Summary Results of an Assessment of Research Projects in the

Superconductivity for Electric Power Systems Program

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Introduction

The Office of Program Analysis (OPA) undertook an assessment of 37 research projects (listed in Appendix A) sponsored by the High Temperature Superconductivity Program. The program is located within the Office of Energy Efficiency and Renewable Energy (EE). This report summarizes the results of that review.

The Office of Utility Technologies is responsible for the management of the High Temperature Superconductivity Program. This program focuses on assisting U.S. industry in bringing advanced, superconductive energy systems to commercial use.

The purpose of the assessment was to determine the following:

1. the quality of research of individual projects,
2. the impact of these individual projects on the mission of the program, and
3. priority future research targets and opportunities.

The assessment was conducted using the quantitative methodology developed by OPA for assessing the quality of research and development programs within the Department of Energy (DOE). This methodology is described in **Procedures for Peer Review Assessments, DOE/ST-0007P**. At the time of this review, it had been used by OPA in 26 prior assessments of over 2,000 projects in various DOE research programs.

The 37 research projects were reviewed by 5 panels of experts in review sessions held in Washington, D.C., during the second week of October and the third week of November 1992. The reviewers in each panel were expert in the technical area (e.g., wire

development) addressed by the 7-10 projects assigned to that panel. The reviewers participating in this assessment are listed in Appendix B.

Rating factors included project scientific and technical merit, mission relevance, appropriateness and level of innovation of the technical approach, quality of the project team, productivity, and probable impact on the program's mission. Each project was also given an overall evaluation supported with written comments.

Quality of the Projects Reviewed

A project's overall evaluation was rated on a scale from 0.0 to 10.0, with numerical values corresponding to a qualitative descriptor (e.g., outstanding, strong, good, needing management attention, or having serious shortcomings). Project overall evaluation ratings of 5.0 to 10.0 signify project quality ranging from good to outstanding. Descriptors below 5.0 identify projects with deficiencies or serious shortcomings that particularly warrant further review and attention from program management.

The figure on the following page summarizes the project overall evaluation ratings established for the 37 projects reviewed by the 5 panels.

A total of 33 projects (89 percent of those rated) were judged to be good or better (i.e., had project overall evaluations of 5.0 or higher). Of the projects, 19 projects (51 percent of those rated) were judged to be strong (i.e., rated 7.0 to 8.9), and one project was rated excellent. Four projects (11 percent) received project overall evaluation ratings lower than 5.0. The reviewers judged these to be projects with some deficiencies, or serious shortcomings, that need to be addressed by program management.

EE Superconductivity Research Peer Review

Overall Ratings of 37 Projects

NOTE: An outstanding project would rate 9 - 10. A strong project deserving of continuing priority support would score 7 - 8.9, while a good project with negligible important shortcomings would receive a score of 5 - 6.9. A project with some deficiencies or concerns that should be addressed would warrant a rating of 3 - 4.9 and a project with serious shortcomings which warrants close reevaluation would rank 0 - 2.9.

Targets for Future Research

Described below are some of the research needs and opportunities identified by the reviewers in the areas of wire development, deposited film technology, and systems development.

Fundamental Pinning Studies

The lack of a fundamental understanding of the pinning mechanism(s) limits the interpretation of the vast majority of the superconducting properties of developmental conductors. Such understanding could lead to a dramatic increase in critical currents by simple changes in processing. Because at present the High-Temperature Superconductivity (HTS) materials are being developed in a very empirical approach, even some simple understanding could provide significantly better products more quickly and efficiently.

Work with model systems is necessary in order to pursue investigations of the flux pinning properties and intrinsic limits for transport currents in HTS materials. Sets of samples with controlled variations in microstructure should be fabricated and characterized physically and electromagnetically. These samples should include high quality single crystals (for example with controlled radiation damage), elements of practical wires (such as textured Bi-2223 and Tl-1223), and both thin and thick films.

Any intrinsic pinning studies should include both theoretical and experimental studies on the simplest systems possible. The theoretical studies should focus on predictive models that could guide the experimental choice of pinning centers.

