggested for studying cracks in the microstructure: an acoustic microscopy and the varied, complicated and somewhat random structure of PIT may make identification of cracks from small-angle neutron scattering very difficult. Either technique needs demonstration before it can be suggested for further comprehensive studies.

Proposal to Develop Standardization of Measurement Procedures and Interpretation for Critical Currents

This proposal, consisting of four sections, was handed out and discussed at the meeting (a copy follows this report).

What is J_c? And Why Examine I-V? There was considerable support for the idea that an adequate description of J_c came by specifying: the current density, J; electric field, E, at which J was measured; and the exponent, n, of the power law expressing the I(V) curve, i.e., $E \alpha J^n$. The value of using the full I(V) for diagnosis, as expressed in the above was noted.

Techniques: Transport vs. Bean-Model Magnetization. There was little discussion of this, but panelists reported good examples of good agreement between these methods and other cases of very bad agreement. One potential problem is that of adequately knowing the effective electric field criterion for the two measurements. Transport measurements have become pretty much the standard for this group.

Standardize Nomenclature. Here several attendees have already established a nomenclature of "engineering" to describe the overall current density, including any Ag sheath material. For deposits, the substrate should be included, although this introduces an uncertainty when thicker-than-necessary substrates have been used for convenience. Thus we recommend reporting the $J_e(E,n)$ for overall current density and $J_s(E,n)$ for current density in the superconductor portion of the conductor package. Unless stated otherwise, it should include all of the oxide material, even if it is not all superconducting.

Data Accumulation. There was no discussion on the method of sending data. It was agreed that such an effort could have value and a number of volunteers agreed to participate. Argonne would act as a collector of such data.

III. MANUFACTURING ISSUES FOR LONG WIRE LENGTHS - SUMMARY

Oxide powder-in-tube Bi-2223 conductor processing has entered the pilot-production mode at U.S. companies, and commercially viable products are seen as near. Many of the details of industry's efforts to improve properties and process control and to scale up to longer lengths are proprietary. There are a number of efforts to develop alternatives to oxide powder-in-tube conductor which have shown significant progress but are at earlier stages of development. The selection of oral presentations emphasized these alternative approaches to conductor fabrication, although time constraints dictated that only a few such processes could be discussed.

The seven 10-minute presentations by individuals from industry, national laboratories and a university are summarized below. The goal of the break out session was to define issues important to the production of long lengths of conductor. The results of that session are also summarized below.

Leszek Motowidlo of Intermagnetics General Corporation described that company's effort to develop high performance round multifilamentary Bi-2212 wires. The conductors are Bi-2212/Ag composites fabricated by the powder-in-tube process. Fabrication involves no rolling and a single heat treatment involving "step-solidification" as developed by E. Hellstrom and others at the University of Wisconsin. Conductors containing 37 and 7 x 37 = 259 filaments have been fabricated, and J_c = 165,000 A/cm^2 in self-field at 4.2 K has been obtained in short samples. J_c increases as the filament size is decreased. Among the advantages of round wires are that coils may be wound instead of pancakes if desired, twist may be introduced with less filament distortion and breakage, J_c is not expected to depend on direction of applied field, and flexibility in the design and geometry of multistrand conductors is gained. As with rolled powder-in-tube conductor, J_c decreases with length of conductor, presenting the primary challenge in scaling up.

Lawrence Masur of American Superconductor Corporation discussed production and properties of long lengths of Bi(Pb)-2223/Ag composite conductor prepared by the oxidation-of-metallic-precursor (OMP) process. Multifilamentary conductors are fabricated by the powder-in-tube process using mechanically alloyed metal powders. Oxidation of the metal precursor is done by diffusion of oxygen through the silver at the later stages of fabrication. Advantages of the OMP process result from the improved fabricability of the metal/metal composite compared to an oxide/metal composite. Higher filament counts can be obtained with the OMP process than with oxide powder-in-tube, resulting in improved strain tolerance. The greater fabricability may also permit use of larger billets. Presently achievable properties of Bi(Pb)-2223 OMP conductor are good, only slightly lower than those of ASC's OPIT conductors. Scale-up to longer lengths, it was said, appears to be straight forward, at least for 20,000 A/cm^2, H = 0, 77 K. Masur stated the view that for both OPIT and OMP conductor a very important impediment to improving J_c is our inability to reliably relate J_c to specific microstructural characteristics.

Professor J. H. Wang of the State University of New York at Buffalo presented results on the processing of $(Tl,Bi)_1$, $(Sr,Ba)_2Ca_2Cu_3O_x$ powder-in-tube conductor. Transport J_cs at 77 K, in self-field greater than 20,000 A/cm^2 have been obtained, the highest reported for Tl-1223 powder-in-tube conductor. Professor Wang attributes the high J_c to improved grain connectivity and excellent dimensional uniformity of the oxide core. Little sausaging is seen. Pressing at room temperature was found to increase J_c significantly. The Tl-1223 cores show little evidence of texture. The J_c at 77 K decreased by a factor of about 30 in a magnetic field of 0.1 T, illustrating the primary problem in development of Tl-1223 powder-in-tube conductor.

John Bingert of Los Alamos National Laboratory described a multifactor experimental design addressing thermomechanical processing of monocore Bi(Pb)-2223 powder-in-tube wire. Ten fabrication and heat treatment variables were chosen, with three levels for each. J_c is the measured response, although microstructures will be examined. Because the number of samples required for a full factorial analysis is prohibitive, a fractional factorial design requiring a total of 178 samples was chosen. At the time of this workshop conductors had been fabricated and heat treatments were in progress, but no J_c results were available.

John DeLuca described GE's process for preparing high J_c Tl-1223 deposits. The field dependence of J_c for these materials at temperatures higher than 40 K is very good. As a consequence, GE is engaged in an effort to scale the process to preparation of long lengths of conductor on a flexible substrate. A Tl-free precursor deposit is prepared by spray pyrolysis of an aqueous $Ba_2Ca_2Cu_3$:XAg nitrate solution on a YSZ substrate. In subsequent steps the nitrates are decomposed in oxygen at 850°C and Tl-1223 is formed by reaction with Tl_2O vapor. Current efforts are directed toward use of flexible metallic substrates and development of processing steps which can be integrated into a continuous conductor fabrication process. DeLuca cited their pre-scale-up goal of a flexible tape capable of 10 A/mm of tape width at 40 K in a 1-5 T field. This may be achieved through increases in $J_c(H)$ and/or preparation of thicker deposits. Scale-up issues listed included the need for higher precursor deposition rates, the need for precise control of the temperature and Tl_2O vapor pressure during thallination, and the length of post-deposition heat treatments.

Ken Marken of Oxford Instruments, Inc. discussed process control issues in their effort to develop Bi-2212 conductors made by both dip-coating and powder-in-tube processes. In the dip-coat process a silver tape is passed through a slurry of precursor powder in a liquid medium containing an organic binder, resulting in coatings on both sides of the tape. The tape is then heat treated to remove the binder and melt-process the deposit. Protection of the coating from handling damage and environmental degradation is a concern for deposits. A silver sheathed conductor may be obtained by sandwiching the coated strip between two more Ag strips prior to final heat treatment. However, the additional silver reduces significantly the engineering J_c, which for bare conductor can be better than for powder-in-tube conductor.

Powder requirements differ for the dip-coat and powder-in-tube processes. Small particles (\|o(_,^<)5 μm) result in good slurry characteristics for the dip-coating and low carbon concentration is not as important as in powder-in-tube fabrication. The primary problem for both processes is that J_c in long length (1-20 m) is 30-50% of J_c in short samples. Among the possible causes of this decrease are cracks, voids, variations in superconductor layer thickness and second phases. Marken stressed the importance of careful control of all of the many process parameters.

Balu Balachandran of Argonne National Laboratory discussed issues in bulk processing of powders, including control of carbon, composition, phase assemblage, particle morphology, and scale-up of batch size as needed for production of long wires. He discussed sources of carbon contamination including exposure to the atmosphere and to organics during milling and mixing operations and in cleaning solutions. He presented results showing that a low temperature, low pressure treatment in flowing gas can effectively reduce high carbon concentrations to acceptable levels.

In the breakout session we attempted to define the important issues concerning HTS conductor fabrication. Since three compounds, Bi-2223, Bi-2212 and Tl-1223, and a number of processes were discussed, and since many issues are specific to a compound or process, only a few issues of general importance emerged. Among these were the need for improved J_c performance with respect to field and temperature, improved strain tolerance, and techniques for making superconducting or very low resistance joints. Of critical importance in guiding future work is a better understanding of the microstructural determinants of $J_c(H)$. In particular the role of cracks in limiting J_c, and the nature of percolative paths for current flow warrant study.

Very significant progress has been made in powder-in-tube fabrication of Bi-2223 conductor. Process parameters leading to high J_c materials have been defined and manufacturers are engaged in efforts to improve process control to obtain short sample characteristics in long lengths. Among the issues important to this development are how and where cracks form, control of core dimensions, and quality of the silver/superconductor interface. Development of on-line, non-destructive characterization methods and modeling of the deformation process were seen as important to improving fabrication control. Information derived may lead to development of interactive, on-line control of the fabrication process. Improvements in precursor powders with respect to purity and homogeneity are also important.

The participants agreed that substantial increases in the "engineering J_c," calculated using the total cross-section of the conductors, are needed. To obtain such increases will require not only improvement in process control but also modifications of process and design which lead to higher J_c than is presently obtained in the best short samples. Minimizing the amount of silver and strengthening the sheath are important. Additional improvements are likely to

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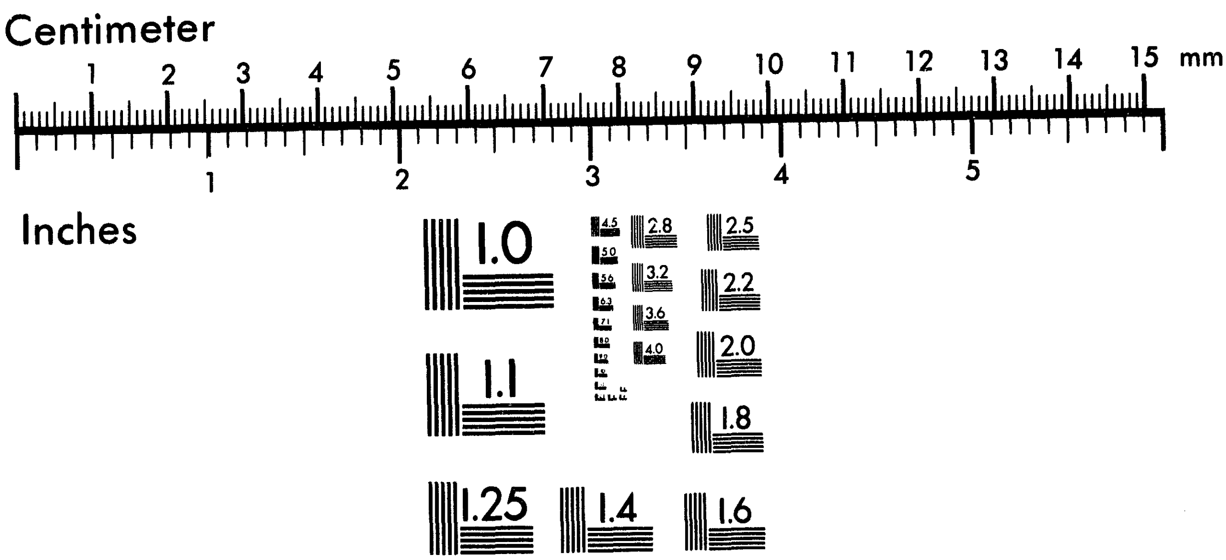


6 of 6

require determination of the mechanism(s) for texture development and ways to improve texture and minimize cracks. Better understanding of phase development and how to minimize the amount and size of second phase particles is needed. Further experimentation to correlate precursor powder characteristics such as phase assemblage with microstructure and properties of reacted conductor is clearly indicated. Better understanding of the microstructure/property relationship is needed.

