SUPERCONDUCTIVITY
FOR ELECTRIC SYSTEMS

High Temperature Superconductivity

# PROGRAM MANAGEMENT REPORT

FY2004/FY2005

Office of Electric Transmission and Distribution
U.S. Department of Energy
October 2004

# U.S. Department of Energy Superconductivity for Electric Systems Program Management Report FY2004-FY2005

## Executive Summary

The U.S. Department of Energy (DOE), Office of Electric Transmission and Distribution leads the Federal role in developing electric power applications of high temperature superconductivity (HTS). This Management Report will address the programs financial report and operating plans along with its performance-based activities for FY2004-FY2005. The Program, Superconductivity for Electric Systems, conducts a rigorous, performance based, Peer Review during the month of August every year. This program assessment was established in 1990, as a broad applied research effort to provide a public forum to evaluate the progress of each project and the overall program. The annual Peer Review has played an important role in the program's success. Approximately 180 people attended the peer review in 2004, and 34 world renowned experts participated as reviewers. The program was reviewed in four separate sessions to evaluate the progress in different parts of the research. The Second Generation Wire Panel reviewed the progress being made with superconducting wire; the Superconductivity Partnerships with Industry Panel evaluated the progress and innovations made with superconducting applications; Strategic Research reviewed characterization and coated conducted technologies; and University Research was evaluated for the progress in University projects. During the 30 days preceding the Peer Review, reviewer comments were compiled, scores were analyzed, project rankings and priorities were determined. Results were reported. The formal Peer Review process was concluded with a post-review assessment meeting and presentation of awards for the best project evaluated by each review panel.

This report provides documentation on the support, planning, and activities involved in the Superconductivity with Electric Systems program. This has been accomplished through analyzing the challenges and achievements of the program. This report will examine, evaluate, and assess the programmatic and technical aspects of the Superconductivity for Electric Systems Program from its achievements in the 2004 fiscal year through its recently funded 2005 fiscal year. This report will encompass the programs two year funding, annual peer review and guidance, along with the projects that have been currently undertaken during this period. A project priority listing has been added to the financial reports identifying projects that are currently the most promising to the industry, using a 1-5 scale, one being the most important and five the least. This report will not present or review specific technical approaches to each project, but will rather discuss the program, project sessions and review processes implemented.

Present Second Generation Wire development activities focus on coated conductor technology, magnetic field tolerance, characterization, and raising the current-carrying capacity in short samples of wire. The program supports the technology improvements needed to allow industry to manufacture long wire lengths that have the equivalent performance to that shown in short experimental lengths. The Second Generation Wire Development Groups research emphasized work at Los Alamos National Laboratory and Oak Ridge National Laboratory to scale-up scientific breakthroughs in properties of short samples to provide industrial manufacturing of

wire with unprecedented performance and low cost. Research on continuous processing of long length wires will continue throughout the years discussed in this report.

Superconductivity Partnerships with Industry activities are carried out mainly by vertically integrated teams composed of a technology user, a manufacturer, and an HTS wire supplier using DOE cost-sharing. The project teams usually include a DOE National Laboratory. SPI projects receive quarterly reviews at field locations in addition to the annual peer review. The SPI portfolio in FY2004 includes nine projects: one cable project, a matrix fault current limiter, a generator, readiness review team (risk mitigation), magnetic separation, a flywheel electricity project, a motor, a transformer, and an open geometry HTS MRI system. In 2005, three new cable projects will begin and the MRI project will be completed.

Strategic Research projects are primarily designed to investigate new approaches in analyzing or producing superconductivity technologies and applications. The research is focused on higher risk projects that will have a more substantial effect on the industry in the long-term, but have not reached its full scientific potential. In 2004 and 2005, nine projects will continue research on improving conductor pinning, buffer layer work, scaling up the width of HTS tapes, improving phase relationships and processing with IBAD and coated conductors, along with overall performance improvements using HTS wires.

University research supports the HTS development by contributing to the Strategic Research component of the program. The Universities work with National Laboratories and industry in conducting the core research needed to support both the Second Generation Wire Development and systems evolution in the Superconductivity Partnerships with Industry. In 2004, there will be seven university projects working on various facets of characterization, buffer thickness, and coated conductor technologies. In 2005, only two projects will continue throughout the year. They are: Conversions of Oxy-Fluoride Based Coated Conductors and Buffer Layer growth and the Thickness Dependence of $J_c$ in Coated Conductors.

The DOE program in Superconductivity for Electric Systems has invested many years to produces a peer review process that is tailored to the unique R&D environment ad is logical, rational, meaningful, and above all, can be effectively implemented , and add value to the national laboratories and their HTS development projects. The peer review process, as practiced by the DOE Superconductivity Program, is credited with providing the following value:

- Continuous improvement of program quality
- Accountability and responsible use of public funds
- Evaluating researchers' performance in a public forum and allowing an active exchange and sharing of information and data
- Management tool for good decision making
- Expert, external inputs that assist managers to effectively and efficiently allocate resources, establish program priorities, scope, direction, and spend plans for subsequent fiscal years.

Reviewers are asked to comment on the program's strengths, weaknesses, and to give their general impressions and recommendations concerning mission and goals, productivity and accomplishments, R&D plans, research coordination, and technology transfer.

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# Background

The National Superconductivity and Competitiveness Act of 1988 (Public Law 100-697) established the Program in Superconductivity for Electric Systems within the Department of Energy. This program was initiated to commercialize the use of high temperature superconductors to take advantage of the energy, economic, and environmental potential of the newly discovered properties. The discovery of high temperature superconductivity (HTS) in 1986 was so exciting that the discoverers were awarded a Nobel Prize in Physics the following year. These superconductors are a new class of ceramic materials that carry large electrical currents without energy losses due to resistance, and the superconductors operate at much higher temperatures than were previously thought possible. This breakthrough was considered comparable to other discoveries that have fundamentally changed modern technology: the transistor, the laser, and fiber optics.

