MIDWEST SUPERCONDUCTIVITY CONSORTIUM

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MIDWEST SUPERCONDUCTIVITY CONSORTIUM

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Office of Basic Energy Sciences
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University of Missouri-Columbia
University of Nebraska
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The Ohio State University
Purdue University

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MISCON BACKGROUND

In April 1988, The Indiana Center for Innovative Superconductor Technology (ICIST), funded by the State of Indiana through the Corporation for Science and Technology (CST), was established. ICIST was a cooperative effort between Purdue University and the University of Notre Dame. The mission of ICIST was to promote the development and application of high critical temperature (T_c) superconducting materials for use by Indiana corporations and to generate long-term economic benefits for Indiana industry. The ICIST administrative office was located at Purdue while the research sites were located at both Purdue and Notre Dame. The research was an interdisciplinary effort, and investigators from the departments of engineering, physics, and chemistry at both universities were involved.

With many midwestern universities involved in superconductivity research, a consortium utilizing the physical facilities, personnel and talent from the best of those universities was a natural extension of ICIST. The plan was to use the structure that was already in place and then include the broader scope of the consortium.

The Midwest Superconductivity Consortium (MISCON) was created in 1989 when President George Bush signed the Energy and Water Development Appropriations Bill for fiscal 1990. Rep. John Myers, R-Ind., a member of the House Appropriations Committee at that time, sponsored the bill and supported the activities of the consortium.

MISCON MISSION

The basic mission of the Consortium was to advance the science and understanding of high- T_c superconductivity and to promote the development of new materials and improved processing technology. Focused group efforts were the key element of the research program. One program area is the understanding of the layered structures involved in candidate materials and the factors that control their formation, stability and relationship to superconductor properties. The other program area had a focus upon factors that limit or control the transport properties such as weak links, flux lattice behavior, and interfaces. Interactions among Consortium groups and with industrial affiliates were an integral part of the program.

RATIONALE

Countries around the world are working at a furious pace to develop patent positions and introduce new products based on high-temperature superconductivity. The primary

application markets include medical instrumentation, telecommunications, computers, sensors, electrical power generation and storage equipment, transportation systems and scientific instrumentation, among others. In addition to large companies, several small high-technology companies have been founded in the U.S. to bring these technologies to the marketplace. The Midwest is well represented by these startup firms. However, in spite of encouraging progress and because of the difficult challenges these unusual ceramic materials present, the commercial promise for major systems applications still lies in the future.

GOALS

- To develop, utilizing effective group efforts, the scientific and technological foundation for industrial applications and commercialization of high-temperature superconductivity;
- To facilitate the transfer of technology from the Consortium research laboratories into the industries of the Midwest; and
- To ensure that there is a continuing supply of engineers and scientists trained in this important field.

ORGANIZATION

The consortium is under the program management of Purdue University and involved the participation of the following universities: Indiana University, Iowa State University, University of Missouri-Columbia, University of Nebraska, The University of Notre Dame, The Ohio State University, and Purdue University. All projects undertaken through this collaboration were selected by a rigorous outside independent peer review by outstanding experts in the field.

APPROACH

The Consortium focused on multidisciplinary and multiuniversity collaborations through investigator exchanges, joint workshops and group meetings, joint publications, and the sharing of research instrumentation, techniques and research materials. These collaborative efforts greatly increased R&D productivity, synergy, scientific excellence and cost effectiveness. The Consortium actively pursued industry affiliation based on meaningful joint collaborative efforts to transfer technology (rather than membership fees). One of the principal means for strengthening the Midwest scientific, technological and industrial bases in this important technology was through the education of graduate

scientists and engineers with special expertise in the field. Nearly all former MISCON graduates are employed in industry, national laboratories and universities.

RESEARCH AND EDUCATION PROGRAM

The programmatic research concentrated upon two interrelated materials problem areas. The first area had a focus on the synthesis and processing of high-temperature superconducting materials. The second focused on understanding limiting features in the transport properties of these materials. Solutions to these problems are essential to industrial developments of components and systems using high-temperature superconductors and to the transport of very high electrical current densities over a range of magnetic fields required of these components and systems. This research was carried out primarily by graduate students under the supervision of leading scientists and engineers. Also involved were selected undergraduate students involved in a research experience.

INTERACTIONS

- An Industrial Affiliate Program promoted collaborations between member scientists and scientists at industrial and national labs. Membership required establishing a collaboration with a university consortium member and producing a joint program plan.
- A Program Augmentation grant was provided under active projects where specific joint technology transfer developments involving participating Affiliates on a cost sharing basis were formally agreed to by both parties.
- A seminar exchange promoted interaction within and between groups.
- A programmatic exchange promoted the use of special instrumentation or facility capabilities to all participants.
- A capital equipment competition addressed group needs (as the primary requirement) for capital equipment. Cost sharing was a key requirement.
- Group Meetings were held in the winter and summer each year. A two-day schedule for each meeting provided an opportunity for interactions among principal investigators, students, and postdocs. A poster exhibit provided students an arena to display and discuss their work.
- A Summer School was held in conjunction with the summer Group Meeting at which both internal and external experts were invited to give presentations and present their materials in a tutorial format.

PARTICIPATING UNIVERSITIES

<u>UNIVERSITY</u>	<u>YEARS PARTICIPATING</u>
Indiana University	1990-2001
Iowa State University	1990-1993
University of Missouri	1990-2001
University of Nebraska	1993-2001
University of Notre Dame	1990-2001
The Ohio State University	1990-2001
Purdue University	1990-2001

TYPICAL PROJECTS

Project Group I

- "Low Temperature Routes for Processing High-Temperature Superconductors"
- "Optical Studies of New -123 and -124 Materials"
- "Flux Pinning and Defect Studies in High T_c Superconductors"
- "Investigation of Structure and Superconducting Property Relationships in Copper free Bismuth Oxides"
- "Hg- and Tl-Based Superconducting Films"
- "Microstructural Dependence of Critical Current Density in Melt Textured YBCO Superconductors"
- "Anisotropic Grain Growth and Isothermal Grain Alignment of Bulk, Superconducting Oxides"
- "Processing of Textured Superconducting Oxide/Noble Metal Microlaminates"
- "The Influence of Oxygen Pressure and Temperature on Oxygen Stoichiometry and Phase Equilibrium in the System BSCCO"
- "Effect of Substitutions on Superconducting Properties of High T_c Materials"
- "Structural Defects and Interfaces in High T_c Superconducting Compounds"
- "High Temperature Superconducting Tubes for Magnetic Shielding Applications"

Project Group II

- "Statistical Mechanics of High T_c Superconductors and Flux Line Liquids"
- "Polarized Neutron Reflectivity Studies of High Temperature Superconductors"
- "Neutron Diffraction and Defect Studies of High T_c Superconductors"
- "Microwave and Optical Studies of High-Temperature Superconductors"
- "Superconducting Quantum Structures"

- "Transport Properties of YBCO Thin Films"
- "High T_c Superconducting Composites, Arrays and Crystals"
- "Atomic Beam Studies of Vortex Lattices at Superconductor Surfaces"
- "Device-Related Properties of High- T_c Films and Multilayers"
- "NMR Studies of Vortex Dynamics in High T_c Superconductors"
- "Equilibrium and Transport Properties of Vortices in High-Temperature Superconductors"
- "Transport Properties of High T_c Superconductors"
- "Study of Vortex Dynamics and Flux Pinning on Different Length Scales"
- "Vortices in Anisotropic Superconductors"

APPENDIX I

NOTABLE ACHIEVEMENTS

1990

P.J. McGinn, University of Notre Dame - The repeatability of our zone melting process has been greatly improved and we now have approximately a 90% success rate for texturing wires in our system. We have achieved zero field J_C values in textured $YBa_2Cu_3O_{6+x}$ greater than $75,000 \text{ A/cm}^2$.

J. C. Garland, The Ohio State University - We have developed a composite high temperature superconductor which combines the mechanical advantages of normal metals (high thermal conductivity, machinability, low normal state resistivity) with the high transition temperatures of oxide superconductors. The composite is made by a powder metallurgy process in which a random matrix of silver metal is intermixed with a fused "skeleton" of yttrium barium copper oxide. Preliminary tests have shown that the composite is superconducting at 90K with as little as sixteen percent volume fraction of superconductor. Although the critical current density of the composite is relatively low, it is believed suitable for use as superconducting enclosures, shields, partitions, high Q tuned cavities and also as a superconducting bonding material. The composite may be readily machined, as demonstrated in a prototype composite cylinder that consists of 50% superconductor.

J.M. Honig and J. Spalek, Purdue University - Our investigation of superconductivity in the La_2NiO_4 system has been extended to include Cu additions. We have found that the progressive replacement of Ni by Cu in the La_2NiO_4 system reduces and ultimately completely suppresses the superconductivity in the host material. This underscores the importance of having a defect-free cation sublattice and that the very small Meissner effect originally reported in La_2NiO_4 could not have been due to accidental contamination by the cuprate.

H. Sato, Purdue University - We have been among the first to find that the quenching of Bi-Sr-Ca-Cu-O from melts result in a somewhat ductile amorphous materials with semiconducting properties of extremely high density, and its use as a precursor for producing high T_C superconductor. Utilizing the amorphous material as a precursor for preparing high T_C superconductor has produced many interesting and important results both in fundamental understanding and for applications. The results indicate that of

some of the non-equilibrium phases, obtained by annealing the precursor at low temperatures, may have a relatively high superconducting transition temperature. The research also shows the possibility of preparing superconducting ceramics of extremely high density, higher than that obtained by the normal reactive sintering techniques.