For fabrication of Bi-2223 and Bi-2212 by the alternative processes discussed on the first day, the primary problem is obtaining short sample characteristics in long lengths. Specific issues were discussed in the oral presentations. For deposits of 2212 there is the opportunity to develop base metal substrates, probably with barrier layers, which are stronger and cheaper than silver.

Some alternatives to the powder-in-tube process which, because of time limitations were not discussed in the oral presentations, show promise. These include continuous deposition and encapsulation of precursor powder on silver strips, the jelly-roll approach and various physical and chemical deposition processes to obtain thick deposits.

Three approaches being investigated for fabrication of Tl-1223 conductor are spray pyrolysis, electrodeposition and powder-in-tube. Success with the powder-in-tube process has been very limited in that weak-link behavior remains extreme and superconducting cores are very poorly textured. Improvement is expected only if ways are devised for obtaining strongly textured material. Success in texturing through deformation processing has been very limited. So far, only a small number of compositions have been investigated.

Technical issues concerning the scale-up of GE's process for thallination of spray pyrolyzed deposits on YSZ to long lengths on flexible substrates were presented by DeLuca in the oral session. In the discussion he commented that this is a large task and that lack of resources is a serious issue. A community of researchers with common interest is needed.

Control of the composition appears to be the primary problem to be overcome in fabrication of lengths of Tl-based conductors by electrodeposition of a Tl-free precursor with subsequent thallination by the same process used for spray pyrolyzed deposits. Thallination of powder deposits prepared by spray drying, painting or dip-coating are methods by which thicker deposits may be obtained, but not enough work has been reported to evaluate these approaches.

Finally, we note that the intrinsic properties of Tl-1212 compounds appear to be good. Very little has been done on conductor fabrication processes using this compound.

IV. PHYSICAL PROPERTIES OF HTS COILS - SUMMARY

The discussions of this group were focused on the issues related to protection of magnets and conductors. The group's consensus of the current key issues on this subject are as follows:

I. Magnet Protection:

Small magnets, which are constructed using high-T_c superconductors, Bi(2212, 2223)/Ag, are very stable and there will not be any need for protection mechanisms. However, when the stored energy of a magnet becomes large, the protection of a magnet from permanent damages after a quench is though to become a serious concern. Thus, as a first step to this problem, comprehensive studies of quench processes should be carried out such that the critical level of the stored energy of a magnet, above which some types of protection schemes will be required, can be analytically determined. Also, the studies should include possible scenarios for discharge modes for the magnets.

II. Conductors:

Currently fabricated Bi(2212, 2223)/Ag composite conductors are extremely fragile. Thus, protecting the conductors from mechanical damage is a major concern for winding, as well as operation of the magnets. Hence, determination of the critical strain and stress levels, below which there will be no degradation in I_c of the conductors, should be made for various conductor configurations to be used for different applications. Means for strengthening the matrix by alloying or attaching supporting members to the conductors, if necessary, may need serious consideration.

III. Other issues:

Since there are applications in which the conductors experience ac fields superimposed on dc fields, such as in generators, it is important to determine the ac losses (<power frequencies) for such cases to assist design efforts of such systems.

March 4, 1994

Proposal to Develop Standardization of Measurement Procedures and Intrepretation for Critical Currents

Ken Gray, Bob Kampwirth and Jeff Hettinger, Argonne National Laboratory

and Marty Maley, Los Alamos National Laboratory

Preamble:

The consistent determination of the critical current, I_c, or critical current density, J_c, is likely the most important result of research of the Superconducting Technology Program for Electric Power Systems (STPEPS). In order to simplify proper comparisons and evaluations of these results, it may be advisable to have more standardized procedures and interpretations. This document is meant to begin the process of developing such procedures by accomplishing the following:

(1) address the importance of the shape of the full I-V curve, vs. just the current at a given voltage criterion or the magnetization after it decays for a certain period of time; and also, in particular, the effect of silver sheath materials;

(2) begin a discussion of the relative merits and pitfalls of various experimental techniques for determining J_c, such as transport or Bean-model magnetization;

(3) standardize the nomenclature as regards cross-sectional area used in J_c and encourage that all reported measurements include sufficient information, e.g., the length and areas of the superconducting sample and sheath being probed;

(4) begin the process of accumulating data (e.g., I-V) from the various STPEPS participants.

NOTE: This document should in no way be construed as the final word on these issues. Constructive suggestions and criticism from any or all STPEPS participants is essential for the evolution of this document and its procedures into a useful vehicle for the program. Thus we anticipate drafting updates, based on such responses, as needed, and certainly within the 6 month to one year time frame.

NOTE 2: This effort is separate from, but will likely be integrated into, the round-robin tests by Loren Goodrich involving circulation of the NIST black box. Together these may begin to form the necessary standardization for the field and the STPEPS program.

NOTE 3: Separate issues concern sample heating, possible training effects and the repeatability of measurements, e.g., after thermal cycling. These issues are related and important, but separate from the focus of this document. It is expected that everyone will address these issues in an appropriate manner. We would appreciate receiving suggestions on standard or best ways to avoid any or all of these problems, and will distribute them to all those who respond to this proposal.

1. What is Jc? And Why Examine I-V?

What is J_c? Transport measurements mostly report the current density flowing at a given fixed voltage criterion (e.g., 1μV/cm). For magnetic measurements, the difference in magnetic moment between increasing and decreasing portions of the hysteresis loop is used with the Bean model and a characteristic sample dimension, R_B. This analysis roughly determines the net current flowing in the sample, but with a non-fixed and often unknown voltage criterion. However, in either case, to specify this as **the** single parameter "J_c" which defines the current carrying capacity of a sample cannot be totally correct since it depends on the voltage criterion chosen and the current-voltage characteristics of different samples are not identical.

Why examine I-V? To obtain a single parameter defining the current carrying capacity requires fitting the I-V to a model which can reproduce a suitable portion of the actual I-V characteristic from the single parameter. Although in general this is a difficult task, it can be done for the limiting cases of I-V characteristics dominated by either a single weak-link, Josephson junction or by purely depinning of flux. Examples are shown in Fig. 1. Note that the shape of the curves alone cannot uniquely differentiate between these extremes, and some insight as to the potential magnitude of the effects is necessary. For example, in Fig. 2, the added dissipation, i.e., voltage, associated with weak-link effects in polycrystalline materials can be obtained by directly comparing with similar measurements on epitaxial or single crystalline materials.

The ability to evaluate the relative importance of grain boundary effects compared to flux depinning in practical wire configurations is clearly as important as being able to define a "J_c" value, since it can provide specific guidance for synthesis and processing to improve the current carrying capacity of wires. The most likely prospect for doing this is by evaluating the I-V curves, and the procedures to interpret these, in complicated configurations of grain boundaries with unknown individual characteristics, is an ongoing research effort in several STPEPS laboratories.

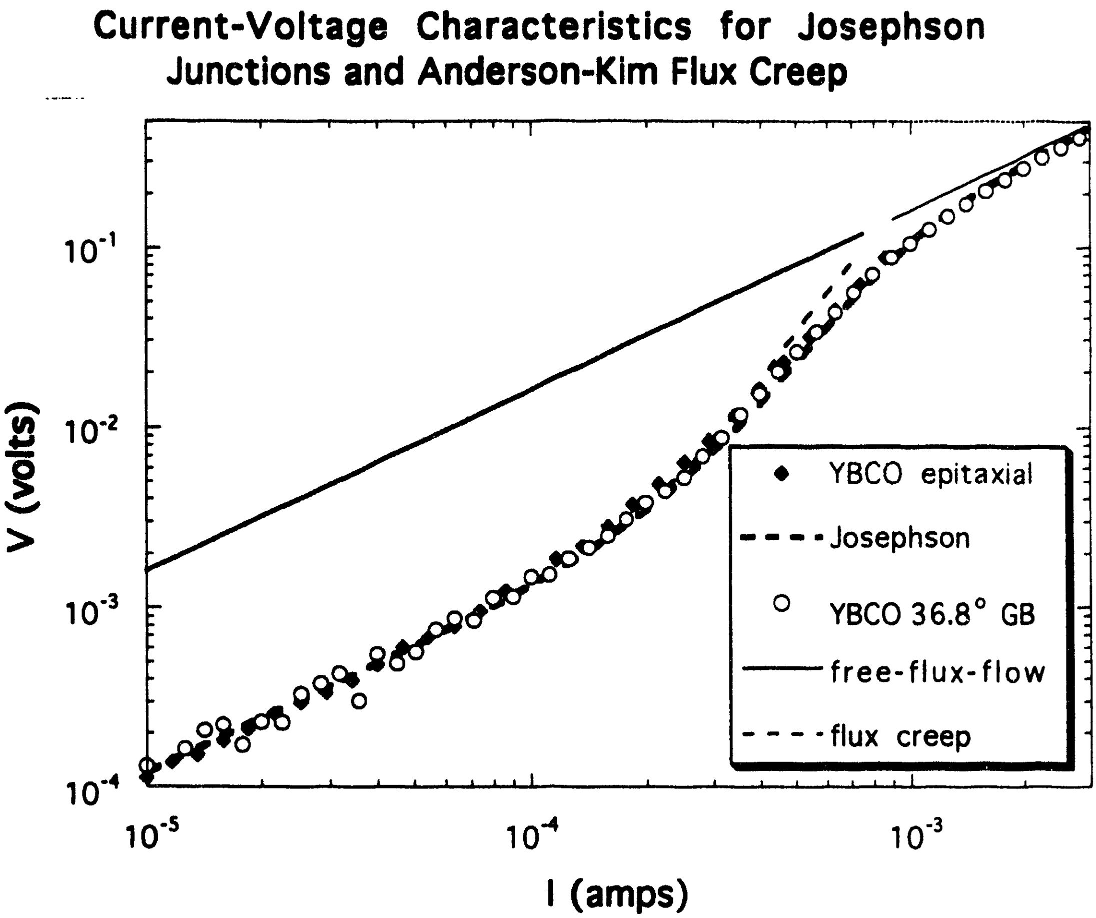


Figure 1

I(V) for $YBa_2Cu_3O_7$:

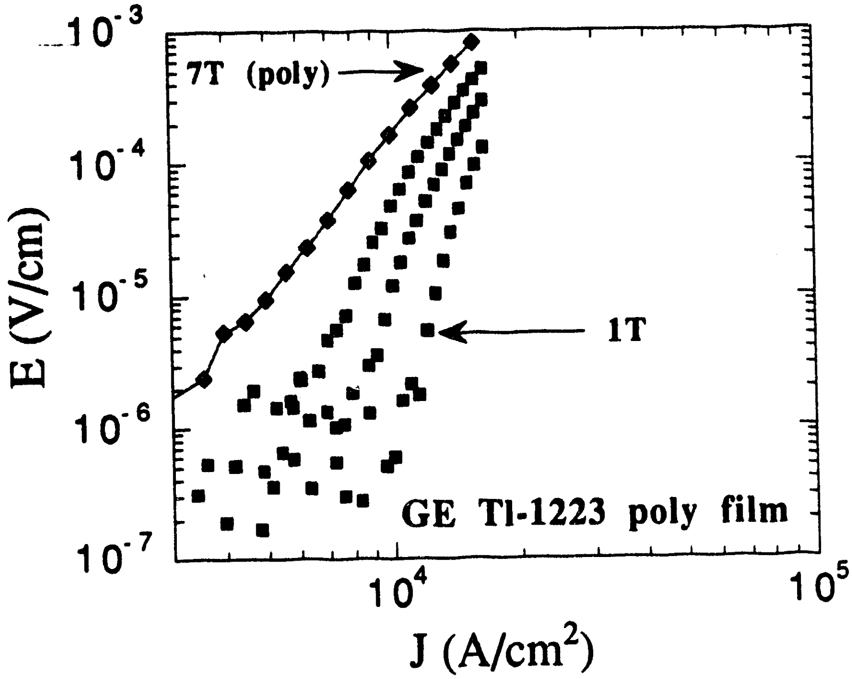
epitaxial film at 1 T parallel to c-axis and 86.5 K;

symmetrical 36.8° bicrystal tilt grain boundary at 0.002 T and 30 K.