The Department of Energy developed a program in applied HTS research that would generate the technology needed for U.S. industry to produce future energy products. A number of public-private partnerships have been initiated by the program to make use of the exceptional research capability of the DOE National Laboratories and to support strong entrepreneurial spirit of U.S. industry. The public-private partnerships included cost sharing and other incentives to encourage joint projects between private companies and national laboratories. U.S. industry provides leadership in all program activities, while DOE laboratories and universities have a key role in solving fundamental problems.

HTS materials are a family of ceramics whose brittleness and granularity has presented a major challenge to the discovery of processing methods that deliver the needed strength and flexibility expected of an alternative to conventional copper wire. The manufacturing processes under consideration includes those techniques for deposition used by the coatings industry and the thin-film industry.

The Superconductivity for Electric Systems Program benefits from HTS research in other Federal programs, chiefly in the DOE Office of Science, and the National Institute for Standards and Technology, in the Department of Defense, and in the National Science Foundation. Program funding is this highly leveraged to provide the many accomplishments seen in the last few years. Participating companies have set most of the world's recent HTS benchmarks, and these companies are positioned to compete for the several billion dollars per year international market for HTS applications that are expected to develop over the next 10 years as commercial versions of the technology are introduced.

HTS power equipment is beginning to undergo filed trial at a critical time for the electric power industry. The electric grid is undergoing severe stresses due to an aging infrastructure (A majority of transformers and other equipment are at or past their design lifetimes), demand growth (largely, due to the unanticipated growth in electronics and computer use), and the growth of competition in the electric industry that is creating the need to develop new pathways for delivering power. HTS equipment will be more reliable and have higher capacity ratings than conventional alternatives. The timing is right to create a market pull for this equipment that coincides with the technology moving from the laboratory to filed application

The Superconductivity Program's peer review process was well established when the Government Performance and Results Act (GPRA) of 1993 (Public Law 103-62) was passed into paw. GPRA requires federal agencies to develop strategic plans, annual performance plans, and performance measures, to gauge progress in achieving the planned targets. Peer review performance results and supplementary qualitative performance measures effectively respond the GPRA evaluation requirements.

## FY2004 Funding

Every year an Annual Operating Plan is developed identifying the funding and actions that can be undertaken for the fiscal year. In FY2004, $33,649,000 million was awarded to the Superconductivity for Electric Systems program.  This spend plan was designed to help fund and promote superconductivity technology into commercialization. The Second Generation Wire, Superconductivity Partnerships with Industry, Strategic Research, and University Research funding are discussed in great detail. The following two documents are the FY2004 budget and the FY2004 Annual Operating Plan.

# *FY2004 Financial Report with Project Prioritization*

**1-HTS Power Delivery System, 2-HTS GE Generator Plant, 3-Eastern Interconnection, 4-PJM Interconnection, 5-Three Energy Storage Systems, 6-Gridwise Partnership Expansion, 7-Silicon Carbide Research Begins, and 8-Project Tracking System*