J. R. Clem and V. G. Kogan, Iowa State University - A quantitative theory has been developed for the structure of a vortex when the coherence length in the c direction is smaller than the periodicity length s in the c direction using a description that takes into account the atomic-level discreteness. We also have derived a general expression for the energy per unit length of a vortex array in terms of a sum of integrals along the Josephson junctions between adjacent layers. This has been used to derive an accurate expression for H_{C1} of a Josephson vortex.

A. H. MacDonald and S. M. Girvin, Indiana University - The effect of the quantization of the electron's cyclotron orbital motion has been observed in low-density layered superconductors (by deHaas-van Alphen measurements). Along with Mike Norman at Argonne National Labs we have completed a calculation which we believe to be a realistic and quantitative study of this effect on the upper critical field for the YBCO superconductors. We find that the usual semiclassical treatment of the magnetic field is valid for fields strengths less than about 100 Tesla. At stronger fields quantum effects begin to become important and T_C can actually *increase* with magnetic field. There is, in principle, no upper limit on the field strength at which superconductivity can exist.

W. J. Tomasch and H. A. Blackstead, University of Notre Dame - We have identified flux-flow in a short cylindrical polycrystalline sample of Y123, with the static magnetic field applied in the plane of the sample. The data unambiguously show a resistivity which varies as $\sin^2(\phi)$ superimposed on an isotropic phase-slip background. Here ϕ is the angle between H and the rf current in the plane of the sample. This provides significant support for a theory we have proposed describing losses in HTSC materials.

We have successfully fit our model for magnetostrictive dissipation to experimental data from five different samples studied in our laboratory. This model includes a modified expression for flux-flow and isotropic phase-slip resistivities which are added in series. The phase slip resistivity is accurately described by an expression given by Tinkham. The samples examined include high quality crystals of BSCCO, Y123, and Gd123 as well as melt-textured Y123 and Gd123.

D. G. Stroud, Ohio State University - We have tentatively found that there is a transition with an irreversibility line in an arrangement of coupled granular superconductors similar to what was seen experimentally by Muller, Takashige, and Bednorz. Near this transition, there are power-law current-voltage characteristics. At lower temperatures, one sees a strong history-dependent behavior with a conductivity which depends on initial conditions of the sample before it was measured. This type of behavior is expected to lead to irreversible behavior in composite superconductors, analogous to what is seen in single-crystal superconductors with random pinning.

1991

Alan I. Goldman, Douglas K. Finnemore, L. Scott Chumbley, Iowa State University - High temperature x-ray studies of the melting of $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8-x}/\text{Ag}$ composites have been used to select precipitates that can be used as pinning centers for high performance conductors. The melting always takes place with the sequential formation of 3 distinct solid phases in equilibrium with the liquid, $(\text{Sr,Ca})_1\text{Cu}_1\text{O}_2$, $(\text{Sr,Ca})_2\text{Cu}_1\text{O}_3$, and $(\text{Sr,Ca})\text{O}$. By controlling the temperature, the oxygen partial pressure, the dispersion of Ag and the amount of excess Bi, the nucleation and growth rates of these phases. This is the first step in understanding the melt-texture processing of these composites for high performance magnet conductor.

R. W. McCallum, L. S. Chumbley, M. J. Kramer, Iowa State University - Using a novel technique, we have produced highly disordered oxide precursors for RE123 materials. For the most common high temperature superconductor, Y123, this precursor material is compositionally homogeneous on a scale of a few microns, at least an order of magnitude better than has been reported with other melt-quenched techniques. For other rare earths, precursors have been made with an unprecedented glassy structure. With these disordered materials, the formation of the RE123 phase is not limited by diffusion of the elements through the sample. Thus, we are in a unique position to study the reaction pathways and crystallization of RE123. This will lead to better control of the microstructure, which in turn affects vital properties of the RE123 high temperature superconductors.

Paul J. McGinn, University of Notre Dame - A high critical current density (J_c), which describes the amount of current that can be passed through a superconducting wire, is a requirement for many applications of superconducting wires. For many applications a

value of 1×10^5 is desirable. We have developed a directional solidification technique for producing $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ (Y-123) wires with transport critical current densities exceeding $9 \times 10^4 \text{ A/cm}^2$. Additions of BaSnO_3 to Y-123 have been found to markedly improve the magnetization properties over similarly textured Y-123 wires in low fields. Magnetic critical current densities (J_c) in excess of $1.2 \times 10^5 \text{ A/cm}^2$ in zero field, and $3.0 \times 10^4 \text{ A/cm}^2$ at 1 T have been observed.

K. M. Choudhary and S. T. Ruggiero, University of Notre Dame - 1. We have established molecular beam deposition technique to prepare 123 high-temperature superconductor thin films. These films show complete superconductivity at 90K. 2. In our laboratory, the thin film deposition process is monitored by conventional sensors, such as quartz crystal thin film thickness monitor. Also, the films are produced in a low-cost ultrahigh vacuum (UHV) system. These are achievements in thin film processing which can make an impact on superconductivity applications in microelectronic devices. 3. For the first time, we have demonstrated that single phase superconductor thin films can be grown in which the ratio of dysprosium, barium and copper is $(1+x):(2-x):3$ instead of $1:2:3$. 4. The value of x in $(1+x)(2-x)3$ superconductors have been determined by simple material characterization techniques such as X-ray diffraction and resistivity measurements. Hence, we have demonstrated that conventional methods can be used to determine the composition and quality of the film and, consequently, this knowledge can be used to prepare high quality thin films for superconductivity applications. 5. We are also working to improve the electronic properties of thin film superconductors by substrate modification. This involves the chemical and ion-beam etching of micro-steps in substrates and deposition of noble metal droplets to introduce flux pinning sites.

James C. Garland, The Ohio State University - Shortly after their discovery, high-temperature ceramic superconductors were found to be brittle, poor conductors of heat, and environmentally unstable. These undesirable physical properties of the pure high- T_c YBCO superconductors limited their role in potentially useful technological applications, where machining and device fabrication were required. In order to improve the mechanical and thermal properties of high- T_c superconducting oxides, we have developed a two-phase random bulk composite material which consists of intermixed "skeltons" of normal metal phase (silver) and a fused superconducting ceramic oxide phase (YBCO). The resulting Ag/YBCO composite was formed by combining powders of the metal and superconducting oxides and then compressing the mixture into a solid under uniaxial pressure, followed by

the required heat treatments (oxygen annealing and sintering). We found that with only 29% of superconducting phase, the composite retains the desirable electrical and magnetic properties (e.g., zero electrical resistance, a high superconducting transition temperature, well-developed Meissner effect) of high T_c superconducting oxides. This composite, however, was not expected to be suited for high current density applications, such as large magnetic fields or power transmission. Rather, potential commercial uses include superconducting enclosures, partitions, shields, motor and generator armatures, contactors and relays, as well as cavities, filters, duplexers and other high-Q devices for use in satellites, avionics, and other specialized technologies.

J. M. Honig and J. Spaček, Purdue University - We have investigated the magnetic ordering effects encountered in the $\text{La}_{2-x}\text{Sr}_x\text{NiO}_4$ and in the $\text{La}_2\text{NiO}_{4+}$ systems, concerning which there has been great uncertainty. By systematically varying the Sr content or the amount of excess oxygen in the parent substance La_2NiO_4 we were able for the first time to demonstrate how the magnetic ordering temperature T_N changes with composition in the two cases. Surprisingly, T_N remains almost independent of how much Sr is added to the system in the composition range $0 \leq x \leq 0.25$. By contrast, T_N is extremely sensitive to even slight departures from the ideal La_2NiO_4 stoichiometry. These differences were totally unanticipated and require a careful theoretical analysis.

We also discovered that, in the range $0.05 \leq x \leq 0.25$, $\text{La}_{2-x}\text{Sr}_x\text{NiO}_4$ is a spin glass, and we have studied the temporal variation of the remanent magnetization in these oxides. The result indicates that La_2NiO_4 and its alloys are closely related in their normal (as opposed to superconducting) properties to the corresponding cuprate systems.

We have also investigated the superconducting characteristics of $\text{La}_{1.8}\text{Sr}_{0.2}\text{Cu}_{1-y}\text{Ni}_y\text{O}_{4+}$ and have demonstrated that the replacement of copper by even small amounts of nickel adversely affects superconductivity of the parent cuprate, so that for $y \geq 0.05$ the material remains in the normal state at all temperatures.

Hiroshi Sato, Purdue University - Growth characteristics of high T_c superconductors obtained from amorphous precursors in the Bi-Sr-Ca-Cu-O system were investigated in detail. The material in this system can be obtained in amorphous forms if quenched from melt, and high T_c superconducting phases grow by annealing such amorphous precursors at appropriate temperatures. The characteristics of growth give us many instructive information with respect to superconducting characteristics of the material. The major interest in this study at this stage was to understand how to control growth characteristics

of high T_c phases out of amorphous precursors so that reliable materials in this system can be obtained for practical application. The other objective was to elucidate the formation of grain boundaries which might serve as sources for weak superconducting linkage in this system. The work was performed in materials with the composition corresponding to $\text{Bi}_2\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+4+}$ with $n=2$, or so called 2212 materials.