Fits: Ambegaokar-Halperin Josephson junction;

free flux flow voltage $V_{fff}=V_n(B/B_{c2})$;

Anderson-Kim flux creep $V=\frac{V_{fff}}{1+\eta\exp(U/kT)/\sinh(AJ/kT)}$.



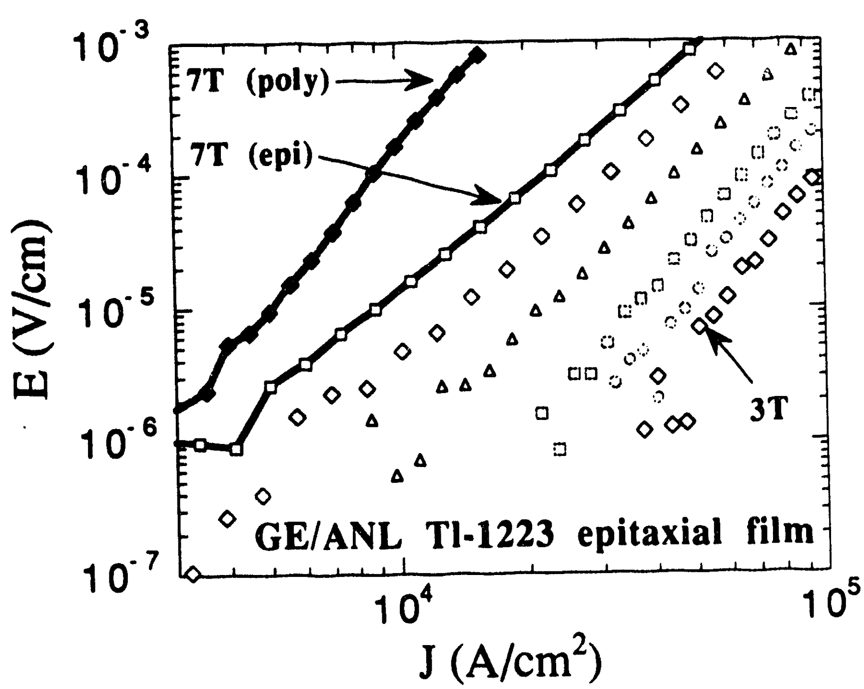


Figure 2. Comparison of I(V) for polycrystalline (a) and epitaxial (b) films of Tl-1223 showing the enhanced dissipation across grain boundaries. An explicit comparison is shown in (b) for a field of 7 T.

2. Techniques: Transport vs. Bean-Model Magnetization

Magnetization. In order to determine J from the Bean model and the sample size R_B, it is required to exceed several times the full-sample-flux-penetration field, H*. However, subsequent measurements below H* are always no more than a *lower* limit on J, since the trapped flux near zero applied field can result in large currents flowing in opposite directions, which thus reduce the net magnetic moment of the sample.

Subdivision of the sample is necessary to establish the sample dimension as the correct R_B for samples with potentially interconnected grains, such as practical wire conductors. Samples of isolated grains allow determination of intragranular J, but that is of limited value for wires, since intergranular transport is essential and weak links generally seem to dominate this transport.

Even if one is above H*, the effective voltage criterion can be strongly field and temperature dependent (see Hettinger, et al, *Appl. Phys. Lett.* **60**, 2153 (1992)).

Transport. Transport can be much more susceptable than magnetization measurements to diabolical defects, i.e., those which occupy a majority of the sample cross section, e.g., scratches or cracks. This may be particularly emphasized in narrow cross sections samples.

Low resistivity sheath materials, e.g. Ag, make the measurements and interpretation complex in regard to defining J and intercomparing with sheath-less samples. It is hard to evaluate to what extent the onset of voltage with current is due to a transfer of current to the Ag sheath, thereby avoiding regions of weak superconductivity. This is another case where the procedures to interpret these in complicated configurations is a necessary ongoing research effort.

Comparison between Magnetization and Transport: Even if there are no diabolical defects and one is well above H*, the equivalence of the measurements requires that they are at the same effective voltage criteria, and this may be difficult or impossible to achieve. Thus in either case the most complete and suitable information is contained in the generic I-V curve (either directly from transport measurements or for magnetic measurements from ΔM-$d\Delta M/dt$ for SQUID magnetization or ΔM-dB/dt, if appropriate for VSM). Even having done this, equivalence is not guarenteed because of the differing effects of low-resistivity sheath materials or diabolical defects on these measurements. A few diabolical defects could have a much smaller effect on magnetization, especially for long, narrow samples since the most important size scale, R_B, is then the sample width.

Recommendation: The preliminary recommendation is to strongly emphasize transport measurements, since for most applications current transport is required and it provides a fixed, known voltage criterion. However, while a determination of the current flowing at a fixed voltage criterion, appropriate to a given application, is the simplest, practical means to compare samples *for that application*, the significance to other applications and intercomparisons of materials between research groups requires the greater information found in the I-V curves.

3. Standardize Nomenclature

It seems unlikely that I-V curves can be used to routinely report the current carrying capability of materials and wire conductors and rather that the existing practice of reporting single, characteristic "J_c" values will continue. In regard to the discussion in Section 1 above, it may be appropriate to include the voltage (actually electric field) criterion when quoting a "J_c" value.

An separate issue for making intercomparisons is the cross-sectional area used. Their value would be facilitated if a standard method is developed for reporting "J_c" values in the *superconducting* material and in the *overall conductor* cross-sectional areas. Materials processors prefer the former, while applications engineers require the latter and the ensuing mixture of definitions makes life more difficult than it needs to be.

Based on discussions at the workshop in St. Petersburg, let us propose the following option for consideration:

A. Define and consistently use J_s when the "superconductor" cross-sectional area is used and another symbol, perhaps J_e when the "engineering" or total overall conductor cross-sectional area is used.

B. Report the electric field criterion, E_{crit}, and power-law exponent, n, measured from the E-J curve at E_{crit} using:

$$E = \text{Const. } J^n$$

thus finally reporting: $J_s(E, n)$ e.g., $J_s = 5\times10^5$ A/cm^2 (@1μV/cm and n=2.1).

4. Data Accumulation

We would like to collect a *small* number of selected data sets from willing participants. These should include a very representive sample(s), but also one for the 'best' J_c. To minimize the amount of data, and to simplify intercomparisons, we suggest reporting data for a field of one Tesla in the unfavorable direction, i.e., parallel to the c-axis or perpendicular to the tape or film and at the following temperatures, which depend on the material. For YBCO and Tl-based compounds the data should be taken at liquid nitrogen temperature, while Bi-based compounds should be at liquid helium temperature. For those without magnetic field capabilities data should be sent for zero field. Depending on the usefulness of these comparisons, it may be worthwhile to extend them to other temperatures and fields.

The data requested for **all** measurements includes:

1. length of sample probed
2. shape, width and thickness of superconductor
3. the sheath or substrate material together with its temperature dependent resistivity, shape, width and thickness
4. expected or measured c-axis orientation
5. zero-field, small current value of T_c
6. the temperature, field value and orientation for each data set
7. technique, i.e., transport, SQUID magnetometer, VSM with field ramp, other?
8. the large data set of I-V or ΔM-$d\Delta M/dt$ for SQUID magnetization (ΔM-dB/dt if appropriate for VSM).
9. the value of "J_c" you would report for this sample.

For **magnetization**, the following should also be included:

10. the results of sample subdivisions
11. the measurement or estimation of the full-flux penetration field, H^*

The large data sets (e.g., I-V) should be sent by email or on floppy disks with one of the following formats:

Floppy disks must be formatted for either a Macintosh, IBM or IBM compatible computer (i.e., some version of DOS or Windows operating system).

Files sent by e-mail can be included as part of the e-mail message or as an attached file. All attached files **MUST** be binhexed before attaching.

From Macintosh computers, files can be sent in either Kaleidagraph, Excel, or ASCII format. Files from PC's other than Macintosh must be in ASCII (text) or Excel format.

Internally, the pairs of data (I, V) or (ΔM, $d\Delta M/dt$), should be separated by Tab, Comma, Space or some other defined character with preferred separation in the order listed, and each pair of data should be separated by a carriage return. File headers do not have to be stripped off, as that can be done later.

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SECTION XI

WORKSHOP EVALUATION RESULTS

DEPARTMENT OF ENERGY HIGH-TEMPERATURE SUPERCONDUCTING WIRE DEVELOPMENT WORKSHOP EVALUATION FORM

1. I represent ☐ industry, ☐ government/laboratory, ☐ university, or ☐ other.

2. Please rate the workshop by checking one box for each statement below:	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
a. The **objectives** for the workshop were clearly stated. Comments ______					
b. **Technical issues** of utmost importance to the DOE program were discussed. Comments ______					
c. The following important functions were fulfilled through my attendance at the workshop:					
1) delineating and clarifying the **key technical issues** in HTS wire development.					
2) sharing **recent progress** that may help resolve key technical issues.					
3) defining **problem areas** that may require special attention within the DOE program.					
4) providing opportunity for **dialogue** with colleagues.					
5) obtaining adequate information on **technology available** from the laboratories and **private companies**.					
6) identifying special **facility and resource needs**.					
7) suggesting **potential new/different approaches** and partnerships to improve HTS wire performance.					
d. There was **adequate exchange** of **technical information**. Comments ______					
e. The time **allotted for each session** was appropriate. Comments ______					

2. Please rate the workshop by checking one box for each statement below:	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
f. The meeting **technical balance** was appropriate. Comments ______ ______ ______					
g. **Working groups** on Thursday were helpful and relevant. Comments ______ ______ ______					
h. Please rate the **overall usefulness of the workshop**...Should DOE **continue** to sponsor such workshops? Comments ______ ______ ______					
i. The **overall workshop objectives** were met. Comments ______ ______ ______					

j. Please rate the:	Outstanding	Excellent	Good	Fair	Poor
Meeting facilities					
Accommodations					
Meals					

3. In your opinion, what are the areas of HTS wire development that are not being fully explored by the industry or the DOE?