| Priority (#) | Project Title/ Description/ Comments (text) | Prime Contract/ Recipient/ Contact Name (Indicate Small Business with SB) | Laboratory Name and Percent Involvement (Use Four Letter Abbreviation; % of work) | Large Subcontract (If Small Business Give % of Work) | FY 2004 Funding ($) | B&R Code (STAR Equivalent) | Original (Planned) Obligations ($) | Obligated ($) | Costed ($) | Competitive Contract=CC, Non-Competitive Contract=NC, Grant=GR, Cooperative Agreements=CA, Earmark=EM | Peer Reviewed (Y or N) | DOE's Cost Share (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Office of Electric Transmission and Distribution** | | | | | | | | | | | | |
| **High Temperature Superconductivity R&D** | | | | | | | | | | | | |
| 3 | Post-doctoral Research Fellows Program | UT-Battelle/R. Hawsey | ORNL 0% | OR Inst of Science Ed | $ 450,000 | TD5001.12 | $ 450,000 | $ 450,000 | $6,369,777 (June 30); | CC | N | |
| 3 | HTS Outreach and Systems Analysis | UT-Battelle/R. Hawsey | ORNL 0% | Bob Lawrence and As | $ 40,000 | TD5001.13 | $ 40,000 | $ 40,000 | | NC | N | |
| 2 | Technical and Analytical Support for HTS | UT-Battelle/R. Hawsey | ORNL 0% | Energetics, Inc-Badin | $ 250,000 | TD5001.13 | $ 250,000 | $ 250,000 | | CC | N | |
| 3 | Research Assistance on HTS Processing | UT-Battelle/R. Hawsey | ORNL 0% | Imtech Corp. | $ 10,000 | TD5001.13 | $ 10,000 | $ 10,000 | | NC | N | |
| 3 | High Voltage Breakdown Studies | UT-Battelle/R. Hawsey | ORNL 0% | Marshall Pace & M.S. | $ 25,000 | TD5001.12 | $ 25,000 | $ 25,000 | | NC | N | |
| 3 | Phase diagram research | UT-Battelle/R. Hawsey | ORNL 0% | NIST-Gaithersburg | $ 250,000 | TD5001.12 | $ 250,000 | $ 250,000 | | IA | Y | 50% |
| 3 | Mechanical Properties of BSCCO and YBCO | UT-Battelle/R. Hawsey | ORNL 0% | NIST-Boulder | $ 200,000 | TD5001.12 | $ 200,000 | $ 200,000 | | IA | Y | 50% |
| 3 | Solution-based Buffer Layer R&D | UT-Battelle/R. Hawsey | ORNL 0% | University of Tenness | $ 150,000 | TD5001.12 | $ 150,000 | $ 150,000 | | CC | Y | |
| 3 | Buffer layer R&D with PVD Techniques | UT-Battelle/R. Hawsey | ORNL 0% | University of Tenness | $ 120,000 | TD5001.12 | $ 120,000 | $ 120,000 | | CC | Y | |
| 1 | Coated Conductor research | UT-Battelle/R. Hawsey | ORNL 0% | American Supercondu | $ 845,000 | TD5001.12 | $ 845,000 | $ 845,000 | | CC | Y | 50% |
| 2 | Program Planning and Analytical Services | UT-Battelle/R. Hawsey | ORNL 0% | TMS Inc | $ 100,000 | TD5001.13 | $ 100,000 | $ 100,000 | | CC | N | |
| 3 | Project Management, Analysis, Outreach | UT-Battelle/R. Hawsey | ORNL 100% | | $ 442,000 | TD5001.12 | $ 442,000 | $ 442,000 | | CC | Y | |
| 1 | ORNL Program Director Taxes/State | UT-Battelle/R. Hawsey | ORNL 100% | | $ 155,000 | TD5001.12 | $ 155,000 | $ 155,000 | | CC | N | |
| 1 | Southwire SPI | UT-Battelle/R. Hawsey | ORNL 100% | | $ 1,760,000 | TD5001.13 | $ 1,760,000 | $ 1,760,000 | | CC | Y | 50% |
| 1 | Waukesha SPI | UT-Battelle/R. Hawsey | ORNL 100% | | $ 325,000 | TD5001.13 | $ 325,000 | $ 325,000 | | CC | Y | 50% |
| 1 | General Electric SPI | UT-Battelle/R. Hawsey | ORNL 100% | | $ 255,000 | TD5001.13 | $ 255,000 | $ 255,000 | | CC | Y | 50% |
| 1 | SuperPower CRADA: MFCL | UT-Battelle/R. Hawsey | ORNL 100% | | $ 55,000 | TD5001.13 | $ 55,000 | $ 55,000 | | CC | N | 50% |
| 1 | SPI Technical Advisory Committee | UT-Battelle/R. Hawsey | ORNL 100% | | $ 104,000 | TD5001.13 | $ 104,000 | $ 104,000 | | CC | N | |
| 3 | YBCO Quench and Stability Res. | UT-Battelle/R. Hawsey | ORNL 100% | | $ 150,000 | TD5001.12 | $ 150,000 | $ 150,000 | | CC | Y | |
| 3 | Cryogenics Analysis & subcontract m | UT-Battelle/R. Hawsey | ORNL 100% | | $ 35,000 | TD5001.12 | $ 35,000 | $ 35,000 | | CC | N | |
| 1 | Oxford CRADA: RABiTS Develop. | UT-Battelle/R. Hawsey | ORNL 100% | | $ 25,000 | TD5001.12 | $ 25,000 | $ 25,000 | | CC | Y | 50% |
| 1 | AMSC CRADA: YBCO/RABiTS Research | UT-Battelle/R. Hawsey | ORNL 100% | | $ 815,000 | TD5001.12 | $ 815,000 | $ 815,000 | | CC | Y | 50% |
| 1 | SuperPower CRADA: RABiTS/PLD | UT-Battelle/R. Hawsey | ORNL 100% | | $ 50,000 | TD5001.12 | $ 50,000 | $ 50,000 | | CC | Y | 50% |
| 3 | Strategic Res.: PLD and Phys. Prop. | UT-Battelle/R. Hawsey | ORNL 100% | | $ 500,000 | TD5001.13 | $ 500,000 | $ 500,000 | | CC | Y | |
| 1 | Strategic Res.: Superconducting Mat. | UT-Battelle/R. Hawsey | ORNL 100% | | $ 900,000 | TD5001.13 | $ 900,000 | $ 900,000 | | CC | Y | |
| 1 | Strategic Research: Substrates | UT-Battelle/R. Hawsey | ORNL 100% | | $ 824,000 | TD5001.12 | $ 824,000 | $ 824,000 | | CC | Y | |