One of the undesirable features of the materials obtained by annealing the amorphous precursors at temperatures between 750°C to 850°C in air (commonly considered to be the most desirable annealing condition for this type of material), is that they tend to exhibit a characteristic "two step" superconducting behavior. On the other hand, the replacement of some of Bi by Pb tends to eliminate this behavior and transition characteristic becomes sharper. We came to a conclusion that this behavior should be interpreted to be due to an inhomogeneity in the distribution of oxygen content, while, the addition of Pb increases the diffusivity of oxygen and thus makes the distribution of oxygen more homogeneous. This conclusion is supported by the increase in the magnetic shielding fraction by the addition of Pb and also by the observation of microwave resistivity.

By annealing amorphous precursors of the 2212 composition, high resolution electron microscopy reveals that high T_c phases of the $n=1$ and the $n=2$ structures develop depending on annealing temperature and time. Annealing at high temperatures above 700°C , the $n=1$ phase mixes with the $n=2$ phase in extremely thin platelets (of the width corresponding to the unit cell size and is called the microsyntactic intergrowth). Grain boundaries nucleate at an early state and grow. The types of grain boundaries thus formed are limited to a small number of coincidence boundaries such as 90° twist boundaries, 180° twist boundaries (in the $n=1$ structure), and (015) twin boundaries. Among these, the (015) twin boundaries (twins with the (015) twin boundaries) although common in materials obtained from the amorphous precursors, have not been found in sintered materials. Detailed characterization of this type of twin boundaries, including their defects, was made by means of high resolution electron microscopy.

John R. Clem and Vladimir G. Kogan, Iowa State University - One of the key obstacles to widespread applications of bulk high-temperature copper-oxide superconductors is that, despite their ability to remain superconducting at high temperatures, these materials usually can carry only small electrical currents before breaking down and producing significant electrical resistance and energy losses. An important characteristic of the high-temperature copper-oxide superconductors is that they all have layered atomic structures,

which makes their electrical and magnetic properties extremely anisotropic. The most anisotropic materials have the advantage of having the highest superconducting transition temperatures but simultaneously the disadvantage of carrying the least amount of loss-free electrical current. Our research supported by the Midwest Superconductivity Consortium, has made significant theoretical progress leading to the understanding of the relationship between the anisotropy of the high-temperature superconductors and their current-carrying ability at liquid-nitrogen temperature, where most applications are anticipated. The theory involves calculations of the magnetic structure whose motion produces energy dissipation. The ultimate goal of this research is to develop a quantitative theory for the maximum practical current densities of the high-temperature superconductors.

Thomas R. Lemberger, The Ohio State University - We have made three important advances in the past year. 1. An essential major technical achievement is fabrication of very long and narrow $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films ($15\text{cm} \times 0.09\text{cm}$), while maintaining a very high critical current density of $J_c \approx 2 \times 10^6 \text{A/cm}^2$ at 4.2K. 2. A technical and scientific achievement is the first ever measurement of Bernoulli voltage in a high- T_c superconductor, with the necessary high sensitivity (1nV) required to study films with $J_c \approx 2 \times 10^6 \text{A/cm}^2$. 3. A third advance involves expansion of the scope of the study. After realizing that precise interpretation of our Bernoulli measurements would be greatly augmented by measurement of the kinetic inductance L_K of the superconducting electrons in the same sample films, in the past several months we set up an apparatus to measure L_K and successfully tested it by measuring L_K on a low- T_c Pb film. This is a difficult measurement because the physical inductance of the sample film is 1000 times larger than the kinetic inductance. Data is shown on the following page.

A. H. MacDonald and S. M. Girvin, Indiana University - We have studied high-temperature superconductors in two regimes, both involving quantum-mechanical effects: near the metal-insulator transition induced by strong Coulomb correlations and in the regime of high magnetic fields. We have demonstrated that near the metal-insulator transition where T_c is suppressed, *quantum* fluctuations can dominate over thermal fluctuations in the order parameter and hence drive the transition. We have demonstrated the existence of universal scaling properties of the conductivity at the critical point separating the insulating and superconducting phases in thin films. The phase diagram

we obtain is in good qualitative agreement with that found by the Minnesota group of Goldman *et al.* for epitaxial PrBaCuO films.

We have obtained the first solutions of the microscopic mean-field Bogoljubov-deGennes equations for the superconducting order parameter in the two-dimensional limit in a strong magnetic field. This is of particular interest in high- T_C materials because of their quasi-two-dimensional structures and very high upper critical fields. Our calculations go beyond the usual Ginsburg-Landau approximation to include microscopic quantum effects of the magnetic field. We find in some limits, unusual additional vortex structure in the Abrikosov flux lattice state.

W. J. Tomasch and H. A. Blackstead, University of Notre Dame - During the past year, we have carried out numerous microwave dissipation experiments on a variety of HTSC materials, including sintered polycrystalline, melt textured single crystal and thin film samples. We have sought to test models describing the observed microwave power dissipation in terms of conventional loss mechanisms. A model, which has been found to work, includes a modified expression for flux-flow, which provides for physically correct high-temperature and low-temperature limits, and phase-slip resistivity which arises in a network of Josephson junctions. Flux-flow resistivity arises as a consequence of the motion of quantized vortex cores in the superconductor. Phase-slip resistivity is a manifestation of time-dependent changes in the magnetic flux in a Josephson junction. Josephson junctions, consisting of thin insulating barriers between superconductors, are generally believed to be present in the boundaries between superconducting crystalline grains. In addition to the analysis of our experiments, we have successfully treated data in the literature from other workers. In every case for which the quality of the materials justified a detailed examination, we have fit a four parameter model to the data, with typical errors on the order of several percent. The implications of the success of this model are significant for potential applications of HTSC materials. 1. Flux-flow is typically responsible for only 10-15% of the observed dissipation at high current densities. Therefore, efforts to substantially improve the current carrying capacity of these materials by the introduction of pinning centers designed to limit the motion of vortex cores will not be successful. 2. Phase-slip in Josephson junctions is the dominant resistivity mechanism. The so-called weak-link (Josephson junction) "problem" appears to be intrinsic to all materials studied, even high quality single crystals. 3. It is concluded that grain boundaries are not the only source of weak links. 4. Elimination of the weak-links (Josephson junctions) is a requirement for this class of superconducting materials to be useful in high current density applications.

M. W. McElfresh and R. Reifenberger, Purdue University - The largest values of critical current densities (J_C) for high temperature superconductors ($<10^7$ A/cm²) are routinely reported for thin films prepared by a variety of methods. Using both scanning tunneling and atomic force microscopies we have studied the surfaces of YBaCuO thin films in search of structural features that may help elucidate the identity of the strong pinning defect centers. Several features have been observed: spirals at a density of $\sim 10^{17}$ /cm² and, at much higher densities, steps associated with both the spirals and a common "island type" growth structure. We recently submitted a paper proposing that the steps may be the universal flux-pinning feature of YBaCuO thin films. This hypothesis was backed up by calculations which showed that a step one unit cell in height had a pinning energy of 3 kT (at T_C). This implies that a 500 Å thick film covered with single steps could produce a $J_C > 5 \times 10^6$ A/cm².

David G. Stroud, The Ohio State University - During the first year of the grant, our work has been directed at modeling transport properties of high-temperature superconductors (primarily in the form of composites) at zero and strong magnetic fields. In a recent publication¹, we have found that the current-voltage (IV) characteristics of a granular superconductor show clear signs of a transition from a vortex fluid to a vortex glass, as predicted by M.P.A. Fisher and collaborators². We have found similar evidence in a recent model calculation of the a.c. conductivity of a model granular superconductor³. Such transitions, we believe, may characterize disordered high-temperature superconductors in a strong magnetic field.

We have also carried out direct calculations of the IV characteristics of Josephson-coupled granular superconductors at $T = 0$. In a preliminary report⁴, we have found that such systems have a critical current which initially decreases with increasing magnetic field, then reaches a plateau. These results may offer an explanation of the plateaus in critical currents frequently seen as a function of magnetic field in high-temperature superconducting composites⁵.

References.

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2. D.S. Fisher, M.P.A. Fisher, and D.A. Huse, Phys. Rev. **B43**, 130 (1991)
3. Z.Q. Wang and D. Stroud, Phys. Rev. B (in press)
4. K.H. Lee and D. Stroud, to be submitted to Phys. Rev. B.
5. See, e.g., K. Sato *et al*, IEEE Trans. Magn. **27**, 1231 (1991)

William B. Yelon and John W. Farmer, University of Missouri-Columbia - The excitement over the new class of materials that exhibit superconductivity at relatively high temperatures (above liquid nitrogen) was tempered by the fact that these materials could not conduct large amounts of current. The current capacity was a significant hurdle to many practical applications of high temperature superconductors (HTC's). Recently, it was found that radiation induced defects can dramatically increase the current capacity of HTC's. We have investigated the role of neutron irradiation defects in enhancing the critical current in work at the University of Missouri through the MISCN funded project "Neutron Diffraction and Defect Studies of High Temperature Superconductors". Irradiation has increased the current capacity by more than a factor of ten with current densities greater than 10^5 amps/cm². Current density at this level is well within the range of the requirements of most of the more exciting applications of high temperature superconductors. In addition, their work has shown that neutron irradiation is the most effective form of irradiation damage to enhance the critical current. Furthermore, neutron irradiation may be more effective than any other method.