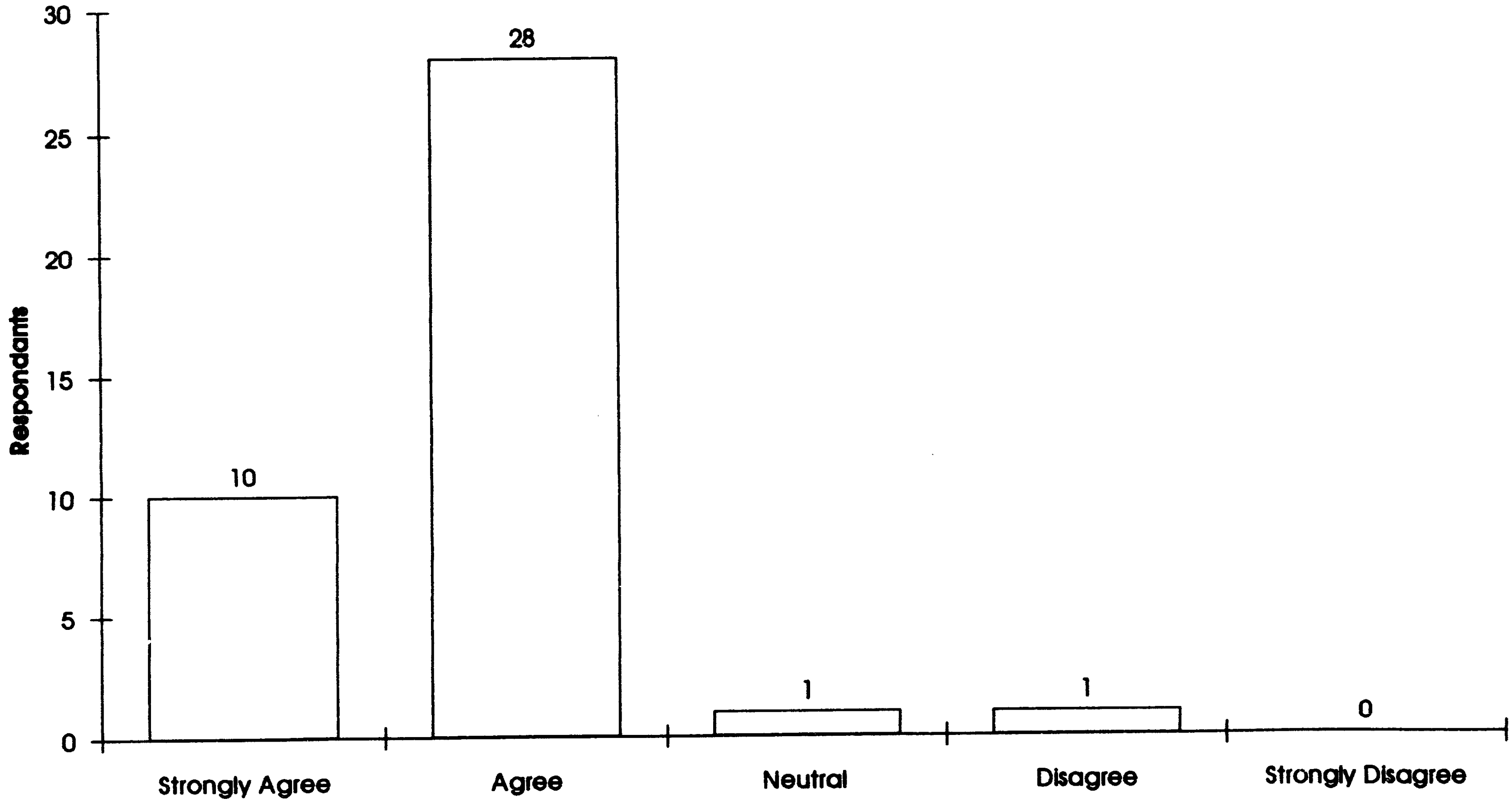
______

4. Comments you would like to add:

______

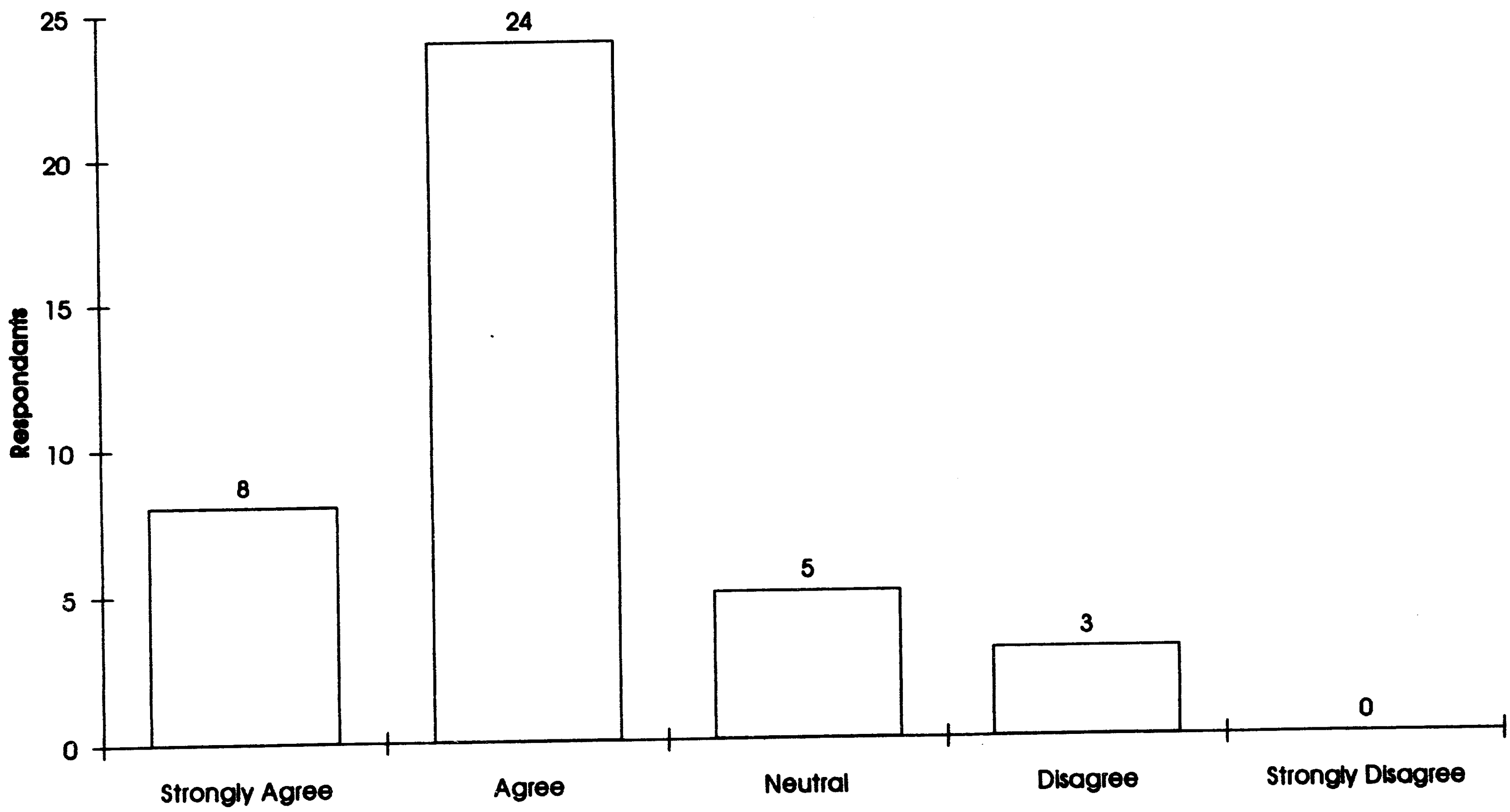
Thank you for attending the
DOE HTS WIRE DEVELOPMENT WORKSHOP, February 16-17, 1994