If flux pinning defects can be identified, it

should be possible to introduce more of them. This would lead to enhanced pinning and should increase the temperature to which the defects are effective due to collective pinning. In addition, knowledge of the existing pinning defects may lead to identification of other defects which may have stronger pinning potential but are not currently present. There is a need to identify existing flux pinning defects, and develop strategies for introducing additional sites in a controlled manner during processing.

Tl-based and Bi-based HTS materials are attractive for wire development because of their very high T_c and relatively forgiving grain boundaries. These materials suffer a common deficiency: weak flux pinning. This weak pinning limits the achievable critical current densities (J_c) and the range of useful operating temperatures and magnetic fields.

The approaches to improving pinning could include: chemical modification/substitution studies, introduction of pinning centers through improved processing to modify the microstructure, optimization of growth related defects, radiation damage, and intentional introduction of precipitates.

Flux pinning in superconducting materials is directly influenced by microstructures, including point defects, dislocations, domain boundaries, stacking faults, and impurity precipitates. The number, density, and size distribution of the above microstructural features affect directly the critical current density. By controlling the nature and density of these defects, current densities can be optimized in these materials.

Many new HTS materials have been discovered besides 123, Bi- and Tl-based materials, and more are being reported on nearly a weekly basis. Most of the reports

discuss preparation details and the superconducting transition temperatures, T_c , only. These new materials should have their intrinsic flux pinning characteristics measured as part of the standard data description for material properties.

It has been demonstrated that pinning mechanisms exist in YBCO films which are not present in the bulk. No such information exists for thin BSCCO tapes, as related to the bulk material. Can flux pinning be improved in BSCCO by material additions or through manipulations of the tape morphology? This is an area that merits further attention.

Mechanical Characterization of Conductors and Constituent Materials

An extensive mechanical properties data base is needed to establish critical parameters for the design and fabrication of HTS coils, the description of mechanical properties as a function of temperature of prototype conductors (in final form), and the characterization of constituent materials (in raw form). Specific properties needed by designers include but are not limited to: coefficient of thermal expansion, bulk compressibility, elasticity, hardness, fatigue due to thermal cycling, fatigue due to flexing, and dependence of $J_c(B,T)$ on mechanical stress. The choice of the "most promising route to practical applications" may be dictated as much by mechanical strengths and weaknesses as by superconducting properties.

There is a need for advanced Non-Destructive Evaluation (NDE) characterization techniques to evaluate both the microstructural and electromagnetic properties of HTS materials to facilitate online monitoring of material properties and structure during processing. Such techniques would be used to monitor micro- and macro-defects in the microstructure which may lead to failure of the ceramic.

Research issues in the area of HTS wires include investigating and developing an understanding of the mechanisms of degradation or failure. The electrical property degradation with respect to time, thermo-mechanical cycling, and environmental conditions needs to be investigated under the range of expected operating conditions. Mechanical degradation in the strength and integrity of the wire due to thermo-magneto-mechanical interactions also deserve study. The interaction of the high Lorentz forces could cause high stresses in the relatively weak platelet boundaries and lead to fatigue failure at these boundaries as a result of repeated loading cycles; such changes in the microstructure will influence the current carrying capability of the wires. Most of the studies have concentrated on the mechanical behavior at room temperature, but the properties must be investigated under more realistic conditions that typically involve combined loading due to thermal, magnetic, and mechanical factors. Mechanical property investigations and component design should be carried out with the promotion of graceful failure rather than catastrophic failure in mind.

Current approaches to long-length production of superconductors require extensive repetitive deformation experiments, where processing variables are neither well-controlled nor understood. The mechanisms by which mechanical processing affects wire thickness variations, core continuity and uniformity, and transverse versus lateral crack development will need to be controlled. Understanding of process instabilities which can lead to core diameter variations and development of means to minimize the amount of noble metal are all significant manufacturing issues that need to be addressed.

A coupling of mechanical processing analysis and in situ investigations of wire structure and uniformity would add to our understanding of

what process parameters need to be controlled and within what limits. Imaging techniques that have potential for being employed include x-radiography, flash laminography, optical microscopy plus real-time video of composite conductors during deformation, or SEM with mechanical deformation stages for studies of strain development, crack formation, and texturing during plastic deformation.