1992

T.G. Miller, M. McElfresh and R. Reifenberger, Purdue University - The tunneling conductance from pulsed laser deposited films of YBa₂Cu₃O_{7- δ} revealed a rich fine structure in both the sub-gap and near-gap regions, which corresponds to the density of electronic states on the different layered planes

A.H. MacDonald and S.M. Girvin, Indiana University - Monte Carlo simulations of vortex dynamics yielded a superfluid-density spatial correlation function which advances the understanding of the flux-lattice melting transition

W.J. Tomasch and E. Moser, University of Notre Dame, and J.R. Clem and V.G. Kogan, Iowa State University - The influence of vortices upon the transmission and reflection coefficients for infrared radiation incident upon high-temperature superconductors was theoretically described.

D.V. Baxter, K.G. Caulton and M.H. Chisholm, Indiana University - A new class of ligand was developed, based on " β -diketonate" class of ligands, which encapsulates YBCO metals for use as precursors for the low-temperature processing of high-temperature superconductors.

K.H. Sandhage, Ohio State University and P.J. McGinn, University of Notre Dame - A novel "oscillating oxidation" process yielded superconducting microlaminates composed of alternating $\text{YBa}_2\text{Cu}_3\text{O}_y$ -rich and Ag-rich layers.

W.J. Tomasch and J.K. Furdyna, University of Notre Dame - A leadless nondestructive microwave technique was developed for the quantitative evaluation of high-temperature superconductors in the presence of substantial d.c. magnetic fields.

1993

P. McGinn, University of Notre Dame, E. Kvam, Purdue University, and D. Shi, Argonne National Laboratory - YBCO processed by the solid-liquid melt growth (SLMG) process form textured 123 phase with fine (ca 100nm) 211-phase precipitates. These samples exhibit extremely good low temperature flux pinning properties. Argonne National Laboratory has filed a patent application for this process.

A. H. MacDonald and S. M. Girvin, Indiana University - A formalism which for the first time makes fully microscopic calculations of the mixed state has been developed and is being applied to calculations of the microwave conductivity.

D. G. Stroud, Ohio State University - The flux-lattice melting temperature of single-crystal YBCO has been calculated without any adjustable parameters, in excellent agreement with experimental results.

J. C. Garland, Ohio State University - Superconducting junction arrays, consisting of 300x300 proximity-coupled, weak-link junctions fabricated of $\text{Ag/YBa}_2\text{Cu}_3\text{O}_7$ on SrTiO_3 substrates, have been fabricated and characterized. These junctions exhibit a Kosterlitz-Thouless-type transition in the superconducting state.

J. R. Clem and V. G. Kogan, Iowa State University - Some key superconducting characteristics for BSCCO have been extracted from the theory of thermal fluctuations of vortices in layered superconductors. These properties include the temperature dependencies of the penetration depth, λ_{ab} , the upper critical field, H_{c2} , and the Ginzberg-Landau parameter, κ .

G. Lafyatis and T. Lemberger, Ohio State University - The first direct measurement of a vortex lattice in a superconducting niobium film was demonstrated by measuring NMR transitions in an atomic beam directed across the surface of the film.

D. V. Baxter, K. G. Caulton, and M. H. Chisholm, Indiana University - The thermal decomposition of 124 leads to the eventual formation of 211, Cu_2BaO_2 , and other phases under a three-step process. In contrast to earlier work, the decomposition of 124, per se, takes place in one step with a characteristic activation energy.

T. R. Lemberger, Ohio State University - The first direct determination of the magnetic penetration depth was made for an oxygen-depleted YBCO film. The results reveal that the penetration depth increases with oxygen depletion, but that its temperature dependence is unchanged, consistent with d-wave superconductivity.

M. W. McElfresh and R. G. Reifenberger, Purdue University - A three-tunnel capacitor model for single-electron tunneling was successfully applied to explain the highly non-linear I-V characteristics obtained with $\text{TlBa}_2(\text{Ca}_{0.8}\text{Y}_{0.2})\text{Cu}_2\text{O}_7$ films.

W. B. Yelon and J. W. Farmer, University of Missouri - A new, direct method has been developed for analyzing magnetic relaxation data. With this method it is now possible to determine the dependence of the pinning potential, $U(m)$, of the magnetic induction, B , as well as to see the effects of oxidation-induced pinning centers on $U(m)$.

M. W. McElfresh and R. G. Reifenberger, Purdue University - Two vortex phase transitions have been observed for Tl-2212. The lower temperature transition corresponds to a vortex-glass transition while the higher temperature transition corresponds to a pancake-vortex coupling transition.

C. Pennington, Ohio State University - Measurements of 2-dimensional ^{89}Y NMR in $\text{YBa}_2\text{Cu}_3\text{O}_7$ to probe vortex dynamics reveal that in fields of several Tesla, vortices do not make spatial jumps of distances comparable to the lattice spacing.

M. Chandrasekhar, University of Missouri - The first Raman scattering studies of the phonon modes of $\text{YBa}_2\text{Cu}_4\text{O}_8$ (Y124) under pressure have been made. The mode Grüneisen parameters of the phonons present in both Y124 and Y123 scale with their bulk moduli. However, the chain modes that are Raman allowed only in Y124 are anomalously different.

W. J. Tomasch and J. K. Furdyna, University of Notre Dame - Improvements have been made to a leadless, nondestructive microwave technique for characterizing high-temperature superconductors in the presence of a sustained dc magnetic field (0-7 Tesla).

It is now possible to infer with reasonable agreement microwave surface impedance directly from the data.

E. Kvam, Purdue University - For YBCO with 211 additions, the enhancement of the critical current through flux pinning has been found to depend on the size of the 211 particles. However, the pinning seems to be induced more by extended defects (dislocations and CuO layer stacking faults) associated with the particles rather than by the particles themselves.

1994

A. E. Miller and S. Bandyopadhyay, University of Notre Dame - A quasi-periodic array of nanometer-scale, Pb quantum dots has exhibited quantum confinement. Quantum confinement resulted in a broadening of the transition temperature from 7°K for bulk lead to 30-7°K from onset to completion for the quantum array.

M. W. McElfresh and E. P. Kvam, Purdue University - Studies on deoxygenated YBCO show that the theoretically-predicted dimensional crossover field H_0 decreases as anisotropy increases. All vortex-glass phase boundaries can be collapsed onto a single universal curve, suggesting that there is a general magnetic phase diagram for all HTS materials.

J. M. Honig and J. Spaček, Purdue University - A quantitative model of a three-dimensional superconductor has been developed which predicts the change in transition temperature with the number of conducting planes.

J. Betanabhatla, University of Nebraska-Omaha, J. R. Hardy, University of Nebraska-Lincoln, R. R. Berliner, University of Missouri-Columbia - Superconductivity has been induced for the first time in materials of the phase $Ba_{1-x}Bi_xO_{3-d}$. The transition temperature is in the vicinity of 25°K, which is the highest reported for a non-cubic bismuth oxide phase.

K. P. Trumble, K. J. Bowman and M. W. McElfresh, Purdue University - Reproducible processing of silver-clad BSCCO tubes by centrifugal slip casting was demonstrated, and a patent for the process filed. This work demonstrated that a high degree of preferred orientation in the centrifugally-cast tubes enables significant densification.

C. Pennington, The Ohio State University - NMR measurements with simultaneously-applied pulsed currents confirm that the vortex system in single-crystal YBCO is in the "liquid" state within the resistive transition temperature region, and that the diffusion distances are much greater than the intervortex spacing within times less than 100 μ sec.

P. J. McGinn, University of Notre Dame, and K. H. Sandhage, The Ohio State University - The melt-texturing of YBCO was found possible in metal-precursor-derived laminates fabricated from Y-Ba-Cu-Ag-Pd tapes without melting the Ag-Pd noble metal alloy.

G. Lafyatis, The Ohio State University - Atomic beam studies of the vortex lattice in Nb films can be fitted with a hexagonal lattice which has sample-wide orientation order and short-range (about 5 lattice constants) translational order.

P. J. McGinn, University of Notre Dame - Significant improvements in the magnetization of YBCO have been achieved by Nd doping; and extended hold times above the peritectic result in increased pinning (and J_c) at 77°K, attributed to increased dislocation density with 211 phase coarsening.

T. R. Lemberger, The Ohio State University - Highly-refined measurements of the magnetic penetration depth in YBCO films now leave no doubt that dopants increase the penetration depth without affecting its T dependence.

G. F. Giuliani, Purdue University - For S-I-S tunneling junctions under suitable situations the inelastic scattering of tunneling electrons with barrier phonons can lead to an increase in tunneling probability.

D. G. Stroud, The Ohio State University - Studies of flux melting in highly anisotropic, high- T_c superconductors, such as BSCCO, show strong evidence for a dimensionality crossover (3D to 2D transition) which is accompanied with a conspicuous change from mean-field-like to fluctuation-dominated behavior.

D. V. Baxter, K. G. Caulton and M. H. Chisholm, Indiana University - A molecular precursor with the correct Y:Ba stoichiometry of YBCO has been successfully synthesized.

S. K. Malik, Tata Institute of Fundamental Research and W. B. Yelon and J. W. Farmer, University of Missouri-Columbia - A new superconducting phase, RNi_2B_2C , was

synthesized with Y and Er. The Y and Er samples had T_c 's of 15.5°K and 11°K, respectively.