The Objectives for the Workshop Were Clearly Stated

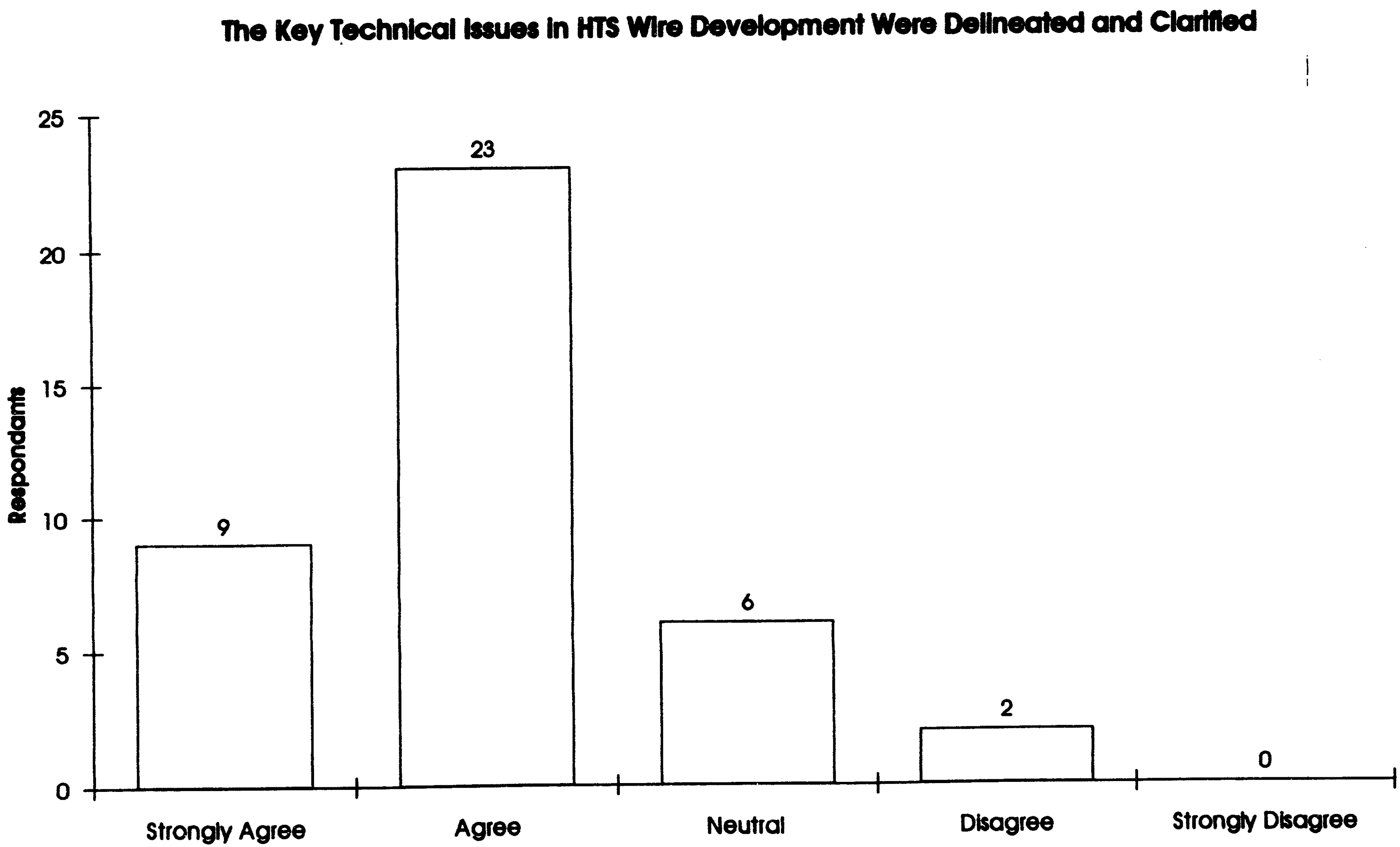


WWSCHA.RTS Chart 1

Technical Issues of the Utmost Importance to the DOE Program Were Discussed

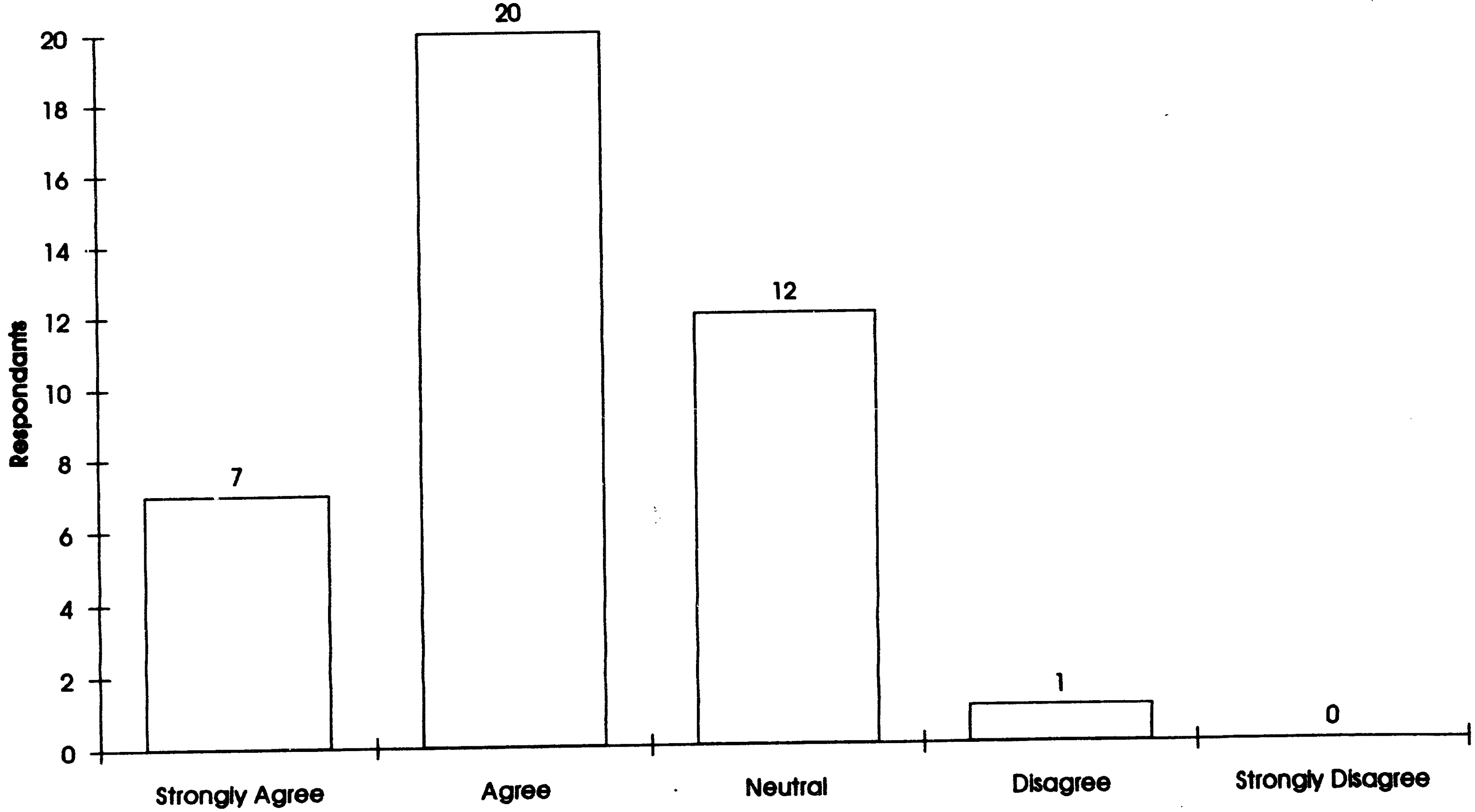


WWSCHA.RTS Chart 2



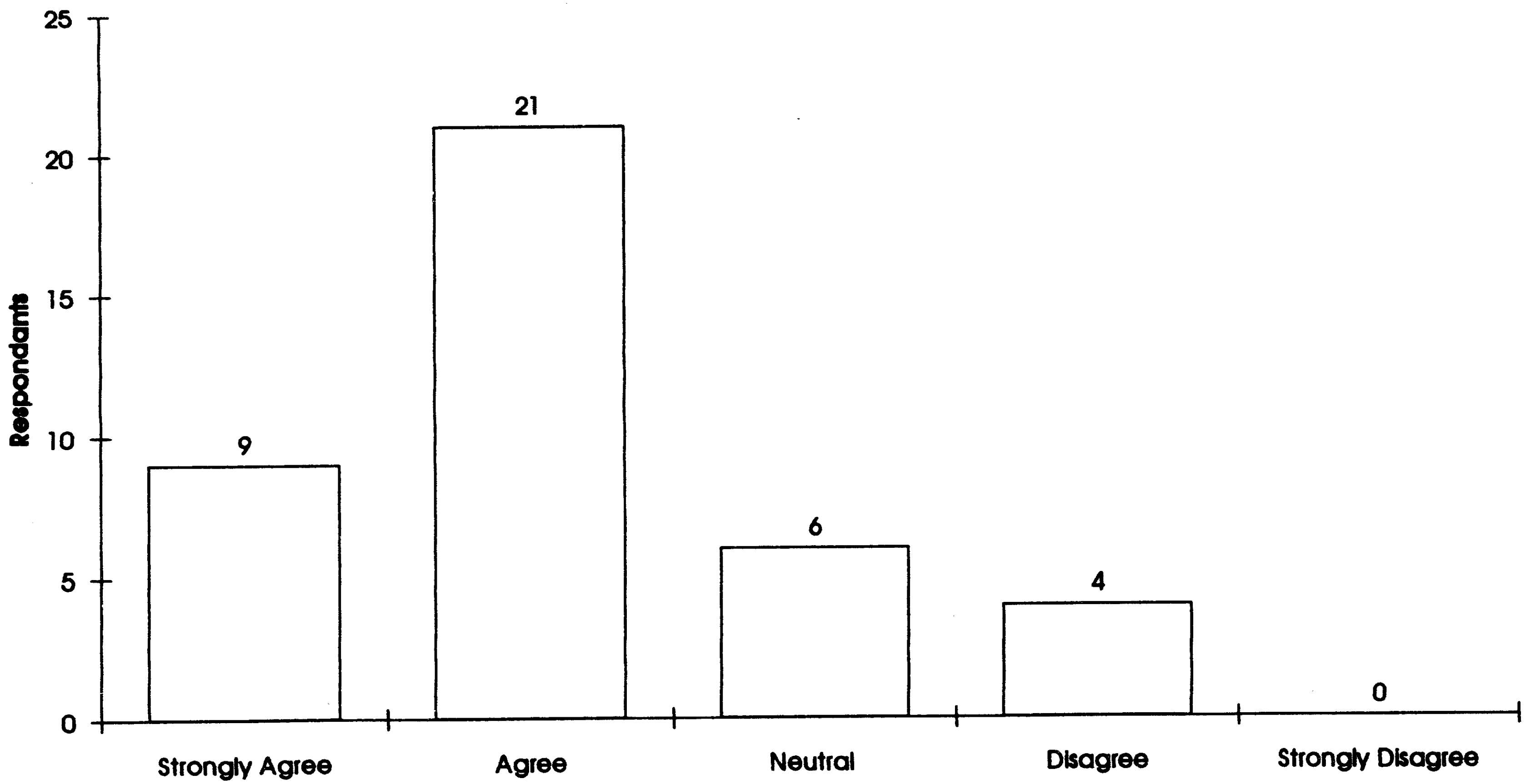
WWSCHA.RTS Chart 3

Recent Progress That May Help Resolve Key Technical Issues Was Shared

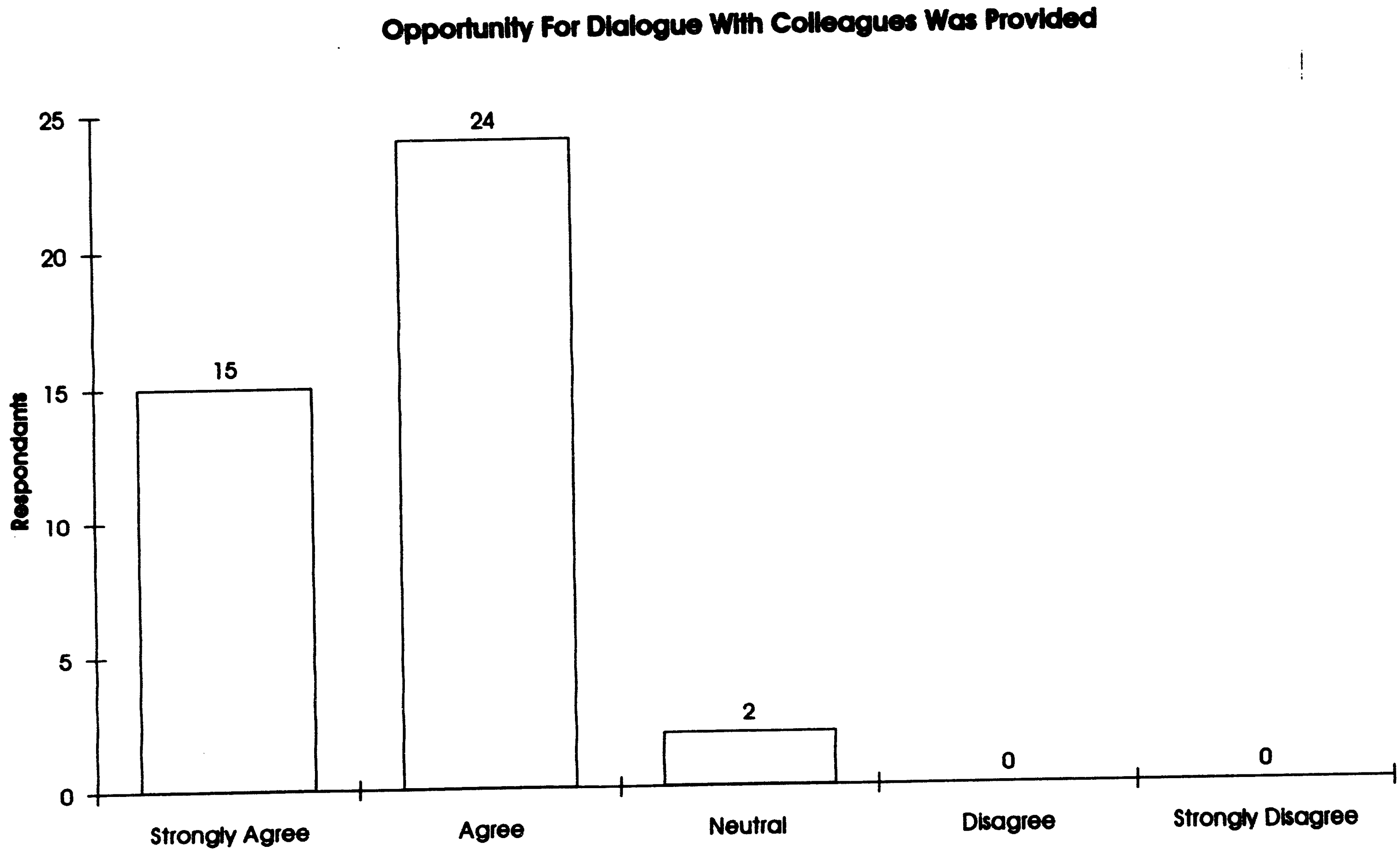


WWSCHA.RTS Chart 4

Problem Areas That May Require Special Attention Within the DOE Program Were Defined