# *FY2004 Financial Report with Project Prioritization Continued*

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ACCI Scale-up reaearch-ORNL | UT-Battelle/R. Hawsey | ORNL 100% | | $ 400,000 | TD5001.12 | $ 400,000 | $ 400,000 | | CC | Y | |
| 3 | HTS Assessment, Planning, | UT-Battelle/R. Hawsey | ORNL 100% | | $ 60,000 | TD5001.12 | $ 60,000 | $ 60,000 | | CC | N | |
| 2 | Wire Development Group | UT-Battelle/R. Hawsey | ORNL 100% | | $ 225,000 | TD5001.12 | $ 225,000 | $ 225,000 | | CC | Y | 50% |
| 2 | Flux Pinning Research | UT-Battelle/R. Hawsey | ORNL 100% | | $ 150,000 | TD5001.12 | $ 150,000 | $ 150,000 | | CC | Y | |
| 3 | BSCCO First Generation Wire (Wire Development Group) | U of Calif./D. Peterson | LANL 100% | | $ 225,000 | TD5001.12 | $ 225,000 | $ 225,000 | | CC | Y | 50% |
| 1 | YBCO Coated Conductor Tape Development with AMSC | U of Calif./D. Peterson | LANL 100% | | $ 225,000 | TD5001.12 | $ 225,000 | $ 225,000 | | CC | Y | 50% |
| 1 | Coated Conductor Tape Development with Superpower | U of Calif./D. Peterson | LANL 100% | | $ 850,000 | TD5001.12 | $ 850,000 | $ 850,000 | | CC | Y | 50% |
| 2 | Development of Magnesium Diboride Wires with Hypertech | U of Calif./D. Peterson | LANL 100% | | $ 200,000 | TD5001.12 | $ 200,000 | $ 200,000 | | CC | Y | 50% |
| 3 | Waste Water Treatment with Magnetic Separation | U of Calif./D. Peterson | LANL 100% | | $ 50,000 | TD5001.11 | $ 50,000 | $ 50,000 | | CC | Y | |
| 1 | Design and Development of a 100 MVA HTS Generator - GE | U of Calif./D. Peterson | LANL 100% | | $ 430,000 | TD5001.11 | $ 430,000 | $ 430,000 | | CC | Y | 50% |
| 1 | HTS MRI System – Oxford Instruments | U of Calif./D. Peterson | LANL 100% | | $ 200,000 | TD5001.11 | $ 200,000 | $ 200,000 | $5,640,000 (June 30); $6,200,000 (Sep. 30) | CC | Y | 50% |
| 1 | Current Controller – Superpower | U of Calif./D. Peterson | LANL 100% | | $ 50,000 | TD5001.11 | $ 50,000 | $ 50,000 | | CC | Y | 50% |
| 1 | Flywheel – Boeing | U of Calif./D. Peterson | LANL 100% | | $ 50,000 | TD5001.11 | $ 50,000 | $ 50,000 | | CC | Y | 50% |
| 1 | HTS Motor – Rockwell/Reliance Electric | U of Calif./D. Peterson | LANL 100% | | $ 50,000 | TD5001.11 | $ 50,000 | $ 50,000 | | CC | Y | 50% |
| 1 | Development of Coated Conductors based on IBAD MgO | U of Calif./D. Peterson | LANL 100% | | $ 1,500,000 | TD5001.12 | $ 1,500,000 | $ 1,500,000 | | CC | Y | |
| 1 | Coated Conductor Processing | U of Calif./D. Peterson | LANL 100% | | $ 1,500,000 | TD5001.12 | $ 1,500,000 | $ 1,500,000 | | CC | Y | |
| 2 | AC Losses in HTS Conductors (Devices) | U of Calif./D. Peterson | LANL 100% | | $ 170,000 | TD5001.11 | $ 170,000 | $ 170,000 | | CC | Y | |
| 2 | AC Losses in HTS Conductors (SR) | U of Calif./D. Peterson | LANL 100% | | $ 80,000 | TD5001.12 | $ 80,000 | $ 80,000 | | CC | Y | |
| 2 | Electron Beam Evaporation | U of Calif./D. Peterson | LANL 100% | | $ 620,000 | TD5001.12 | $ 620,000 | $ 620,000 | | CC | Y | |
| 1 | Coordinated Characterization of 2G wires with IGC-SuperPower | U of Chicago/U. Balachandran | ANL 100% | | $ 450,000 | TD5001.13 | $ 450,000 | $ 450,000 | | CC | Y | 50% |
| 1 | Phase Evolution & characterization of 2G wire with American Superconductor | U of Chicago/U. Balachandran | ANL 100% | | $ 300,000 | TD5001.13 | $ 300,000 | $ 300,000 | | CC | Y | 50% |
| 1 | Processing of 1st generation wires with American Superconductor | U of Chicago/U. Balachandran | ANL 100% | | $ 50,000 | TD5001.13 | $ 50,000 | $ 50,000 | | CC | Y | 50% |
| 1 | In-house R&D in the area of 2G wire fabrication by ISD process | U of Chicago/U. Balachandran | ANL 100% | | $ 166,000 | TD5001.12 | $ 166,000 | $ 166,000 | $1,100,000 | CC | Y | |
| 2 | Grad Students for In-house R&D in the area of 2G wire fabrication by ISD process | U of Chicago/U. Balachandran | ANL 100% | | $ 28,000 | TD5001.13 | $ 28,000 | $ 28,000 | | NC | N | |
| 3 | IEA Research and Analysis | U of Chicago/U. Balachandran | ANL 100% | | $ 45,000 | TD5001.12 | $ 45,000 | $ 45,000 | | CC | N | |
| 2 | Management and Peer Review | U of Chicago/U. Balachandran | ANL 100% | | $ 61,000 | TD5001.13 | $ 61,000 | $ 61,000 | | CC | N | |
| 1 | Practical conductor development utilizing High-Tc oxides: YBCO tape processing | Brookhaven Sci. Assn./D. Welch | BNL 100% | | $ 400,000 | TD5001.13 | $ 400,000 | $ 400,000 | $ 400,000 | CC | Y | |
| 1 | Practical conductor development utilizing High-Tc oxides: AC losses | Brookhaven Sci. Assn./D. Welch | BNL 100% | | $ 100,000 | TD5001.13 | $ 100,000 | $ 100,000 | $ 100,000 | CC | Y | |