Constitutive equation-based processing has been crucial in the development of net-shape forming of parts from intermetallic powders. Software which describes the rheology of the deformable system has already been incorporated in a DOE Cooperative Research and Development Agreement (CRADA) at Lawrence Livermore National Laboratory in collaboration with Sandia National Laboratory. Such tools could be extended to the processing of ceramic superconductor powder in metal matrix and sheath approaches to enable science-based control over deformation processing.

This science-based constitutive equation approach to deformation combined with in situ structure characterization of wires during deformation will greatly shorten the cost and time path for development of successful deformation processing of long length ceramic superconductors.

Melt-textured YBCO has been shown to have the highest current carrying capability at 77K among HTS. Values of J_c in excess of 30,000 Amp/cm² at 2 tesla are currently achieved in this material. At room temperature, however, the material is brittle and difficult to fabricate in wire form using conventional means.

Recently, it has been demonstrated at elevated temperatures, that melt-textured YBCO yields and flows at relatively low stresses, and that it can be extensively deformed (in excess of 50 percent strain). The mechanism of

deformation at these temperatures is believed to be a combination of slip and grain boundary sliding. In addition, the high-temperature deformation results in enhancing the current density and also reducing the current density anisotropy exhibited by this material. The exact characteristics of this behavior is not yet determined and needs to be developed. This high-temperature deformation gives promise for the fabrication of superconducting wires using melt-textured YBCO.

The studies of stresses and fracture toughness behavior of the high T_c superconductor materials, especially for conductor and magnet applications, are useful. The HTS conductors mostly consist of composite structure involving ceramic and metallic materials with considerably different physical properties and associated interfacial stresses. The anticipated reliability problems in solenoid fabrication, handling, Lorentz force during operation, etc., need to be addressed through the studies of mechanical behavior.

Bi-2223 Wires

A major impediment to the reproducible fabrication of high J_c Bi-2223 wires is the lack of understanding of their high-temperature chemistry. Detailed thermodynamic studies would optimize the starting phases used to form Bi-2223, the overall Bi-2223 composition, and the time-temperature-oxygen pressure combinations used during processing. For a multicomponent system like Ag-Pb-Bi-Sr-Ca-Cu-O, coulometric titration is probably the only viable technique for obtaining this information. A few thermodynamic studies of the Bi-Sr-Ca-Cu-O system in air or one atmosphere oxygen at a fixed temperature have appeared. While these studies provide a good starting point for more detailed work, they do not address such critical issues as: the effects of lead and silver on Bi-2223 stability, the possible formation of transient liquids during

processing, and changes in Bi-2223 stability and solid solubility as a function of temperature and oxygen pressure.

The current strategy for fabricating Bi-2223 Oxide-Powder-In-Tube (OPIT) wire is to load the tube with powder that is not fully reacted to Bi-2223 and perform the final reaction in the wire. Empirically, it is often found that two powders of identical overall composition which have been synthesized identically and are indistinguishable by X-Ray Diffraction (XRD), result in OPIT wires with different microstructures, phase assemblages, and electromagnetic properties after identical thermal processing. Making reproducible Bi-2223 wires will not be possible until the powder can be made and processed in a reproducible manner.

There is a clear need to be able to characterize powders and identify the important parameters that distinguish one powder from another: to identify and quantify all of the phases (particularly the nonsuperconducting phases) present in the powder mixtures that are loaded into tubes, and to identify those powder characteristics (phases, size distribution, moisture, etc.) that will be predictive of how powders will react during wire formation.

Thermomechanical processing of OPIT materials is the most widely applied approach to processing long length conductors. Superior conductor properties have been achieved in silver-clad tapes of Bi-2223. While it is generally perceived that deformation helps achieve texture and results in materials that are not weak linked, basic understanding of the deformation process is lacking. Currently available information is highly empirical.

The constitutive behavior of superconductor powders in a variety of phase assemblages, of silver-oxide powder mixtures, and of tubes and tapes of silver containing these powders, are

all of interest for fabricating uniform long length conductors. The relationship between deformation under a variety of stress states representing rolling, drawing, extruding, etc., and superconductor texture needs to be understood. Basic information of this nature will guide the development of optimal conductor fabrication strategies.