E. P. Kvam, Purdue University - In YBCO with 211 additions, the flux pinning seems to be induced by extended defects (dislocations and CuO-layer stacking faults) associated with the particles rather than directly by the particles themselves.

J. M. Honig and J. Spaček, Purdue University - Fluorination has been found to enhance significantly the superconductivity of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4+y}$.

G. F. Giuliani, Purdue University - In small Josephson junctions, Abrikosov vortex penetration tends to increase I_c . Specifically, for suitable vortex configurations the dependence $I_c(H)$ is determined by the magnetization in such a way to lead to an increasing $I_c(H)$.

G. L. Liedl, A. L. Bement, Jr., and S. Mansour, Purdue University - The preferred orientation of YBCO films deposited on MgO substrates by the metallo-organic deposition process can be varied with increasing firing temperature from a broad fiber texture to an epitaxial orientation.

H. A. Blackstead, University of Notre Dame - The Blackstead-Dow model, which asserts that Ba-site substitution by magnetic Pr^{+3} ions breaks electron-pairs while rare-earth site substitution does not, has been verified experimentally.

A. H. MacDonald and S. M. Girvin, Indiana University - Monte Carlo calculations establish that the superconducting vortex state does not occur at finite temperatures in the limit of 2D films with point disorder.

J. C. Garland, The Ohio State University - The H-T phase diagram for single-crystal BSCCO consists of a penetration (or depinning) field boundary and a 2D-3D crossover field boundary (which separates phases of 3D vortex lines and interacting 2D vortices) for c-axis-oriented fields of $H > H_{c2}$.

P. J. McGinn, University of Notre Dame, and K. H. Sandhage - The Ohio State University A process for fabricating spiral-wound tubes from Ag-Pd sheet has been developed for the powder-in-tube processing of YBCO composites.

1995

G. Lafyatis, The Ohio State University - The first direct measurement of temperature-driven dynamics in the vortex chain state of a YBCO untwinned single crystal was performed using an atomic-beam imaging technique. The predictions of the London model were confirmed, and a hysteresis between the freezing and melting of the vortex chains was observed.

J. M. Honig and J. Spaček, Purdue University - A quantitative, 3-dimensional model of a high-temperature superconductor as a non-Fermi liquid has been formulated which calculates explicitly the transition temperature and the spatial modulation of the order parameter. Agreement between theory and experiment is excellent. The derived formula allows for a prediction of the T_C value within a given family for the number of CuO_2 layers not yet studied experimentally to include a limiting value of T_C for a large number of CuO_2 planes within the group.

S-H Liou, University of Nebraska-Lincoln - For the first time (Hg,Tl)-1223 films have been fabricated and have exhibited the highest T_C (133K at onset) reported for a superconducting film.

D. V. Baxter, K. G. Caulton and M. H. Chisholm, Indiana University - The reagents Et_3PO and Me_3NO have been found to bind to $\text{BaCu}_2(\text{O}^t\text{Bu})_4$ (normally insoluble) and solubilize it. This finding makes possible the processing of this precursor into oxides by thermolysis and hydrolysis methods.

A. H. MacDonald and S. Girvin, Indiana University - A technique for determining the absolute time scales for relaxation dynamics near the vortex glass transition has been developed. Knowledge of the absolute time scale allows an experimentalist to predict the scale of frequency needed to see deviations from a DC response.

D.G. Stroud, The Ohio State University - The first calculation of the fluctuation magnetization in a high- T_C superconductor (in this case YBCO) has been carried out in excellent agreement with experiment. This result is important because it shows that we now have an excellent description of the thermodynamics of flux motion in high- T_C superconductors, especially at high fields.

E. P. Kvam, Purdue University - The possibility of growing high-quality, biaxially-aligned, thin films of YBCO with distinctly different in-plane directions on vicinal SrTiO₃ substrates was demonstrated for the first time. This result is particularly significant for some applications and for the study of transport properties of thin films.

C. Pennington, The Ohio State University - Transverse relaxation (T_2) contribution in YBCO, resulting from the ^{89}Y - $^{63,65}\text{Cu}$ magnetic dipole interaction, has been calculated using no adjustable parameters. This relaxation mechanism fully explains normal state data.

J.C. Garland, The Ohio State University - A method has been developed for producing BSCCO single-crystal samples that are ideally suited for studying the vortex glass phase in a layered system where the number of Josephson-coupled Cu-O bilayers can be varied.

T.R. Lemberger, The Ohio State University - The first observation of two superconducting transitions in $\lambda(T)$ in a multilayer superconductor have been made in films composed of several alternating layers of Bi₂201 and Bi₂278. We observed that the proximity effect between the two layers increases the transition temperature of the Bi₂201 layer from 20K to 40K.

M.W. McElfresh and E.P. Kvam, Purdue University - Modifications in the relaxation of magnetic flux in strong pinning superconductors due to demagnetization effects have been determined both experimentally and theoretically. The distribution of currents is quite different from that expected from the standard Bean Critical State model and as a result the relaxation behavior is different from the expected behavior.

Ken H. Sandhage, The Ohio State University and Paul J. McGinn, University of Notre Dame - A new method has been developed for fabricating YBa₂Cu₃O_y/noble metal microlaminates which takes advantage of the malleability of mixtures of Y and Ba powders. Y-Ba powder packed between an inner ingot of Ag-Cu and an outer tube of Ag can be rolled to form a geometrically uniform Y-Ba inner layer, which when oxidized forms YBa₂Cu₃O_y by concurrent diffusion of Cu from the Ag-Cu core.

J. Betanabhatla, University of Nebraska-Omaha, J. R. Hardy, University of Nebraska-Lincoln, and R. R. Berliner, University of Missouri-Columbia - Pure PrBa₂Cu₃O_{7- δ} has been synthesized in order to understand the effect of Pr substitution on superconductivity

of "124" cuprate phase, its use as a buffer layer in thin film device applications, and why it is not a superconductor.

T.R. Lemberger, The Ohio State University - It has been shown that the T-linear behavior in clean YBCO crystals and films comes from nodes in the order parameter and not from thermal fluctuations suggested by current theory.

Ken H. Sandhage, The Ohio State University - A solid-state process involving elevated oxygen pressures has been developed to align grains in silver-sheathed $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8+\delta}$. This process avoids the coarsening of non-superconducting grains that occurs in commonly used melt texturing.

P. McGinn, University of Notre Dame - The melt texturing of Y-123 samples in air with excess rare earth additions (Nd_2O_3 , La_2O_3 , and Sm_2O_3) showed improvements in both magnetization and T_c . The enhanced magnetization is thought to be due to pinning effects caused by rare earth ions being present on Y^{3+} and/or Ba^{2+} sites in the 123 lattice.

P. Muzikar, Purdue University - Calculations of the effects of impurity scattering for different types of superconducting order parameters have shown that for certain types of order parameters, the addition of impurity scattering can actually increase the superfluid density in certain directions.

David R. Gaskell, Purdue University - The production of phase-pure 2212 and 2223 in the system Bi-Sr-Ca-Cu-O has been achieved permitting the study of the influence of oxygen pressure and temperature on the partitioning of Ca and Sr between equilibrated 2212-2223 couples.

G.F. Giuliani, Purdue University - An extended theory to all orders of inelastic scattering in a Josephson junction predicts that in suitable situations the inelastic scattering can enhance the pair tunneling and lead to a corresponding maximum in the critical current.

H.A. Blackstead, University of Notre Dame - For the first time, dissipation from Josephson vortices has been demonstrated in $(\text{Y},\text{Pr})\text{Ba}_2\text{Cu}_3\text{O}_7$. These vortices strongly effect the electromagnetic properties of this layered superconductor.

1996

S-H Liou, University of Nebraska-Lincoln - A reproducible fabrication process has been developed which yields patterned YBCO/STO/YBCO multilayer circuits with the best critical current density and transition temperature reported to date.

J.C. Garland, The Ohio State University - The first direct evidence for separate vortex lattice melting and line decoupling phase transitions has been reported for high-quality BSCCO single crystals. Also, the first observation that the melting transition is current dependent suggests that this transition occurs away from thermodynamic equilibrium in the presence of a driving current.

A.H. McDonald and S.M. Girvin, Indiana University - A model has been developed that captures the principal qualitative aspects of superconducting fluctuations on the thermodynamics of superconductors at any magnetic field strength.

M.W. McElfresh, P. Muzikar and E.P. Kvam, Purdue University - Evidence has been found for 3D vortex fluctuations along the entire phase boundary of the vortex liquid to solid transition for both low and high magnetic fields in deoxygenated YBCO thin films. At the lower fields, the fluctuations are of the 3D XY character. At high magnetic fields they correspond to the Landau level picture.

H.A. Blackstead, University of Notre Dame - The independent observation by two Japanese investigators that Pr123 superconducts at $T_c \sim 90K$ confirms a key prediction by Dow and Blackstead and shows that Pr123 would be unsuitable as an insulation material for S-I-S junctions.

D.G. Stroud, The Ohio State University - Monte Carlo simulations give time-dependent models of flux melting, to include subdiffusive motion of individual disclinations in a dense liquid phase, that gives a calculated melting curve in excellent with experiment.

P.F. Micelli, University of Missouri-Columbia - The capability of measuring Ångstrom-scale variations in the surface roughness of buried interface layers in YBCO films has been demonstrated using polarized neutron reflectivity.