# *FY2004 Financial Report with Project Prioritization Continued*

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Waukesha Electric Systems HTS Transformer Project | Waukesha Electric/E. Pleva | | | $ 400,000 | TD5001.11 | $ 400,000 | $ 200,000 | $ 200,000 | CA | N | 50% |
| 1 | Boeing HTS Flywheel Demonstration Project | Boeing/M. Strasik | | | $ 215,000 | TD5001.11 | $ 215,000 | $ 215,000 | $ 215,000 | CA | N | 50% |
| 1 | General Electric HTS Generator Demonstration Project | General Electric/J. Fogarty | | | $ 1,855,000 | TD5001.11 | $ 1,855,000 | $ 1,855,000 | $ 300,000 | CA | N | 50% |
| 1 | Dupont HTS Magnetic Separator Project | E.I. Dupont/C. Rey | | | $ 425,000 | TD5001.11 | $ 425,000 | $ 500,000 | $ 180,000 | CA | N | 50% |
| 1 | SuperPower HTS Cable Demonstration Project | SuperPower/C. Weber | | | $ 4,050,000 | TD5001.11 | $ 4,050,000 | $ 4,050,000 | $ 2,000,000 | CA | N | 50% |
| 1 | American Superconductor HTS Cable Demonstration Project | American Superconductor/M. McCarthy | | | $ 4,700,000 | TD5001.11 | $ 4,700,000 | $ 4,600,000 | $ 3,900,000 | CA | N | 50% |
| 1 | SuperPower HTS Matrix Fault Current Limiter Project | SuperPower/L. Kovalsky | | | $ 1,250,000 | TD5001.11 | $ 1,250,000 | $ 1,250,000 | $ 1,250,000 | CA | N | 50% |
| 1 | Electrodepostion of biaxial textured Ni buffer layer for paramagnetic Ni-W substrates | Midwest Res.Inst./R. Bhattacharya | NREL 100% | | $ 60,000 | TD5001.12 | $ 60,000 | $ 60,000 | | CC | Y | |
| 1 | Electrodeposition of non-magnetic Ni-W on textured Cu-based substrates | Midwest Res.Inst./R. Bhattacharya | NREL 100% | | $ 60,000 | TD5001.12 | $ 60,000 | $ 60,000 | | CC | Y | |
| 1 | Qualify the quality of the substrate by subsequent CYC and superconducting YBCO layer | Midwest Res.Inst./R. Bhattacharya | NREL 100% | | $ 65,000 | TD5001.12 | $ 65,000 | $ 65,000 | | CC | Y | |
| 1 | Development of electropolishing technique to improve the base textured substrate quality | Midwest Res.Inst./R. Bhattacharya | NREL 100% | | $ 50,000 | TD5001.13 | $ 50,000 | $ 50,000 | | CC | Y | |
| 1 | Electrodeposition of Cu stabilizer on YBCO-coated conductor in collaboration with SuperPower corporation | Midwest Res.Inst./R. Bhattacharya | NREL 100% | | $ 50,000 | TD5001.12 | $ 50,000 | $ 50,000 | $80,000 (June 30); $233,000 (Sep. 30) | CC | Y | 50% |
| 2 | Develop a “melt-quench-melt-growth” process which facilitates an open reaction and eliminates loss of material during processing | Midwest Res.Inst./R. Bhattacharya | NREL 100% | | $ 50,000 | TD5001.13 | $ 50,000 | $ 50,000 | | CC | Y | |
| 2 | Explore techniques for improving Bi-2212 by nano-particle additions (Flux Pinning). Oxford Instrument CRADA | Midwest Res.Inst./R. Bhattacharya | NREL 100% | | $ 50,000 | TD5001.13 | $ 50,000 | $ 50,000 | | CC | Y | 50% |
| 1 | Assist Oxford Superconducting Technology on HTS MRI system (including characterization) | Midwest Res.Inst./R. Bhattacharya | NREL 100% | | $ 10,000 | TD5001.12 | $ 10,000 | $ 10,000 | | CC | Y | 50% |
| 2 | Technical Communications for the DOE Headquarters | Midwest Res.Inst./R. Bhattacharya | NREL 100% | | $ 5,000 | TD5001.12 | $ 5,000 | $ 5,000 | | CC | N | |
| 1 | Solution deposition processes for coated conductors | Sandia Corp./P. Clem | SNL 100% | | $ 200,000 | TD5001.12 | $ 200,000 | $ 200,000 | $ 195,000 | CC | Y | |
| 2 | Ceramic processing capabilities for assisting high-rate solution deposition | Sandia Corp./P. Clem | SNL 100% | | $ 200,000 | TD5001.13 | $ 200,000 | $ 200,000 | $ 200,000 | CC | Y | |
| 2 | Buffer Layer Growth and the Thickness Dependence of Jc in Coated Conductors | U of Wisconsin/D. Larbalestier | | | $ 300,000 | TD5001.13 | $ 300,000 | $ 300,000 | | CA | Y | |
| 2 | Conversion of Oxyflouride-based coated conductors | MIT/Y. Iwasa | | | $ 200,000 | TD5001.13 | $ 200,000 | $ 200,000 | | CA | Y | |
| 1 | DOD Title III Solicitation for 2G Wire Development | SuperPower/P. Pellegrino | | | $ 500,000 | TD5001.12 | $ 500,000 | $ 500,000 | $ 500,000 | IA | Y | 50% |
| 1 | DOD Title III Solicitation for 2G Wire Development | American Superconductor/J. Scudiere | | | $ 500,000 | TD5001.12 | $ 500,000 | $ 500,000 | $ 500,000 | IA | Y | 50% |
| 3 | Performance Enhancement of 2G Conductors by Investigation of Flux Pinning and AC Loss Issues | Wright State U - Albany Nanotech/P. Haldar | | | $ 954,000 | TD5001.14 | $ 954,000 | $ 954,000 | $ - | EM | N | |
| 3 | HTS Subject Portal and CD-ROM of Peer Review | OSTI | | | $ 30,000 | TD5001.13 | $ 30,000 | $ 30,000 | $ 30,000 | NC | N | |

Office of
Electric Transmission & Distribution
Superconductivity Program

# Superconductivity for Electric Systems

# ANNUAL OPERATING PLAN
# FY 2004

U.S. Department of Energy

William Parks, Acting Director Office of Electric Transmission and Distribution

James Daley, Team Leader, Superconductivity,

Program Managers
Marshall Reed
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# 1.0 Introduction

This Annual Operating Plan (AOP) provides an overview of the Superconductivity Program for Electric Systems for FY-2004. The report describes the activities planned to advance the superconductivity technology towards the commercial marketplace in electric power applications. The Second Generation Wire Development, Strategic Research, and Superconductivity Partnerships with Industry (SPI) are three primary programmatic areas discussed in this plan.

## 1.1 Office of Electric Transmission and Distribution

The Office of Electric Transmission and Distribution (OETD) was created in August 2003 in order to help ensure a robust and reliable U.S. transmission grid for the 21$^{st}$ century. This formation occurred after the release of three powerful reports: National Energy Policy, May 2001; National Transmission Grid Study, May 2002; and Transmission Grid Solutions Report, Sept 2002. These reports laid out the groundwork that helped establish the overall OETD goals. The Office of Electric Transmission and Distribution goals include:

- √ Modernization of America's electricity infrastructure to meet the needs of the 21st century;
- √ Completion of the transition to competitive regional markets;
- √ Better transmission system operations;
- √ Effective transmission system investments;
- √ Aligning electricity policies with R&D; and
- √ Providing effective federal leadership in achieving these goals.