Thallium Oxide Systems

An obvious need exists for the determination of phase equilibria diagrams in systems containing thallium oxide as one of the components. The first and most basic need is for a temperature versus Tl_2O pressure diagram at oxygen pressures both below and above one atmosphere, in order to delineate the equilibrium regions of $Tl/Tl_2O/Tl_2O_3$ as well as a vapor pressure decomposition diagram. Secondly, we need "binary" phase equilibria diagrams of temperature/composition at various partial and/or total oxygen and thallium oxide pressure for the systems containing thallium oxide-alkaline earth oxides (CaO , SrO , BaO) as well as for TlO_x-PbO_x and TlO_x-BiO_x ; and probably those with TlO_x-ReO_x as well. "Ternary" phase diagrams are then needed for TlO_x and mixed alkaline earths, particularly $TlO_x-BaO-CaO$, but also the other combinations. The four component equilibria are also needed for $TlO_x-BaO-CaO-CuO_x$. These diagrams are not going to be easy to obtain, but starting the 4-component system without knowledge of the binary and ternary systems is hopeless. Expert experimental analyses of the basic thallium oxide binary and ternary phase equilibria diagrams are badly needed.

YBCO Wire

Research is needed to develop practical manufacturing methods for long melt textured Y-123 wires in a metal-stabilized multifilament configuration. These wires will enable high

magnetic field/high critical current density applications at 77K. This research should involve extensions of currently proven techniques as well as exploration of novel approaches.

Y-123 has strong intrinsic pinning and is the only material with a transport critical current density in excess of 10^4 A/cm² in 2 tesla at 77K. Several groups have demonstrated melt textured wires up to a meter long that are compatible Ag-Pd alloys. Logical extensions of this research include: methods to increase the speed of solidification, methods to increase the overall production rate by using multiple solidification zones, and improved metal sheath and/or substrate materials.

Successful production of long lengths of high J_c wires from 123 type materials will require overcoming the problem of weak links. The approach of producing textured materials by melt processing fails to achieve the high growth rate in Y-123 which is required for broad industrial usefulness. The low growth rate is due to the peritectic decomposition of the Y-123 composition.

Phase equilibrium studies have shown different solid compatibility relations for the rare earth systems. While the possibility of a congruently melting RE-123 material is small, increased growth rates may be possible for some Rare Earth (RE) substitutions. Also, the ability of RE elements to substitute on the Ba sites allows a degree of nonstoichiometry not possible in Y-123. This may also allow faster processing of melt textured 123 materials for wire applications. How the different solid relations influence the liquidus relations and whether such differences will improve the processing of 123 wire merits attention.

Grain boundaries in high- T_c materials limit current carrying capability by providing weak links due to short coherence length in these

materials. If these boundaries can be modified structurally or chemically to suppress weak links, the critical current densities can be enhanced considerably. This will lead to significant advancement in the usage of polycrystalline high T_c materials.

Alloys Compatible with HTS

While it is known that only silver and more expensive (gold, platinum, and palladium) metals are compatible with HTS, there is reason to believe that a 'metal' matrix alloy can be developed which has both chemical and mechanical compatibility with one or more HTS materials.

Just as iterative and Edisonian approaches led to the development of stainless steel, once considered as an impossibility, a similar approach with respect to HTS in which Sessile drop-type experiments are conducted with silver alloys first and even nickel and iron base alloys could be worthwhile. In particular, the latter materials melt well above 1000°C and would thus permit melt-texture processing in situ to allow wire processing on a large scale.

Scale-Up Technology

For HTS materials to be useful conductors in wire applications, development of processing techniques for producing long (several km) wire is important. Similarly, there are many applications (tape, conformal coatings, and magnetic shields) where large area films are needed. Studies in area and length scale-up will be a necessity.

The scale-up studies will necessarily be material specific. For Tl-based materials, for example, continuous processing studies for electrodeposition should be initiated. For Bi-based compounds, attempts at continuous tape processing or improvements of Powder-In-Tube (PIT) processing should be emphasized.