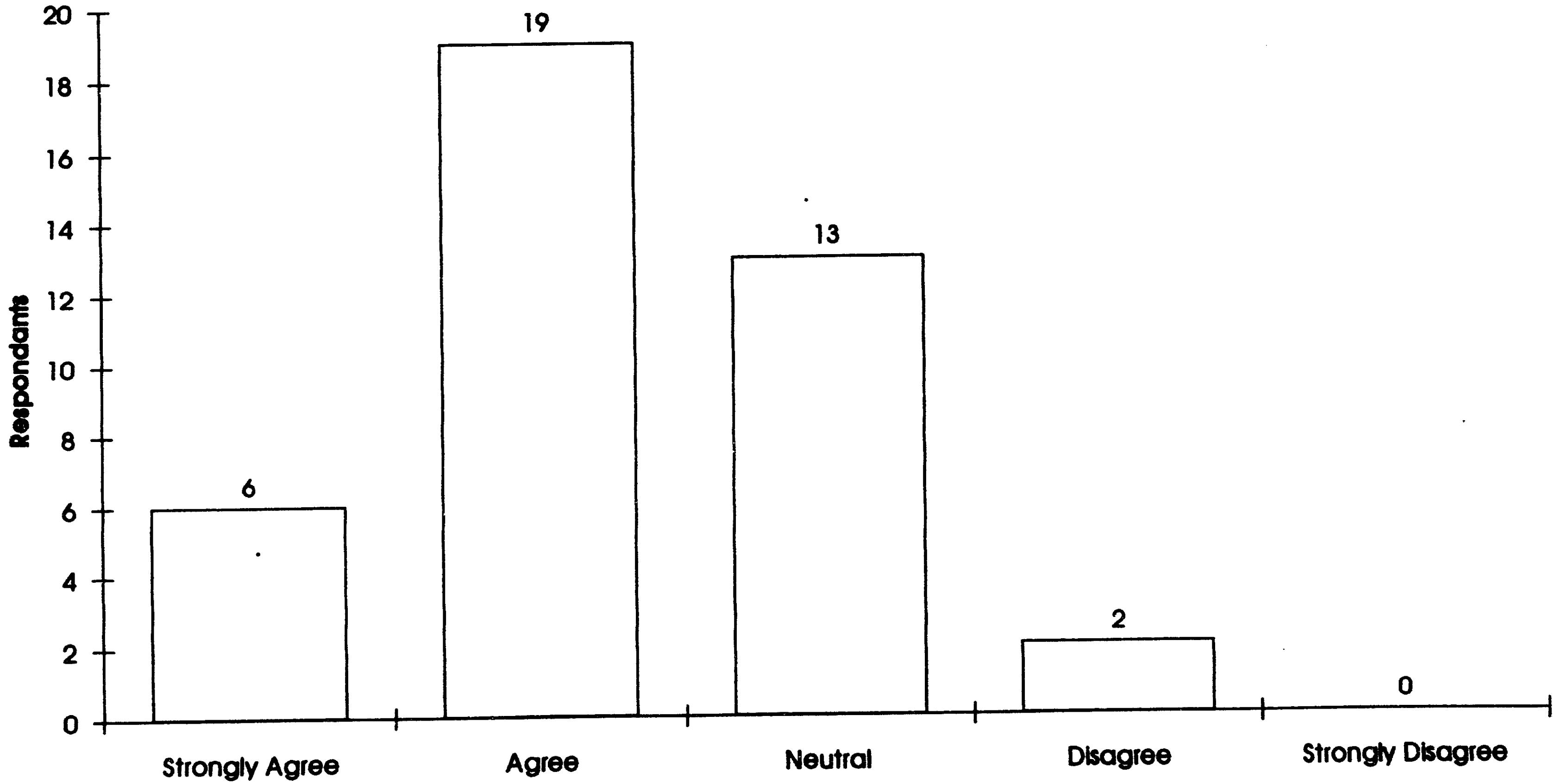


WWSCHA.RTS Chart 5



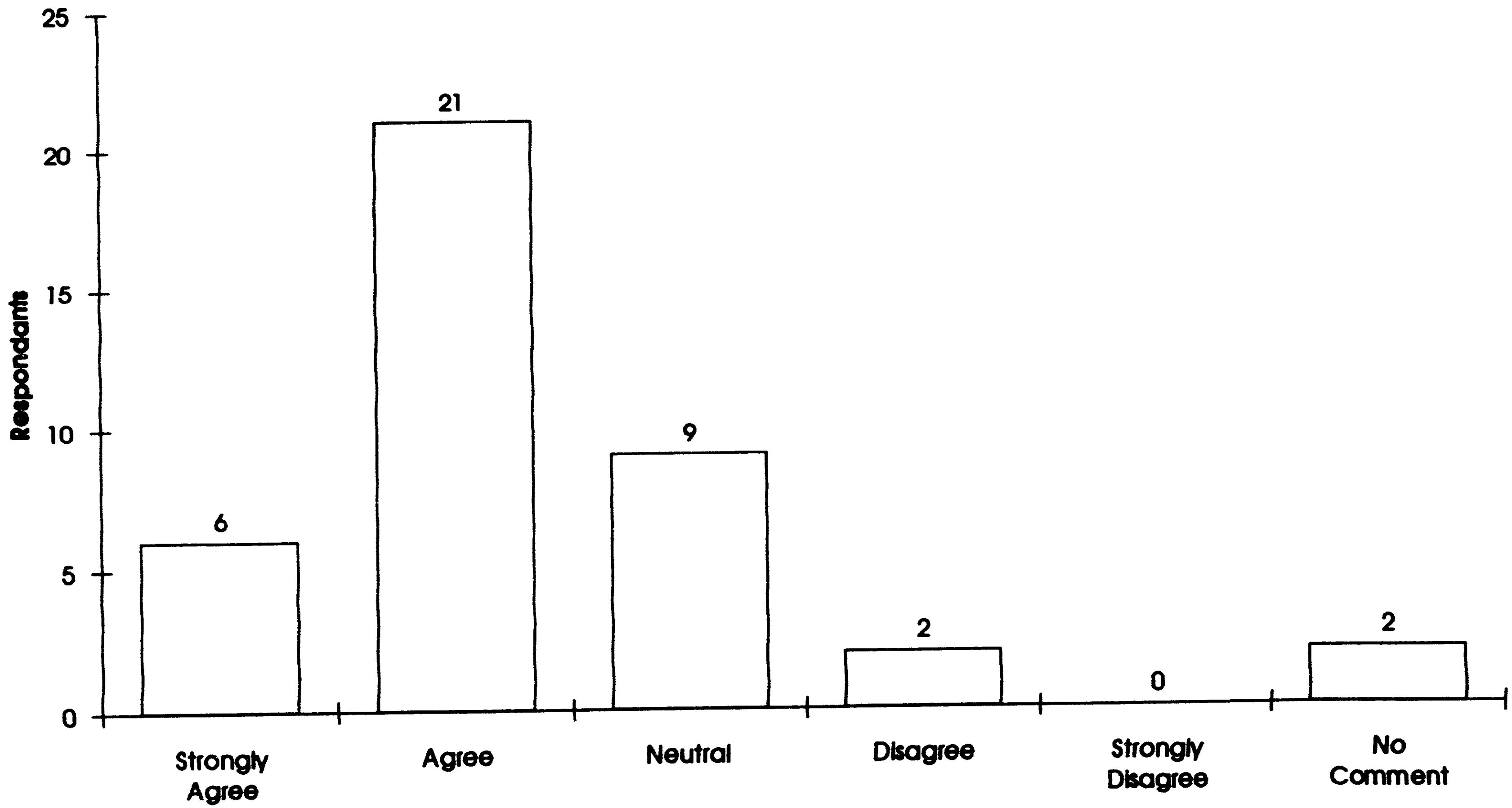
WWSCHA.RTS Chart 6

Adequate Information on Technology Available from the Laboratories and Private Companies Was Provided

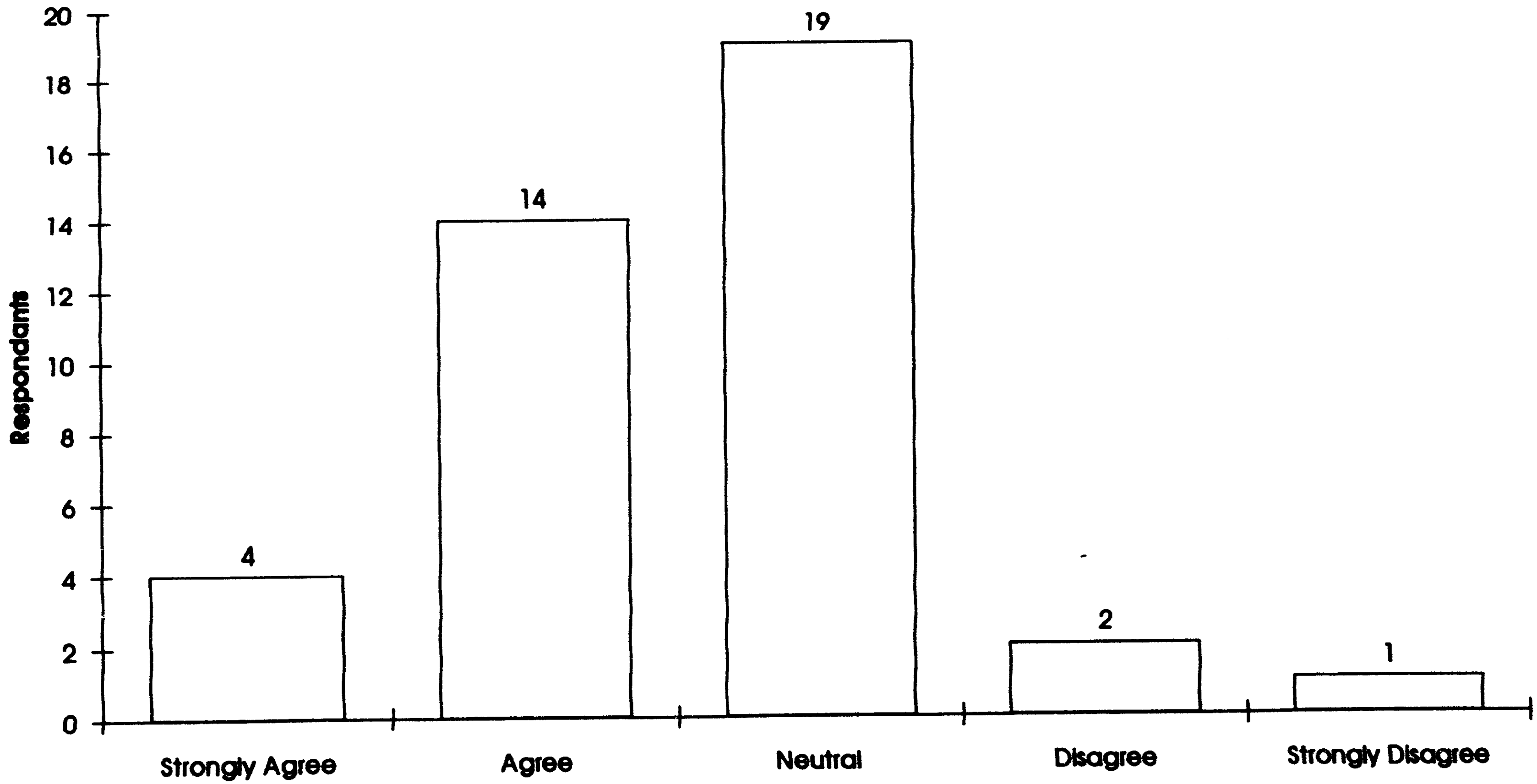


WWSCHA.RTS Chart 7

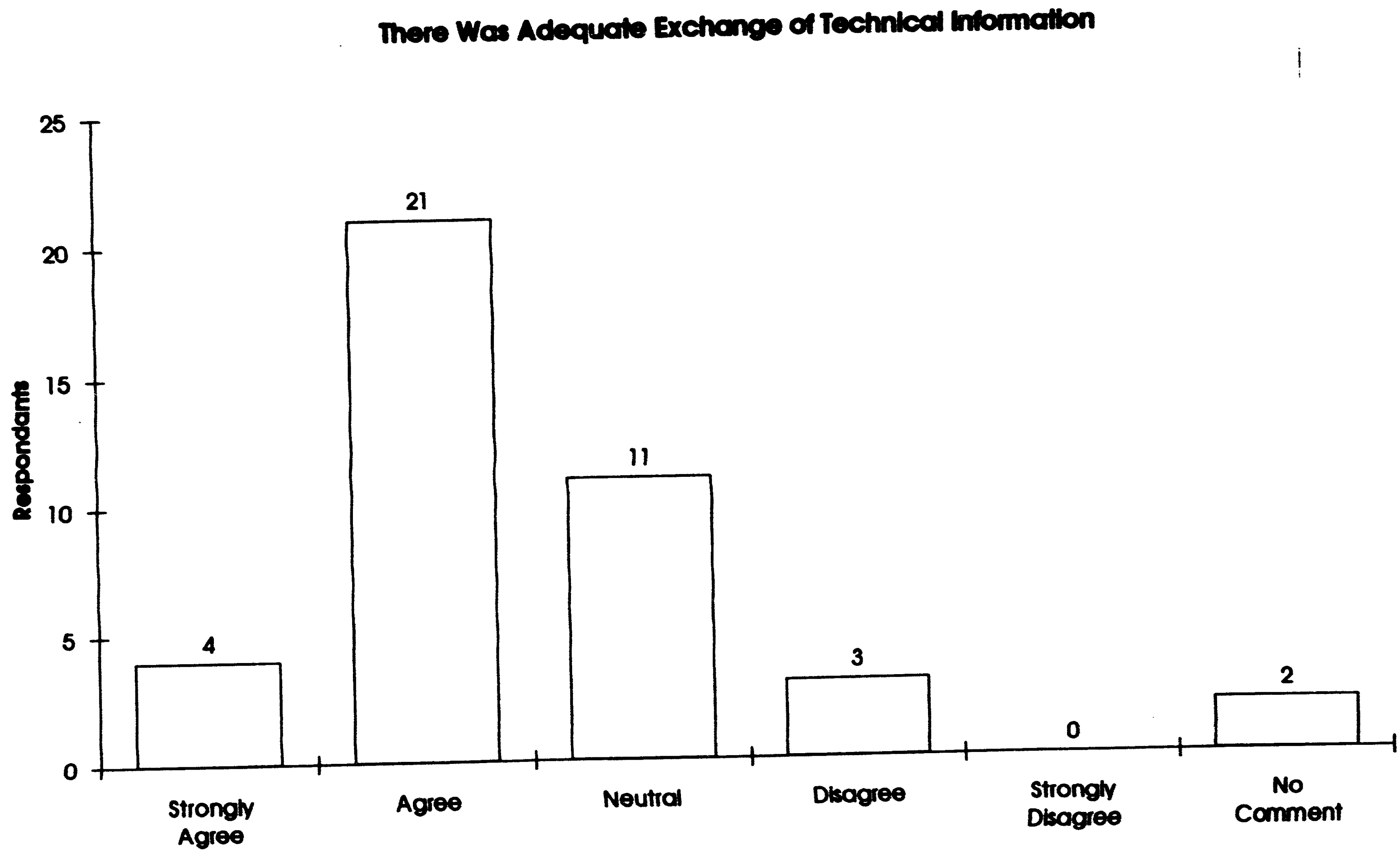
Special Facility and Resource Needs Were Identified