## 1.2 Mission

This AOP addresses the Superconductivity Program Mission: "*To work in partnership with industry to develop high-temperature superconducting wire and perform other research and development activities leading to the commercialization of high-temperature superconductivity (HTS) electric power applications by U.S. companies.*" The primary functions that will take place in order to achieve the Superconductivity Program mission are to help facilitate in the development of:

1. HTS wire that will carry 100 times the current without the resistance losses of comparable diameter copper wire; and,
2. HTS equipment will be half the size of conventional alternative with the same power rating and will have only half the energy losses.

The Superconductivity Program is implementing the necessary research and development (R&D) efforts that will help the utilities and industry meet future energy requirements in the United States. The Superconductivity Program mission also addresses the goal to "*Improve the reliability of the nation's electricity system.*" As a result of this coordinated and comprehensive effort, the mission and goals of this program contributes to the achievement of the OETD goals.

## 1.3 Superconductivity Program

The High Temperature Superconductivity Program has moved into a technological field that does not currently exist as a commercial market. Due to this, extensive planning and identifying potential markets for the technology where the value proposition supports the cost of enhanced performance capabilities continue to take place. Business considerations are heavily weighed when determining cost and performance targets. The Superconductivity Program bases this AOP and its long-range research on strategic planning conducted by Oak Ridge National Laboratory and several subcontractors. The strategic planning is subjected to intense analysis by the contractors of informed industrial reviewers. Continual review is conducted by the industrial partners in the Superconductivity Partnerships with Industry projects as they develop the prototypes for new HTS electrical systems.

## 1.4 Performance-Based Peer Review

The Oak Ridge National Laboratory (ORNL) coordinates a yearly, public program review and peer evaluation of research projects funded by the Superconductivity Program for Electric Systems. An international panel of experts evaluates the research management and accomplishments of the projects conducted by the participants in the Superconductivity program. The panel then provides comments to ORNL on the strengths and weaknesses exhibited by the projects. The results of the Peer Review are communicated to DOE - HQ for use in the management of the program. The July 2003, Peer Reviewers were asked the following set of five questions and their responses follow:

*Are the program's research mission and goals adequately defined and do they reflect the present status of science, technology, and needs of the industry? Is the program moving into applications at a sufficient pace?*

> Reviewers unanimously agreed with the adequacy of the programs mission, goals, and program pace: "The Program's mission and goals are really excellent. The goals are very well defined and do reflect the present needs and state of technology. The pace could be faster, but considering the potential for higher failures, the pace is just right."

*How would you assess the program's research productivity and accomplishments so far?*

> The reviewers show a very positive response to the overall program productivity and accomplishments: "This year's progress has been the best in years."

*Do you feel that the quality of the proposed FY 2004 R&D activities is impressive and ambitious? Are the key research areas receiving the proper emphasis to achieve program goals? Are the R&D milestones realistic and achievable?*

> The reviewers positively endorsed this set of questions as well. One reviewer stated, "The milestones are realistic and achievable, you are right on target with risk mitigation measures to assure that you reach the objectives at the appropriate time." Another commented, "The FY 2004 R&D activities are excellent. DOE's mission to develop technology for U.S. industry to proceed with commercial development of power application is great. New "people" with ideas about commercialization in the national labs may be able to help reach those goals."

*The teaming between industry, universities, and the national laboratories is an important element of the program. Are the present arrangements appropriate for success and future commercialization?*

> Responses included: "SPI program should be the standard for DOE, as well as the annual peer review. One must not forget it is very important to make sure the needs of end-users (industry, utilities) are addressed by the researchers. The present arrangements are ingenious, especially for the SPI developments. It results in speedy development with value in mind."

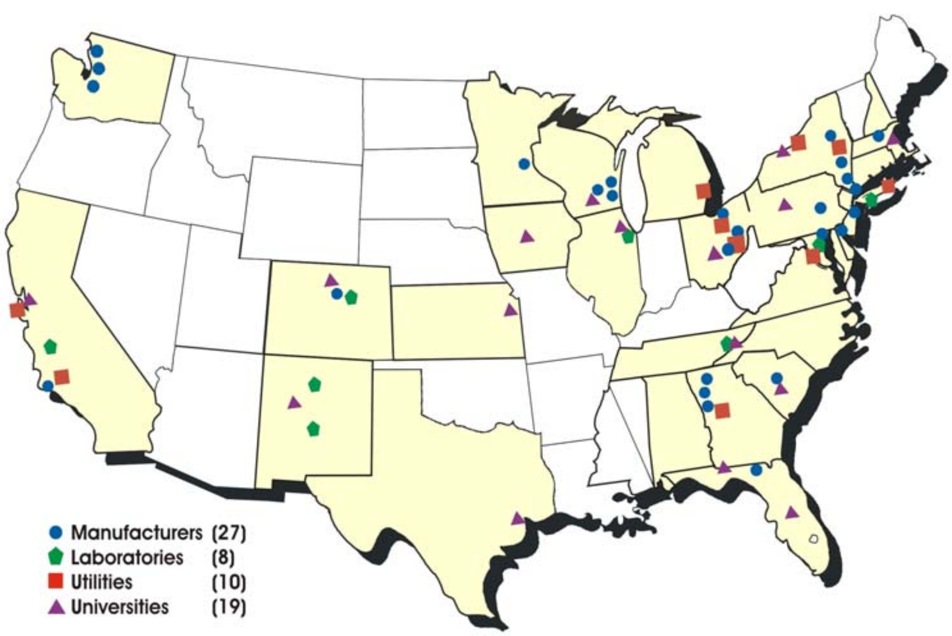
*Has DOE performed the proper planning ensuring the success of the program and is DOE's role appropriate?*

> Reviewers responded in agreement unanimously to this question. "I strongly believe the only reason for where we are with the HTS and their application, is because of DOE. Without DOE, the United States would have been very far behind Japan and Europe. No complaining at all. DOE is doing a wonderful job."