For Y-based materials, continuous processing techniques consistent with the requirements of in plane grain alignment should be initiated. These areas of investigation could utilize grain aligned metallic substrates.

The research projects are typically staffed by materials scientists and physicists with few staff having the engineering skills needed for scaling up to true manufacturing levels. A suggested approach is to identify a process currently under development and which is one of those furthest along and put together an experienced scale-up team of development engineers to work with the materials scientists. Because of its more universal appeal, such an activity should probably be aimed at one of the PIT processes now under development.

Tape Conductors

High-Temperature Superconductivity conductors based on thick films deposited on flexible metal substrates are the primary alternative to more traditional wire configurations in which a larger effort has been invested. Historically, tapes have been used successfully for superconductors with desirable electrical properties but intractable processing problems, notably, Nb_3Ge . The major advantages are the accommodation of alternative HTS compounds to BSCCO and unique opportunities to control the texture, microstructure, and flux pinning in the superconductor. They offer the best opportunity for joining lengths of conductor without significant losses at the joint.

High-Temperature Superconductivity tape conductors require a high-rate, continuous process for the deposition of thick films. The process must compete on both technical and economic bases with the multiple deformation processes used for other conductor configurations. Several promising approaches (electrodeposition, electrophoresis, and spray

techniques) deserve investigation as part of efforts focused on high-current tapes. For the deposited-film approach to be commercially viable, the ratio of film thickness to substrate thickness must be maximized.

Although most of the worldwide effort in HTS conductor development has been based on the BSCCO compounds for their mechanical properties and relatively forgiving grain boundaries, YBCO and the 1223 phase of TBCCO have much better flux pinning properties at liquid nitrogen temperatures. One of these compounds could dramatically alter the status of conductor development if an appropriate conductor configuration can be found which takes advantage of their superior properties. The tape conductor configuration is one viable approach for further evaluating the potential of these compounds but is not the only possible approach.

The investigation of interactions between superconductors and supporting materials (usually silver and silver alloys) can best be performed by examining the interface between substrates and superconducting films. For a PIT conductor, this represents a model system. For tape conductors, the properties of this interface are critical to the conductor performance. Of particular interest is the effectiveness of buffer layers or diffusion barriers in preventing a deleterious interaction.

It would be desirable to develop new, convenient, high-speed, biaxial texturing techniques for long YBCO conductor fabrication, as YBCO has the best flux pinning properties among the three main HTS compounds. Unlike BSCCO or TBCCO, the YBCO material tends to exhibit more severe weak-link behavior even in the C-axis textured configuration, and hence requires essentially perfect (bi-axial) alignment of grains. The use of textured metallic substrates or texture-

inducing buffer layers for thick film deposition could be explored.

Magnetic shielding, accelerator cavities, and low frequency antenna structures are examples of HTS applications which require deposition of HTS coating on complex-non-planar surfaces. It is proposed that in addition to currently investigated methods of magnetron sputtering or laser deposition, a wider range of techniques be investigated. Possible deposition approaches include electrophoresis, spray pyrolysis, plasma spray, electro-deposition, sol-gel, and others as appropriate.

In wire drawing and rolling, the softness of the silver compared to the superconductor is a concern which has been addressed through solution strengthening and dispersion strengthening. Would it be worthwhile to draw or swage the silver at very low temperature? The increased yield strength and work hardening may decrease the disparity between the silver and the superconductor to alleviate "sausaging."

The effect of the silver/superconductor interface on texture development needs to be clarified so it can be better exploited into the wire development program. More detailed study of the interface should be carried out as part of microstructural characterization of tapes and wires. Processing optimization should include a systematic study of variables that will improve texturing at the interfaces.

Low-temperature Cooling Systems

The specifications for high T_c materials depend critically on the operating temperatures that can be easily and economically attained. Designing a better cooling system may be a more solvable problem than trying to increase the maximum operating temperature of a particular superconducting material by introducing flux pinning centers. Thus, efforts to see that improved cooling systems are developed for high T_c wires is merited.