J. Betanabhatla, University of Nebraska-Omaha, J.R. Hardy, University of Nebraska-Lincoln, and R.R. Berliner, University of Missouri-Columbia - Pure Y124 has been synthesized for the first time at ambient oxygen pressure which will facilitate the fabrication of S-I-S Josephson junction devices.

W. B. Yelon, University of Missouri-Columbia - Studies of $\text{NdBa}_{2-x}\text{Pr}_x\text{Cu}_3\text{O}_7$ show that superconductivity persists up to $x = 0.3$. The distinct preference for Pr to occupy the Ba site casts doubt on the hypothesis that a small amount of Pr on the Ba site is responsible for the suppression of T_c .

D.G. Stroud, The Ohio State University - Clear numerical evidence for a dynamical phase transition in the I-V characteristics of a moving vortex lattice has been obtained in excellent agreement with experiment.

Meera Chandrasekhar, University of Missouri-Columbia - Measurements of phonon vibrational frequencies have shown conclusively that nickel substitutes preferentially in the Cu chain sites in YBCO.

Paul J. McGinn, University of Notre Dame - Two first-time observations have been made for YBCO: the segregation of Y211 during the zone melting of wires and the occurrence of a magnetization peak effect in Ce-doped YBCO.

S.T. Ruggiero, University of Notre Dame - The first measurements of the responsivity of YBCO to far-infrared wavelengths at 25 microns have been accomplished.

H.A. Blackstead, University of Notre Dame - The first observation of the coexistence of ferromagnetism and superconductivity has been made in two cuprate superconductors.

G.F. Giuliani, Purdue University - A theory has been developed of the proximity effect in an S-N-S Josephson junction in the presence of an inelastic interaction of the tunneling electrons with phonons in the barrier region.

T.R. Lemberger, The Ohio State University - Measurements of inductive and resistive transitions in a variety of YBCO films show that they are always different from those observed in bulk crystals. Furthermore, the real and imaginary parts of the conductivity violate the Kramers-Kronig relations.

John W. Farmer, University of Missouri-Columbia - Measurements and analyses of flux creep have demonstrated a universal mechanism for single fluxoid pinning in "clean" single crystals of YBCO.

Paul J. McGinn, University of Notre Dame and Ken H. Sandhage, The Ohio State University - A mechanical segregation/metallic precursor approach has been successfully used to fabricate BSCCO/Ag laminate tapes.

Meera Chandrasekhar, University of Missouri-Columbia - The first measurement of a distinct anomaly in the phonon frequency and linewidth of Hg 1201 was reported.

K.P. Trumble, K.J. Bowman and M.W. McElfresh, Purdue University - The first direct observations of the effects of silver and oxygen partial pressure on the thermal stability of BSCCO-2223 have been characterized that not only clear up inconsistencies in the literature but also provide new directions in the orientation processing of silver-BSCCO products.

Ken H. Sandhage, The Ohio State University - The effect of cation non-stoichiometry on the grain growth behavior of $\text{Nd}_{1-x}\text{Ba}_x\text{Cu}_3\text{O}_y$ (for $x \leq 0.4$) has been determined.

E.P. Kvam, Purdue University - New variants of crystallographic orientations of YBCO have been observed when grown by laser ablation on SrTiO_3 buffer layers on zirconia substrates.

1997

S-H. Liou, University of Nebraska-Lincoln - A fabrication process has been developed that allows for the first time multilevel high-temperature superconducting structures consisting of bicrystal grain boundary Josephson junctions in a stacked geometry. These structures exhibit interesting electronic properties and can be used to make novel device structures such as very low impedance dc SQUID interferometers.

P.F. Micelli, University of Missouri-Columbia - For the first time it has been demonstrated that neutrons can observe vortices in a thin film superconductor, providing the potentiality of directly measuring vortex distributions in thin film samples.

P. Muzikar, Purdue University - For the first time, exact solutions for the changes in the spatial distribution of the order parameter and magnetic field around a stationary vortex line pinned at an impurity have been achieved.

D.G. Stroud, The Ohio State University - Theoretical modeling of flux lattice melting behavior have shown that two separate transitions occur at low and high fields.

respectively. At high fields the thermodynamics are dominated by field-induced vortices and at low fields by the influence of thermally-activated vortex loops.

C. Pennington, The Ohio State University - Nuclear magnetic resonance spin echo techniques have been developed as a quantitative probe of vortex dynamics in high-temperature superconductors. Measurements in the vortex solid state show that small displacements of vortices from equilibrium positions occur over short time scales.

H.A. Blackstead, University of Notre Dame - Granular superconductivity at ~12K has been observed in a predicted superconducting compound, $\text{Gd}_{2-z}\text{Ce}_z\text{Sr}_2\text{Cu}_2\text{TiO}_{10}$. The previously predicted superconductivity in $\text{PrBa}_2\text{Cu}_3\text{O}_7$ (Pr-123) has now been confirmed independently by several research groups in Japan.

J. Betanabhatla, University of Nebraska-Omaha; J.R. Hardy, University of Nebraska-Lincoln; and R.R. Berliner, University of Missouri-Columbia - Neutron diffraction studies on ^{58}Ni substituted YBCO indicate for the first time that the nickel atoms in both the "123" and "124" phases distribute randomly on both planes and chain copper sites. This finding is at variance with a number of theoretical models for high- T_c superconductivity.

K.H. Sandhage, The Ohio State University - A method for fabricating laminates of silver and BSCCO-2212 with excellent geometric uniformity relative to OPIT (oxide powder in tube) tapes has been developed. The oxide/Ag interfaces of such laminates are much less rough and flatter than is typically observed for OPIT tapes.

P.J. McGinn, University of Notre Dame - Ceria (CeO_2) substitution for platinum in melt-textured YBCO "123" pellets can provide comparable levitation properties and can be effective in driving down levitator costs.

J.C. Garland, The Ohio State University - Transport measurements of BSCCO single crystals in external magnetic fields have revealed that, in contrast to the vortex glass model, these crystals exhibit linear current-voltage characteristics in fields greater than 1 Tesla.

T.R. Lemberger, The Ohio State University - Measurements of the magnitude and temperature dependence of the magnetic penetration depth in optimally-doped LSCO films have been shown to be consistent with a d-wave order parameter.

P. Bauman and D. Phillips, Purdue University - The first mathematically complete treatments have been achieved for nucleation to the superconducting state in two- and three-dimensional objects.

G.F. Giuliani, Purdue University - The former prediction of a universal behavior for the magnetic field dependence of the critical current in long Josephson junctions has now been experimentally verified.

P.F. Micelli, University of Missouri-Columbia - A technique has been developed that permits measuring the London penetration length, λ , directly in YBCO using polarized neutron reflectivity.

J. Betanabhatla, University of Nebraska-Omaha; J.R. Hardy, University of Nebraska-Lincoln; and R.R. Berliner, University of Missouri-Columbia - Evidence has been found for the first time for a superconductivity transition around 12K in the Sr-Bi-O system, specifically in the compound $(\text{Sr}_{1-x}\text{K}_x)_3\text{Bi}_2\text{O}_y$ with $x \geq 0.12$.

P.J. McGinn, University of Notre Dame - Significant vortex pinning can be achieved in YBCO by doping with discrete amounts of Ce (as CeO_2 or BaCeO_3) and MgO .

K.P. Trumble, K.J. Bowman and M.W. McElfresh, Purdue University - Particle orientation has been observed to affect the grain growth and sintering rates for BSCCO-2223, suggesting a direct link between orientation, sinterability, and grain growth for 2223 powder compacts.

W.B. Yelon, University of Missouri-Columbia - Improvements in counting statistics and the small sample geometries accommodated in the MURR diffractometer permit the neutron diffraction studies of high-temperature superconductors containing rare earths with high neutron cross sections in a reasonable amount of time (such as Gadolinium- and Europium-based compounds which have been hitherto not considered possible).

M.W. McElfresh and E.P. Kvam, Purdue University - Off-axis deposition coupled with the use of a barricade has been shown effective for producing smooth, particulate-free films by pulsed laser deposition.