## 1.5 Public – Private Partnerships

The Superconductivity Program for Electric Systems is a national program that supports national energy, economic, environmental, and educational interests throughout the Unites States. The programs participants range from manufacturers, Laboratories Utilities and Universities. The national scope of this program and its stakeholders can be seen below in Exhibit 1.

**Exhibit 1: Superconductivity National Program Participants and Performers**



The Superconductivity Program for Electric Systems works in partnership with industry to perform the wire research and technology development required for U.S. companies to commercialize High Temperature Superconductivity (HTS) in electric power applications. To achieve commercialization of the technology, the Superconductivity Program engages in research and development which aims to:

1. Improve the performance of superconducting wire while reducing manufacturing costs (Second Generation Wire Development)
2. Demonstrate the applicability and the potential benefits of superconductivity in electric power systems (Superconductivity Partnerships with Industry).

Second Generation Wire research seeks methods to produce wire that has higher current carrying capacity, reduced manufacturing costs, and better industrial application characteristics, such as durability, flexibility, and tensile strength. Near-term research in this area focuses on conquering scale-up issues of more developed HTS wire technologies for electric system applications such as cables and other systems that use HTS wires and coils. Longer-term wire research activities concentrate on next generation superconducting wire, which includes research on YBCO (yttrium barium copper oxide), BSCCO (barium calcium copper oxide), and other compounds for coated conductors. Wire research also includes the investigation of the underlying physics of high temperature superconductivity.

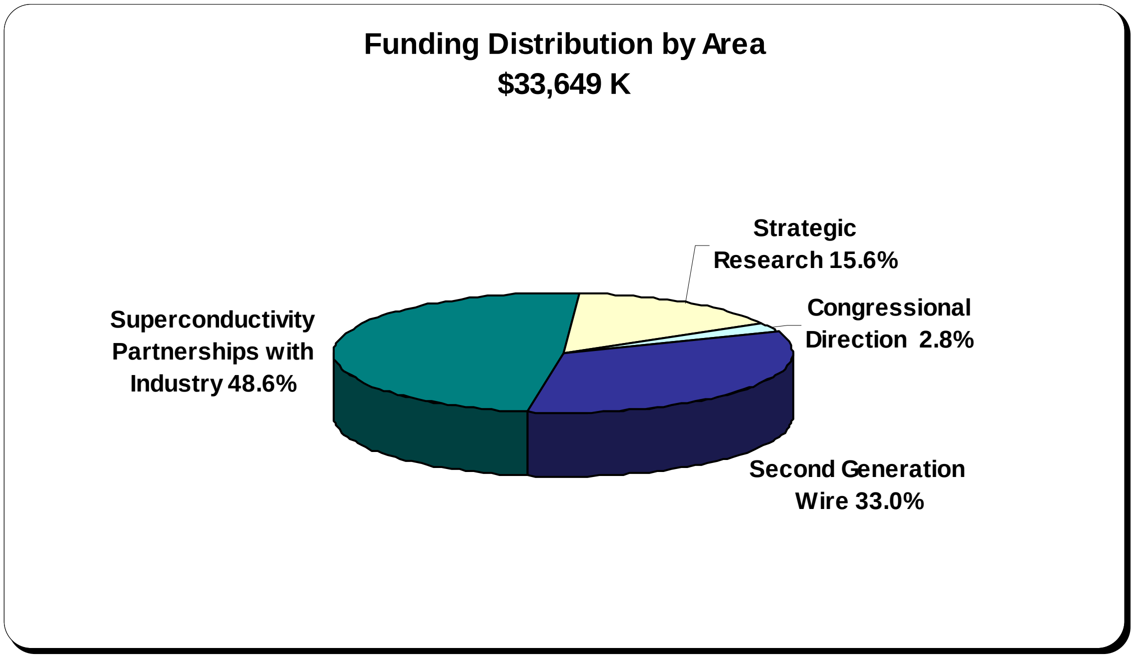
Superconductivity Partnerships with Industry (SPI) research activities focus on electric power system applications of HTS technology and involve industry-led cooperative projects. Researchers investigate adaptability issues for using superconducting wire in power system applications, which include power cables, transformers, fault current limiters, magnetic resonance imaging (MRI), generators, and flywheel electricity systems. In addition, program efforts target end-user applications in energy-intensive industries, including large electric motors and magnetic separators. Application issues include the development of efficient cryogenic systems, power cables, and magnetic field research. The public - private partnerships philosophy is needed in HTS systems development to encourage private investment in research by reducing the financial risk. The Superconductivity Partnerships with Industry research with industrial partners is cost shared 50-50.

The Strategic Research activities focus on the stability and normal zone propagation properties of Second-Generation Wires. Accompanying R&D in this area, work to develop dielectric materials and investigate alternate processes and wire geometries that may lead to an improved performance ratio for second generation conductors. This is achieved by laboratory, industry, and university research focused on the program and its activities which additionally include close communication, systems analysis, and outreach with stakeholders.