APPENDIX A

List of Research Projects Reviewed

HTS Applications

Feasibility of MHD Ship Propulsion Using HTS Magnets

Nondestructive Evaluation of HTS Ceramics: A) Neutron Diffraction and Ultrasonics; B) Microradiographic Imaging

Cryogenic Design of an HTS Motor

Near Term Applications of High-Temperature Superconductors

HTS Coil Development for Electric Power Applications

Demonstration of Magnetic Refrigeration for HTS Equipment Applications

Superconducting Characterization

Practical Conductor Development for Electric Power Systems Utilizing HTS Oxides: Device-Technology Development Task

Deposited Conductor Development

HTS Electronic Devices and Applications

Investigation of the Synthesis and Processing of Thallium-Based HTS Films

HTS Thin Film Materials Development

Microwave Cavities

HTS Conductor Development Using Electrodeposition

Oxidation of Metals and Alloys with Emphasis on Superconducting Oxides

HTS Powder Synthesis By Aerosol Pyrolysis

Synthesis and Characterization of Tl Superconductors

Critical Process Research on Material Synthesis of HTS Conductors

Critical Current and Vortex Dynamics

Synthesis and Fabrication of Superconductors with Controlled Defects

HTS Powder Synthesis/Tape Processing

Grain Boundary Chemistry and Pinning Site Generation in Y- and RE-123 and Y-124

Practical Conductor Development for Electric Power Systems Utilizing HTS Oxides: Conductor Development Task

Microfilamentary Conductors

Melt Process Routes for Conductor Fabrication

Melt Processing of HTS Conductors

Phase Formation/Stability of HTS Conductors

Process Development of HTS Wire and Tape

Microstructural Development of HTS Materials with Improved Properties

HTS Deformation Processing and Mechanical Properties

Microstructural Evolution in Bulk Conductor Processing

Mechanical Processing of Superconducting Wires

Conductor Development by Thermo-Mechanical Processing

Commercially Viable HTS Wire Program

APPENDIX B

Reviewers

Timothy Armstrong
Pacific Northwest Laboratory

Robert Beyers
IBM

John Blendell
National Institute of Standards
and Technology

Key Youngdahl Blohowiak
Boeing Defense and Space Group

Roger W. Boom
University of Wisconsin-Madison

John Bower
Babcock and Wilcox

Donald Bowling
Naval Weapons Center China Lake

Samuel Brown
Naval Surface Warfare Center
Annapolis

Julian Cave
IREO

Yet-Mingh Chiang
Massachusetts Institute of
Technology

Dale Chimenti
The Johns Hopkins University

Owen Christensen
Westinghouse Electric Corporation

Wei-Kan Chu*
University of Houston

Minh Chyu
Texas Tech University

Alan Clark*
National Institute of Standards
and Technology

Mark Robert Deguirre
Case Western Reserve University

John A. Deluca
General Electric Corporate Research

Dave Divecha
Naval Surface Warfare Center

Christopher Fortunko
National Institute of Standards
and Technology

Steven M. Green
Neocera, Inc.

John W. Halloran*
University of Michigan

Eric Hellstrom
University of Wisconsin at Madison

Alan Herman
University of Colorado at Boulder

Sungho Jin
AT&T Bell Laboratories

D. Lynn Johnson*
Northwestern University

Wen Y. Lee
IBM

Greg Lyons
Massachusetts Institute of
Technology Lincoln Laboratories

John McDevitt
University of Texas at Austin

Jagdish Narayan
North Carolina State University

Charles E. Oberly
Wright Laboratories

K. Ravi-Chandar
University of Houston

Alexana Roshko
National Institute of Standards
and Technology

Robert S. Roth
National Institute of Standards
and Technology

Kamel Salama
University of Houston

Justin Schwartz
University of Illinois

E. Anne Sivers
T&W Equipment Company

John Talvacchio*
Westinghouse STC

Clyde E. Taylor
Lawrence Berkeley Laboratory

Kenneth E. Tempelmeyer
Southern Illinois University

William H. Warnes
Oregon State University

Jack H. Wernick
AT&T Bell Laboratories

L. D. Woolf
General Atomics

***Chairperson**

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