APPENDIX II
Research Title, Principal Investigators, and University

1990

"Crystallization Of High Temperature Superconducting Filaments"

Alan I. Goldman, Douglas K. Finnemore, L. Scott Chumbley
Iowa State University

"Crystallization of REBa₂Cu₃O₇ High Temperature Superconducting Materials from the Solidified Melt"

R. W. McCallum, L. S. Chumbley, M. J. Kramer
Iowa State University

"Critical Current Density in Textured YBa₂Cu₃O_{6+x} and Related Compounds"

Paul J. McGinn
University of Notre Dame

"Study of Compositional Modulation in High-Temperature Superconductor Structures and its Influence on Their Superconducting Properties"

K. M. Choudhary and S. T. Ruggiero
University of Notre Dame

"High T_c Superconducting Composites/Films"

James C. Garland
The Ohio State University

"Normal, Magnetic and Superconducting Properties of La_{1-x}Sr_xNiO_{4+δ} and La_{2-x}SrCu_{1-y}Ni_yO₄ Systems, and Real Space Paring in High-T_c Systems"

J. M. Honig and J. Spalek
Purdue University

"Study of Naturally Modulated High T_c Superconducting Compounds"

Hiroshi Sato
Purdue University

"Thermally Activated Flux Motion in High-Temperature Superconductors"

John R. Clem and Vladimir G. Kogan
Iowa State University

"Experimental Study of Transport in Y₁Ba₂Cu₃O_{7-δ} and Y₂Ba₄Cu₈O_x Films"

Thomas R. Lemberger
The Ohio State University

"Superconductors in Strong Magnetic Fields"

A. H. MacDonald and S. M. Girvin
Indiana University

"Microwave Dissipation in High-Temperature Superconductors: Flux-Lattice Dynamics, Crystal Anisotropy and Flux Pinning"

W. J. Tomasch and H. A. Blackstead
University of Notre Dame

"Intrinsic and Induced Weak Link Behavior in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Films"

M. W. McElfresh and R. Reifenberger
Purdue University

"Dynamical Properties of Josephson-coupled Systems: Application to High-Temperature Superconductors"

David G. Stroud
The Ohio State University

"Neutron Diffraction and Defect Studies of High T_c Superconductors"

William B. Yelon and John W. Farmer
University of Missouri-Columbia

1991

"Crystallization Of High Temperature Superconducting Filaments"

Alan I. Goldman, Douglas K. Finnemore, L. Scott Chumbley
Iowa State University

"Crystallization of $\text{REBa}_2\text{Cu}_3\text{O}_7$ High Temperature Superconducting Materials from the Solidified Melt"

R. W. McCallum, L. S. Chumbley, M. J. Kramer
Iowa State University

"Microstructural Dependence of Critical Current Density in Textured $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ Superconductors"

Paul J. McGinn
University of Notre Dame

"Study of Compositional Modulation in High-Temperature Superconductor Structures and its Influence on Their Superconducting Properties"

K. M. Choudhary and S. T. Ruggiero
University of Notre Dame

"High T_c Superconducting Composites/Films"

James C. Garland
The Ohio State University

"Normal Properties, Magnetism, and Onset of Superconductivity in $\text{La}_{1-x}\text{Sr}_x\text{NiO}_{4+\delta}$ and $\text{La}_{2-x}\text{SrCu}_{1-y}\text{Ni}_y\text{O}_4$ Systems, and Real Space Pairing in High- T_c Systems"

J. M. Honig and J. Spalek
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Hiroshi Sato
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R. W. McCallum, L. S. Chumbley, M. J. Kramer
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"Improved Synthetic Techniques for High- T_c Superconductors with Deliberate Additions of a Second Phase"

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APPENDIX III
Principal Investigators, Funding Received, and Capital Equipment Awards

PI	Total Funding Rec'd	Funding Period	Equip Awards
John R. Clem and Vladimir G. Kogan Iowa State University	\$324,694	90-93	
Alan I. Goldman Douglas K. Finnemore, and L. Scott Chumbley Iowa State University	\$421,285	90-93	
R. W. McCallum, L. S. Chumbley, M. J. Kramer Iowa State University	\$231,000	90-93	
David V. Baxter, Kenneth G. Caulton, and Malcolm H. Chisholm Indiana University	\$816,633	91-2001	\$48,213
A. H. MacDonald and S. M. Girvin Indiana University	\$770,280	90-2001	\$40,000
Meera Chandrasekhar University of Missouri-Columbia	\$451,312	92-2001	\$15,250
J. Farmer University of Missouri-Columbia	\$136,195	96-2001	\$19,400
P. F. Miceli University of Missouri-Columbia	\$429,700	94-2001	\$46,300
William B. Yelon and John W. Farmer University of Missouri-Columbia	\$683,939	90-2001	\$33,150
J. Betanabhatla, University of Nebraska-Omaha, J. R. Hardy, University of Nebraska-Lincoln, and R. R. Berliner, University of Missouri-Columbia	\$431,347	94-2001	\$40,000
S. Bandyopadhyay University of Nebraska-Lincoln	\$80,819	97-2001	\$43,000

S. Liou University of Nebraska-Lincoln	\$374,600	94-2001	\$43,000
H. A. Blackstead University of Notre Dame	\$756,000	91-2001	\$71,307
K. M. Choudhary and S. T. Ruggiero University of Notre Dame	\$338,787	90-93	\$7,500
Paul J. McGinn University of Notre Dame	\$1,022,791	90-2001	\$96,500
A. E. Miller, B. Das, S. Bandyopadhyay University of Notre Dame	\$376,001	93-2001	
S. T. Ruggiero University of Notre Dame	\$326,688	93-2001	\$31,050
W. J. Tomasch and H. A. Blackstead University of Notre Dame	\$429,009	90-93	\$15,011
Patrick K. Gallagher The Ohio State University	\$234,803	91-96	
James Garland The Ohio State University	\$825,449	90-97	\$140,125
Gregory Lafyatis and Thomas Lemberger The Ohio State University	\$427,247	91-97	
Thomas R. Lemberger The Ohio State University	\$615,423	90-2001	
Charles Pennington The Ohio State University	\$491,806	92-2001	
Ken H. Sandhage, The Ohio State University and P. J. McGinn, University of Notre Dame	\$631,212	92-2001	

Ken H. Sandhage The Ohio State University	\$766,651	91-2001	\$74,050
David G. Stroud The Ohio State University	\$533,904	90-2001	
P. Bauman and D. Phillips Purdue University	\$85,958	97-99	
D. R. Gaskell Purdue University	\$319,950	94-99	
G. F. Giuliani Purdue University	\$501,500	91-99	\$14,150
J. M. Honig and J. Spalek Purdue University	\$516,121	90-99	
Eric P. Kvam Purdue University	\$1,254,561	90-2001	\$15,000
G. L. Liedl and A. Bement, Jr. Purdue University	\$889,643	90-2001	
M. W. McElfresh and R. Reifengerger Purdue University	\$435,039	90-94	
M. McElfresh and E. P. Kvam Purdue University	\$648,790	96-2001	\$107,000
Paul Muzikar Purdue University	\$284,747	94-99	
Hiroshi Sato Purdue University	\$450,731	90-93	
K. P. Trumble, M. W. McElfresh, and K. J. Bowman Purdue University	\$861,761	92-99	\$37,500

APPENDIX IV
Students/Degrees

Project	Students	Degree
Low Temperature Routes to Processing of High-Temperature Superconductors Baxter/Caulton/Chisholm Indiana University	V. DiStasi C. Smotzer W. Chiang B. Borup	Ph.D. M.S. Ph.D. Ph.D.
Quantum Effects in Quasi-Two-Dimensional Superconductors MacDonald/Girvin Indiana University	Min-Chul Cha J. Hu K. Moon R. Hyman Y. Wang	Ph.D. Ph.D. Ph.D. Ph.D. Ph.D.
Optical Studies of New -123 and -124 Materials M. Chandrasekhar University of Missouri-Columbia	D. J. Payne	Ph.D.
Neutron Diffraction and Defect Studies of High T_c Superconductors Yelon/Farmer University of Missouri-Columbia	H. Xie X. Ding D. Bradford	M.S. Ph.D. Ph.D.
Hg- and Tl- Based Superconducting Films S. H. Liou University of Nebraska-Lincoln	H. Li	Ph.D.
Microstructural Dependence of Critical Current Density in Melt Textured $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ Superconductors P.J.McGinn University of Notre Dame	D. Balkin S. Sengupta V. Chakripani H. Yang H. Balwada S. Yeung	Ph.D. Ph.D. Ph.D. M.S. M.S. Ph.D.
Superconducting Quantum Structures Miller/Bandyopadhyay University of Notre Dame	A. Balandin	Ph.D.
Far-Infrared and Microwave Magneto-Dissipation in High-	E.K. Moser	Ph.D.

Temperature Superconductors
Tomasch/Furdyna
University of Notre Dame

Growth of Single Crystals and/or Textured Specimens of
High Tc Superconductors using Oxygen Seeding
P.K. Gallagher
The Ohio State University

High Tc Superconducting Composites, Arrays and Crystals
J. C. Garland
The Ohio State University

Atomic Beam Studies of Vortex Lattices at Superconductor Surfaces
G. P. Lafyatis
The Ohio State University

Device-related Properties of Doped $\text{YBa}_2(\text{Cu}_{1-x}\text{M}_x)_3\text{O}_{7-\delta}$ Films
T. R. Lemberger
The Ohio State University

NMR Studies of Vortex Dynamics in High Tc Superconductors
C. Pennington
The Ohio State University

Processing of Textured Superconducting Oxide/Noble Metal Microlaminates
Sandhage/McGinn
The Ohio State University and
University of Notre Dame

Anisotropic Grain Growth and Isothermal Grain Alignment of Bulk
Superconducting Oxides
K. H. Sandhage
The Ohio State University

Dynamical Properties of Josephson-coupled Systems:
Application to High-Temperature Superconductors
D. G. Stroud
The Ohio State University

S. Choi Ph.D.

H.T. Herbert Ph.D.
Y.M. Wan Ph.D.
C. Ash M.S.
J. S. Markus M.S.
S.M. Ammirata Ph.D.

S. Dapore-Schwartz Ph.D.

Ju Young Lee Ph.D.
E. Ulm Ph.D.