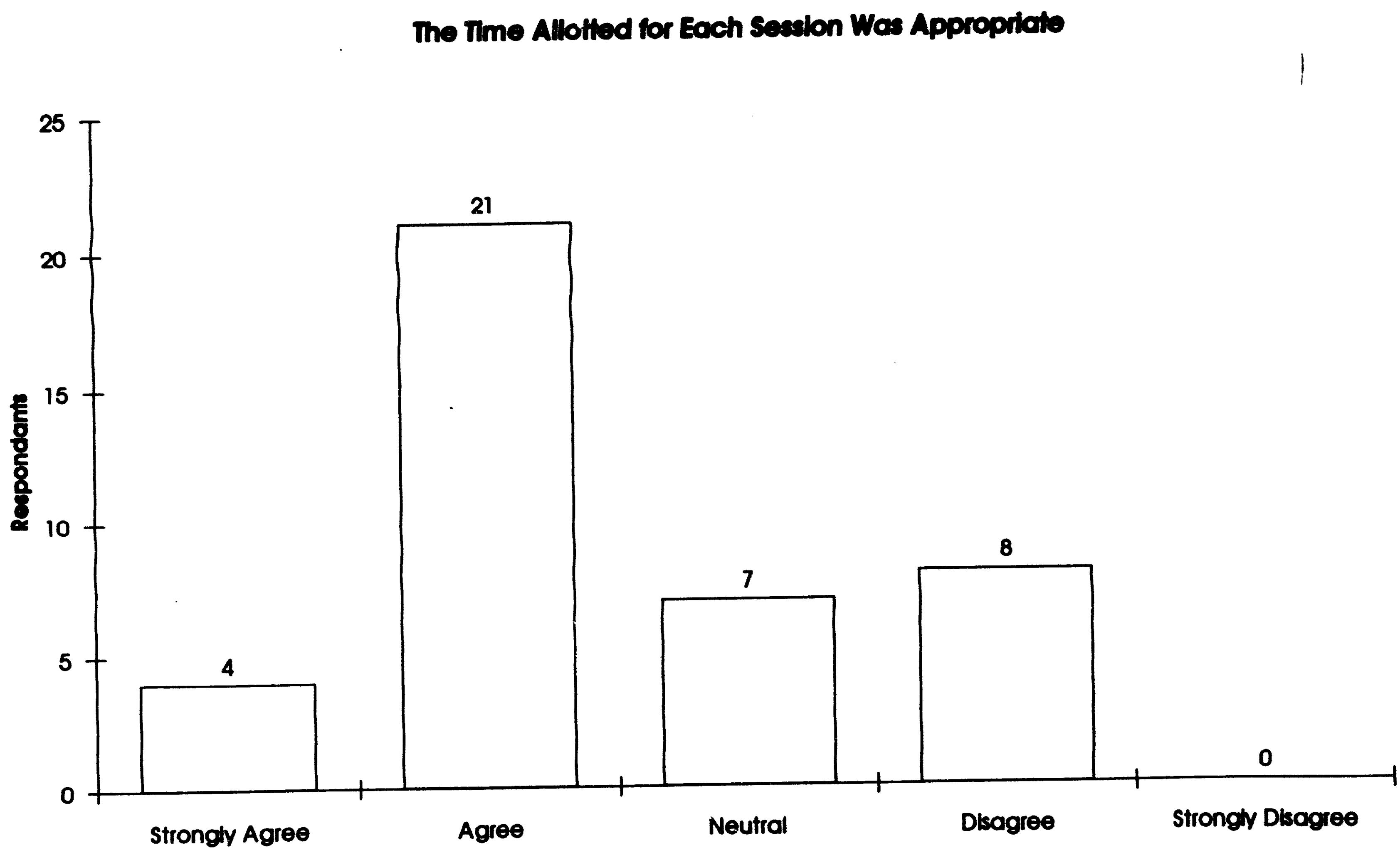
Potential New/Different Approaches and Partnerships to Improve HTS Wire Performance Were Suggested