C. Hahm M.S.
C. H. Recchia Ph.D.
V. Nandor Ph.D.

S. Vilayannur Ph.D.

D. Chmielewski M.S.
H. Miron M.S.

E. Roddick Ph.D.
B. Zou M.S.
R. Sasik Ph.D.
Ing-Jye Hwang Ph.D.

Effects of ac Magnetic Fields on Superconducting ac Currents:
Moving Toward an Understanding of Three-Phase Electrical
Power Transmission Using Superconductors
Bauman/Phillips
Purdue University

M. Royer Ph.D.
T. Giorgi Ph.D.

Pair Breaking Phenomena in the $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Ni}_y\text{O}_4$ Systems
Experiment and Theory
Honig/Spalek
Purdue University

P. Metcalf M.S.

Structural Defects and Interfaces in $\text{YBa}_2\text{Cu}_3\text{O}_7$
E. P. Kvam
Purdue University

A. Zanota M.S.
V.R. Iyer M.S.
D. Linehan M.S.
R. Zhu M.S.

Processing and Texture Development in $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$
Films from Metallo-Organic Precursors
Liedl/Bement
Purdue University

C. Venkatramaan Ph.D.

Study of Vortex Dynamics and Flux Pinning on Different Length Scales
McElfresh/Kvam
Purdue University

J. Deak Ph.D.
L. Hou Ph.D.
S. Li Ph.D.

Intrinsic and Induced Weak Link Behavior in $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$
McElfresh/Reifenberger
Purdue University

T. G. Miller Ph.D.

Vortices in Anisotropic Superconductors
P. Muzikar
Purdue University

H. Kim Ph.D.
G. Preosti Ph.D.

High Temperature Superconducting Tubes for Magnetic Shielding Applications
Trumble/Bowman/McElfresh
Purdue University

D. Aldrich B.S.E.
C. Peterson B.S.E.
A. Trissler B.S.E.
T. Brent B.S.E.
N. Medendorp, Jr. M.S.E.
G. Steinlage Ph.D.
R. Moon M.S.E.

APPENDIX V
Publications and Presentations

PI	Publications	Presentations
John R. Clem and Vladimir G. Kogan Iowa State University	29	62
Alan I. Goldman Douglas K. Finnemore, and L. Scott Chumbley Iowa State University	5	9
R. W. McCallum, L. S. Chumbley, M. J. Kramer Iowa State University	3	2
David V. Baxter, Kenneth G. Caulton, and Malcolm H. Chisholm Indiana University	12	44
A. H. MacDonald and S. M. Girvin Indiana University	29	83
Meera Chandrasekhar University of Missouri-Columbia	5	16
J. Farmer University of Missouri-Columbia	9	17
P. F. Miceli University of Missouri-Columbia	3	11
William B. Yelon University of Missouri-Columbia	21	27
J. Betanabhatla, University of Nebraska-Omaha, J. R. Hardy, University of Nebraska-Lincoln, and R. R. Berlner, University of Missouri-Columbia	2	10
S. Bandyopadhyay University of Nebraska-Lincoln	1	14

S. Liou University of Nebraska-Lincoln	17	15
H. A. Blackstead University of Notre Dame	75	63
K. M. Choudhary University of Notre Dame	6	10
Paul J. McGinn University of Notre Dame	73	66
A. E. Miller, B. Das, S. Bandyopadhyay University of Notre Dame	8	7
S. T. Ruggiero University of Notre Dame	3	10
W. J. Tomasch University of Notre Dame	2	9
P. K. Gallagher The Ohio State University	0	1
James Garland The Ohio State University	28	49
Gregory Lafyatis The Ohio State University	2	3
Thomas R. Lemberger The Ohio State University	18	25
Charles Pennington The Ohio State University	7	14

Ken H. Sandhage The Ohio State University	3	32
David G. Stroud The Ohio State University	44	65
P. Bauman and D. Phillips Purdue University	0	6
G. F. Giullani Purdue University	22	45
J. M. Honig and J. Spalek Purdue University	32	40
Eric P. Kvam Purdue University	12	15
G. L. Liedl and A. Bement, Jr. Purdue University	1	10
M. W. McElfresh Purdue University	27	80
Paul Muzikar Purdue University	17	19
Hiroshi Sato Purdue University	5	8
K. P. Trumble, M. W. McElfresh, and K. J. Bowman Purdue University	9	37

APPENDIX VI **MISCON SUMMER SCHOOL**

Title	Location	Date	Chairmen	Participants
Type-II Superconductors: Basic Properties, Measurements, and Selected Advanced Topics	Univ. of Notre Dame	July 8-9/93	John Clem & Mike McElfresh	98
Synthesis, Processing and Analysis of High Temperature Superconductors	Purdue University	August 11-12/94	Paul McGinn & Ken Sandhage	103
The Josephson Effect and Device Applications	Univ. of Missouri- Columbia	July 13-14/95	Jim Garland & Steve Ruggiero	77
Preparation and Properties of High Temperature Superconducting Thin Films	Univ. of Notre Dame	August 15-16/96	Mike McElfresh & Dave Baxter	89
Magnetic Vortices in Superconductors	Purdue University	July 24-25/97	Mike McElfresh & Tom Lemberger	95
Material Issues Related to Applications of High T_c Superconductors	Univ. of Missouri- Columbia	July 30-31/98	Sy-Hwang Liou, Tom Lemberger & Ken Sandhage	59

APPENDIX VII ORGANIZATION

<u>Office of the Director</u>	<u>University/Affiliation</u>	<u>Participation Date</u>
A. I. Schindler, Director	Purdue University	1990-91
G. L. Liedl, Acting Director	Purdue University	1991-92
Arden L. Bement, Jr., Director	Purdue University	1992-2001
Rebecca F. Herr, Assistant to the Director	Purdue University	1990-2001
<u>Steering Committee Members</u>	<u>University/Affiliation</u>	<u>Participation Date</u>
Kenneth L. Kliewer	Purdue University	1990-92
Robert Greenkorn	Purdue University	1992-94
Luis Proenza	Purdue University	1994-2001
Thomas L. Sweeney	The Ohio State University	1990-92
Richard Stoddard	The Ohio State University	1992-2001
Nathan O. Hatch	University of Notre Dame	1990-96
James L. Merz	University of Notre Dame	1996-2001
Michael M. Crow	Iowa State University	1990-92
Stuart Hadley	Iowa State University	1992-93
Ronald J. Turner	University of Missouri	1990-96
Stephen Lehmkuhle	University of Missouri	1997-2001
James B. Milliken	University of Nebraska	1994-2001

Joseph A. Franklin	Indiana University	1990-94
George E. Walker	Indiana University	1994-1996

<u>Program Committee Members</u>	<u>University/Affiliation</u>	<u>Participation Date</u>
Malcolm Macfarlane	Indiana University	1996-2001
A. I. Schindler (ExOfficio Member)	Purdue University	1990-91
G. L. Liedl (ExOfficio Member)	Purdue University	1991-99
Arden L. Bement, Jr. (ExOfficio Member)	Purdue University	1992-2001
Newton Cattell (ExOfficio Member)	Midwestern University	1990-99
A. I. Schindler	Purdue University	1990-91
Gerald L. Liedl	Purdue University	1991-99
Arden L. Bement, Jr., Director	Purdue University	1992-2001
Michael McElfresh, Assistant Director	Purdue University	1992-99
Paul McGinn (Also Group I Leader)	Notre Dame University	1990-2001
John R. Clem (Also Group II Leader)	Iowa State University	1990-93
James Swihart	Indiana University	1990-92
David Baxter	Indiana University	1992-2001
Jurgen M. Honig	Purdue University	1990-2001
Wai-Yim Ching	University of Missouri	1990-92
Meera Chandrasekhar	University of Missouri	1992-2001
James C. Garland	The Ohio State University	1990-95

Thomas Lemberger	The Ohio State University	1995-2001
Robert J. Gottschall (DOE Rep)	U.S. Dept. of Energy	1990-2001
John Mundy DOE Program Manager	U.S. Dept. of Energy	1990-99
Peer Reviewers	University/Affiliation	Participation Date
Malcolm Beasley	Stanford University	1990-92
Stuart Wolf	U.S. Naval Research Lab	1990-92
Sungho Jin	AT&T Bell Labs	1990-90
Martha Greenblatt	Rutgers University	1990-98
Arthur Sleight	Oregon State University	1991-98
A. I. Schindler	Retired	1992-94
Lev Gorkov	Florida State University	1993-98
John Goodenough	University of Texas at Austin	1993-98
James Eckstein	Ginzton Research Center	1993-94
Don Gubser	U.S. Naval Research Lab	1993-98
Theodore H. Geballe	Stanford University	1993-98
Aharon Kapitulnik	Stanford University	1993-98
John B. Vander Sande	MIT	1994-98
Brian Maple	University of California-San Diego	1995-98
Paul Grant	EPRI	1995-98

APPENDIX VIII INDUSTRIAL AFFILIATES

Advanced Technology Materials, Inc.

American Superconductor Corporation

AT&T Bell Labs

Bellcore

Conductus, Inc.

DuPont Superconductivity

HYPRES, Inc.

IBM Thomas J. Watson Research Center

Intermagnetics General Corporation

Jet Propulsion Laboratory

Keithley Instrument Company

Lake Shore Cryotronics, Inc.

Lucent Technologies

National Institute of Standards and Technology

Plastronics, Inc.

Quantum Magnetics/Quantum Design

Ribbon Technology Corporation

Superconductive Components, Inc.

TRW Superconductivity Research

Public Service Indiana

Weizmann Institute of Science

Wright Patterson AFB