WWSCHA.RTS Chart 9

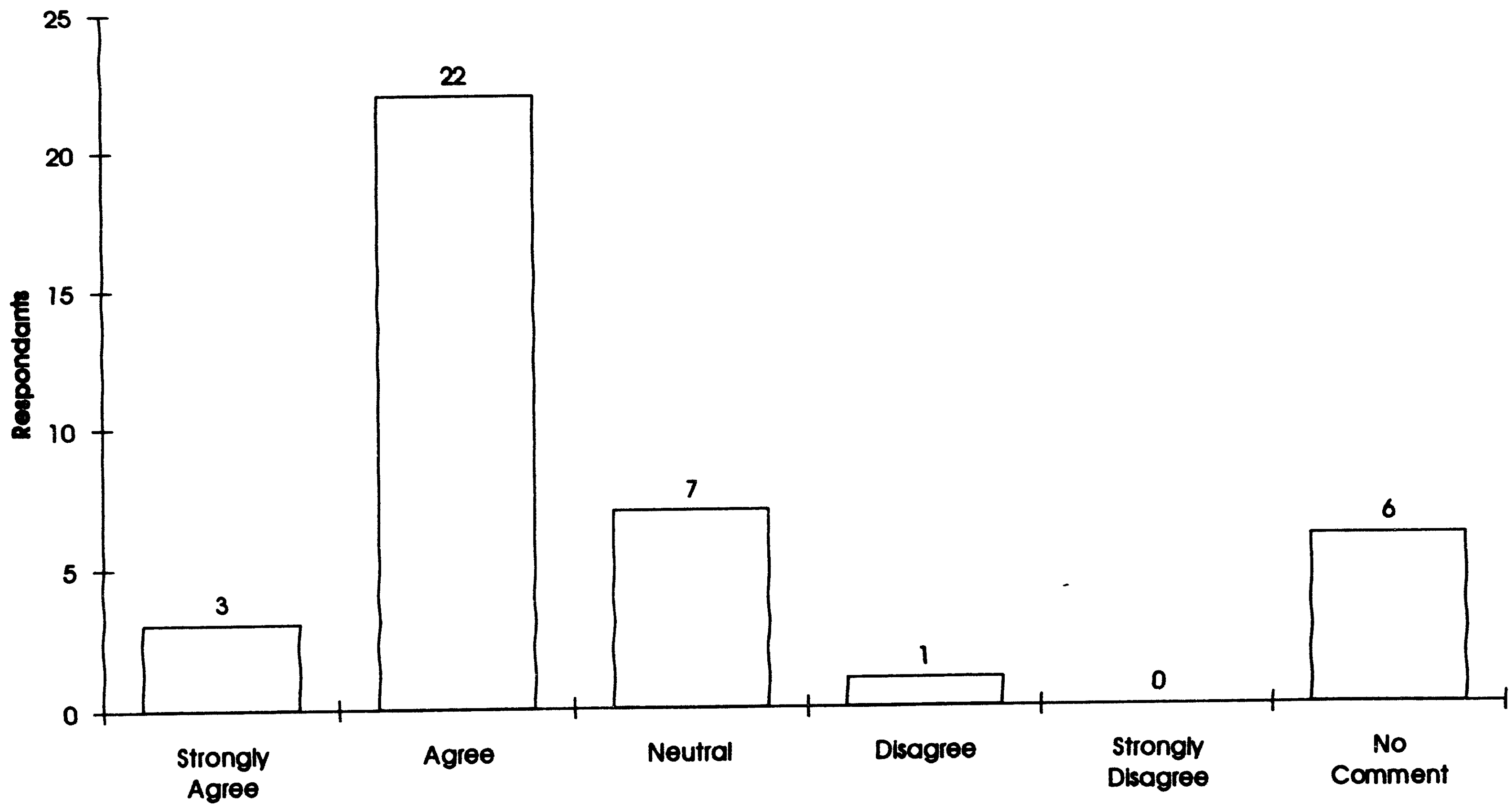


WWSCHA.RTS Chart 10

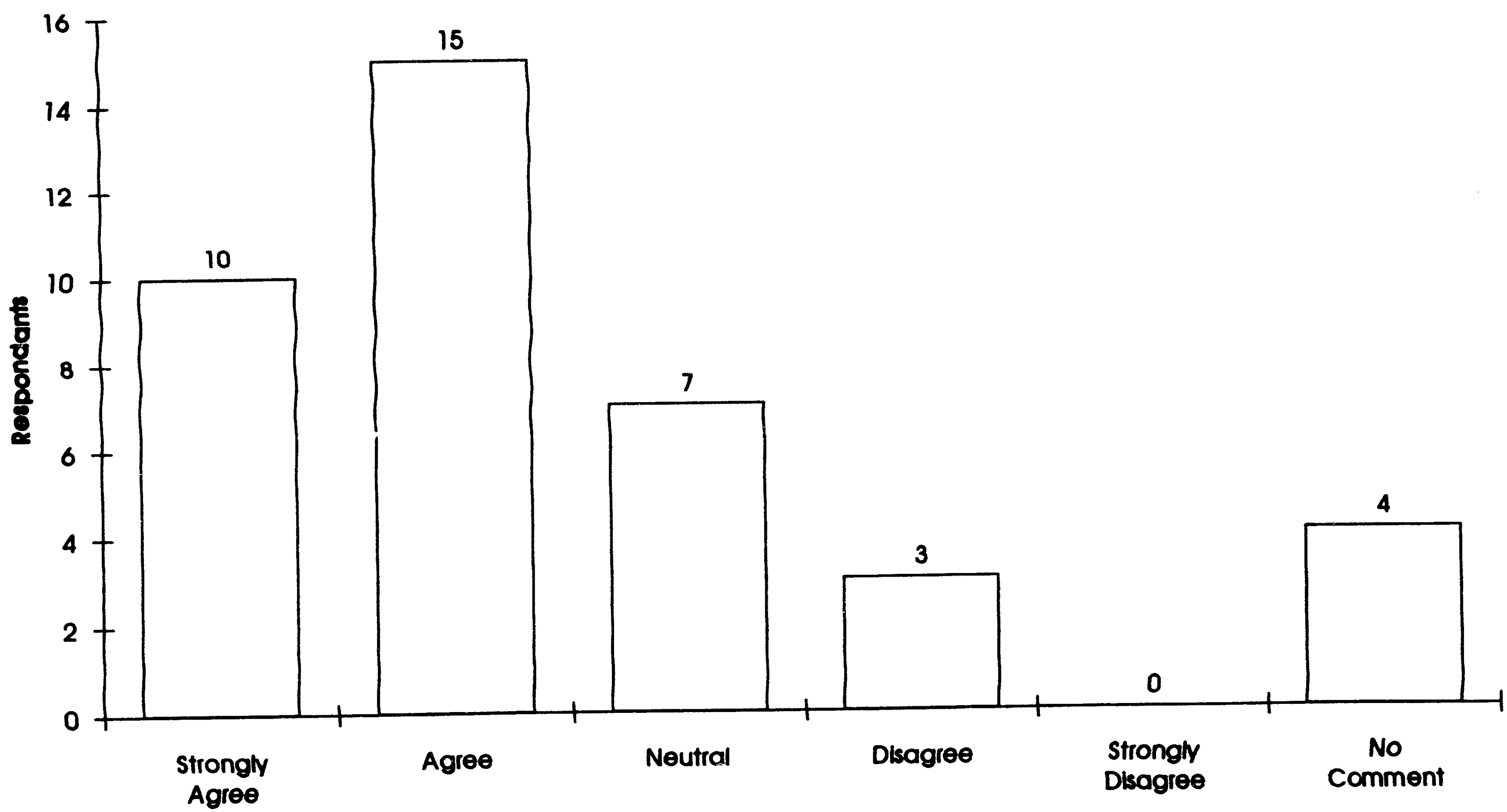


WWSCHA.RTS Chart 11

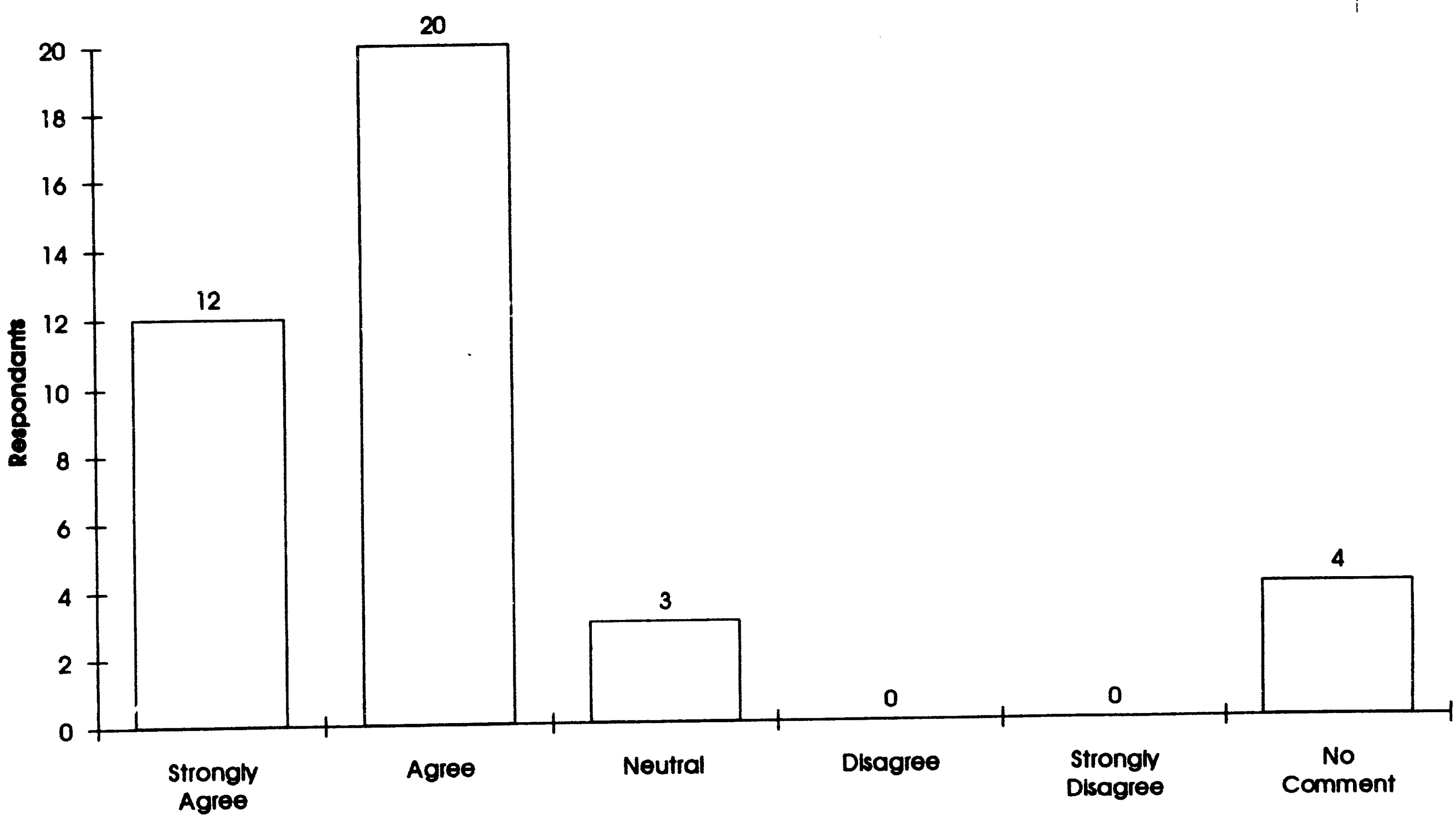
The Meeting Technical Balance Was Appropriate



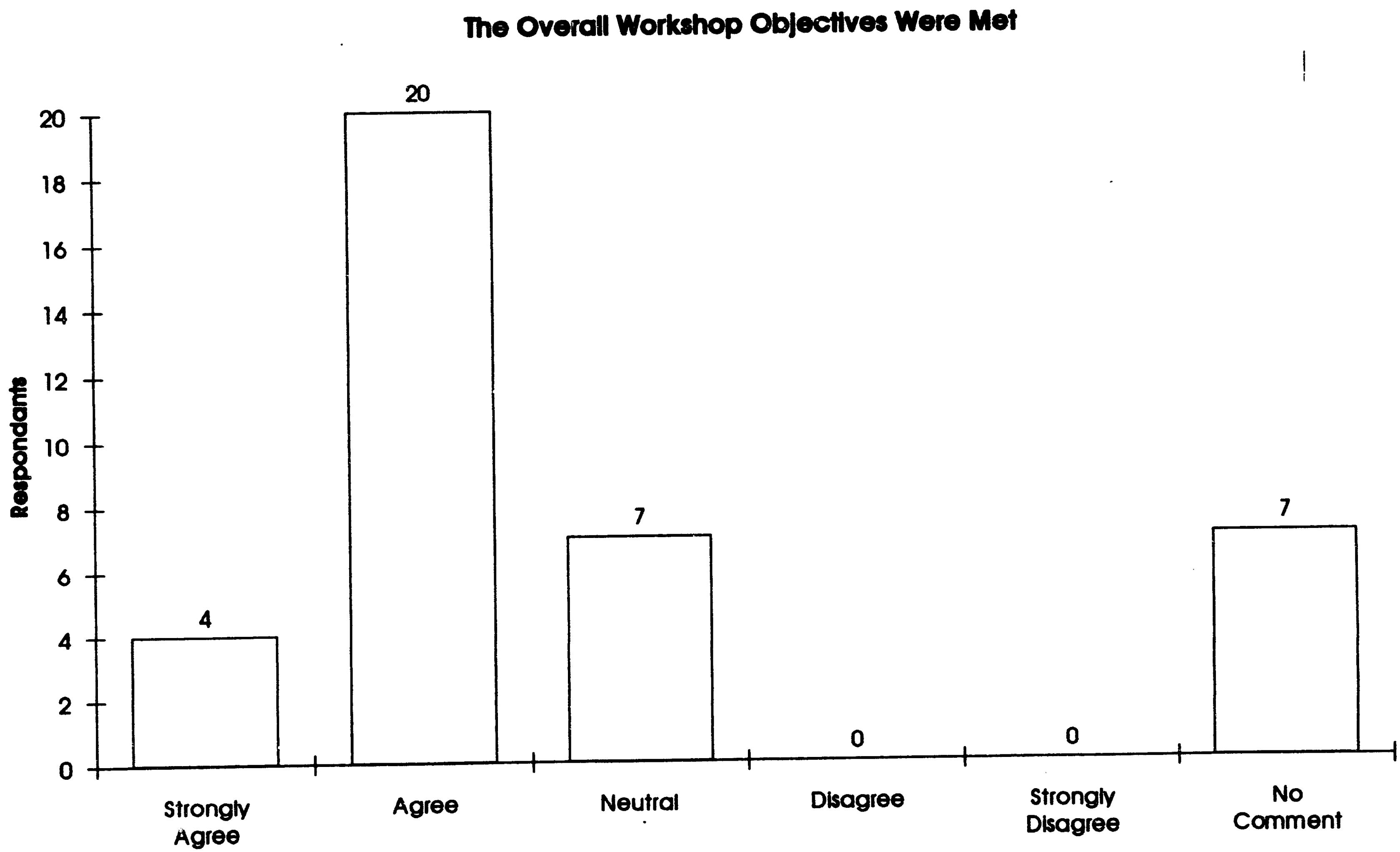
Working Groups on Thursday Were Helpful and Relevant



Overall Usefulness of Workshop/Should DOE Continue to Sponsor Such Workshops?

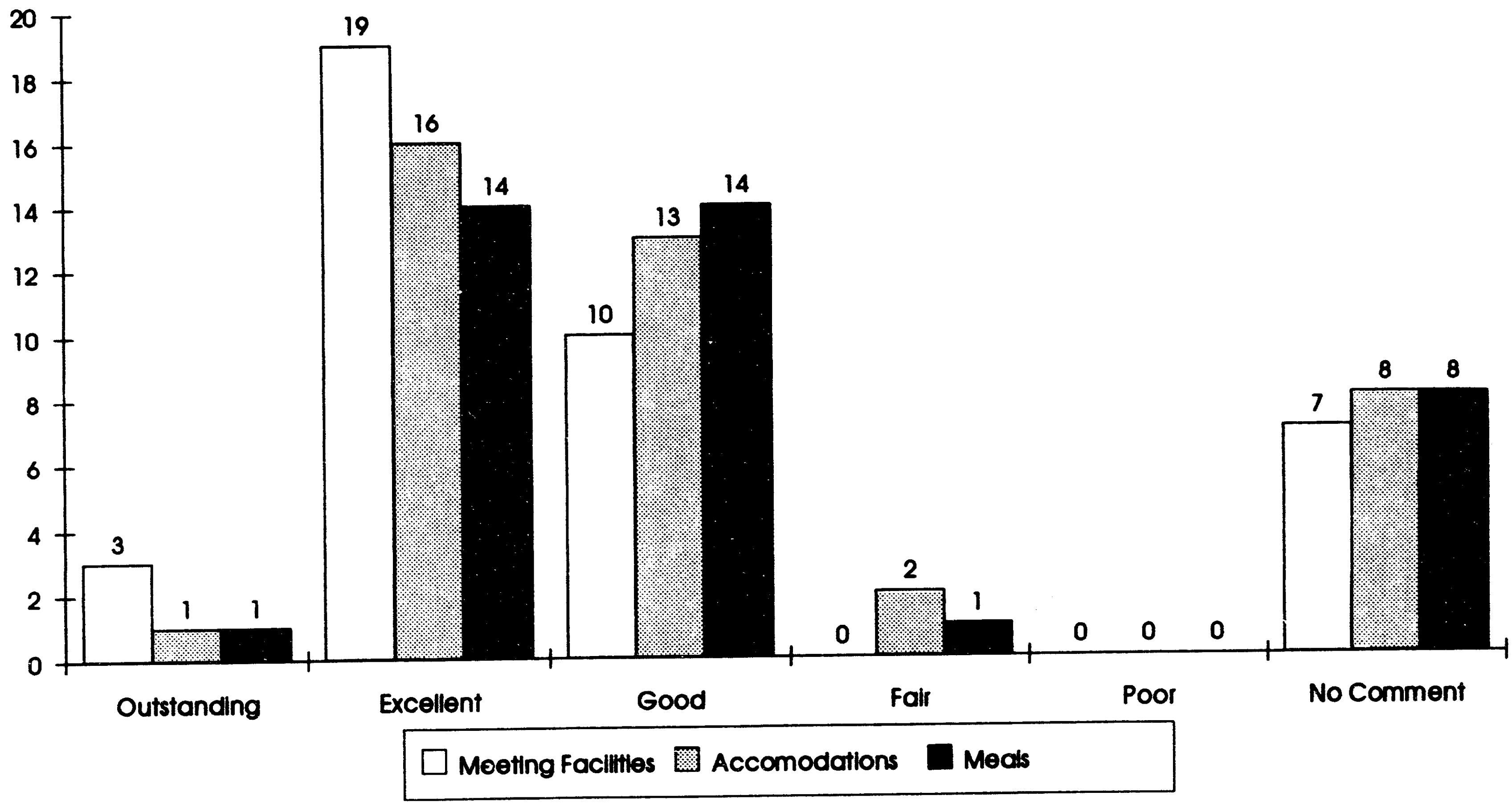


WWSCHA.RTS Chart 14



WWSCHA.RTS Chart 15

Rating of Workshop Facilities/Accomodations/Meals



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99. Laboratory Records Department
100. Laboratory Records Department - RC
101-102. Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831
103. Assistant Manager of Energy Research and Development, DOE-ORO, P.O. Box 2008, Oak Ridge, TN 37831-6269