## 1.6 FY – 2004 Planned Activities

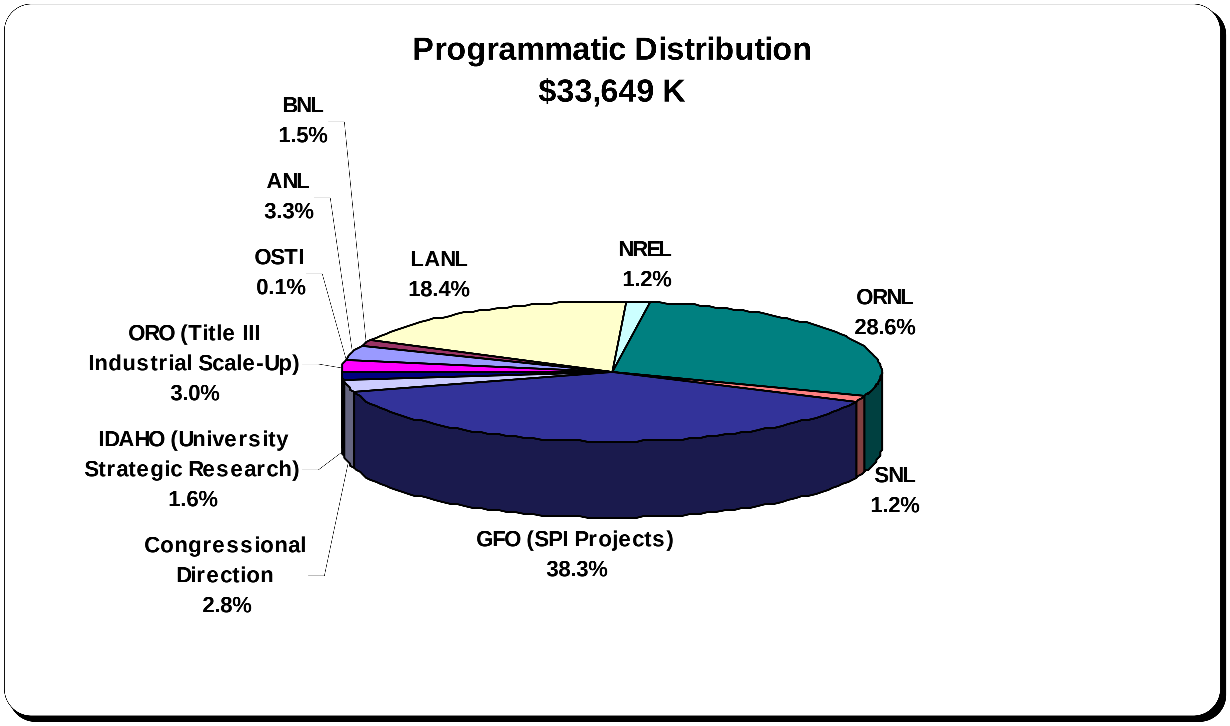
Superconductivity R&D activities are described in relation to the overall program with classifications reflecting upon the commercial applicability of the research. Second Generation Wire Development consists of R&D projects which are driven by specific stakeholders and government; with the potential to increase efficiency and performance of superconductivity applications by creating new types of HTS wire. Superconductivity Partnerships with Industry (SPI) efforts are driven by the needs of the electric utility industry and electrical equipment manufacturers. SPI projects include the most advanced HTS technology applications which are nearing commercialization. Strategic Research applications work to promote advanced, cost shared research that lead to further development of HTS. The programmatic funding by area and distribution between partners is shown in Exhibits 2 and 3.

**Exhibit 2: FY - 2004 Superconductivity Program Funding by Area**




| PROGRAM DISTRIBUTION | $ (K) |
|---|---|
| Second Generation Wire | $11,095 |
| Strategic Research | $5,242 |
| Superconductivity Partnerships with Industry | $16,358 |
| Congressional Direction | $954 |
| **Total** | **$33,649 K** |

### Exhibit 3: FY - 2004 Superconductivity Program Funding Distribution




| ORGANIZATION | $ (K) |
|---|---|
| Oak Ridge National Laboratory | $9,620 |
| Los Alamos National Laboratory | $6,200 |
| Argonne National Laboratory | $1,100 |
| Brookhaven National Laboratory | $500 |
| National Renewable Energy Laboratory | $400 |
| Sandia National Laboratory | $400 |
| Congressional Direction | $954 |
| GFO (SPI Projects) | $12,895 |
| IDAHO (University Strategic Research) | $550 |
| ORO (Title III Industrial Scale-Up) | $1,000 |
| OSTI | $30 |

**Total** **$33,649 K**

# 2.0 Program Management

## 2.1 DOE-HQ

The responsibility of the Superconductivity Program for the Office of Electric Transmission and Distribution has been assigned to four staff members at the Department of Energy Headquarters (DOE-HQ). These individuals are responsible for planning, organizing, and managing the national program. The principle goals of the headquarters office are to uphold the mission and objectives created for the program; formulate and justify the annual budget, and to provide overall program guidance and direction. Funding the Superconductivity for Electric Systems activities i.e. salary, travel, training, and support comes from the Program Direction Budget of the Office of Electric Transmission and Distribution. The names of the headquarters staff are as follows:

**James Daley, 202-586-1165, Team Leader, Superconductivity for Electric Systems**

**Program Managers**
**Marshall Reed, 202-586-8076**
**Harbans Chhabra, 202-586-7471**
**Roland George, 202-586-9398,**

## 2.2 Field Management

DOE Golden Field Office: Paul Bakke, Superconductivity Project Manager in the Golden Field Office (GFO), issues solicitations requesting proposals for projects to be cost shared with the Superconductivity Partnerships with Industry division. These proposals are competitively evaluated by the peer-review, and funding for successful proposals is awarded as DOE cooperative agreements with industry teams.

DOE National Laboratories: Each DOE National Laboratory receiving funding from the Superconductivity Program for Electric Systems has an internal management team to direct the individual researchers, to administer cooperative agreement (CRADA) work with industry, and to solicit proposals and execute subcontracts.

# 3.0 Electrical Wires (Second Generation Wire Development)

**FY – 2004 Funding: $ 11,095,000**

## 3.1 Second Generation Wire Development

**FY – 2004 Funding: $ 11,095,000**

The Second-Generation Wire Development consists of an industrial consortium aimed to research and develop economic, high performance HTS wire. The research conducted takes place at six different DOE National Laboratories where increased engineering current density, improved flux pinning properties in strong magnetic fields, and reduced alternating current losses through materials processing are evaluated. This HTS research is also being conducted at numerous universities as well as private industrial laboratories. This extensive array of participants is privy to an abundance of resources and each contains distinctive knowledge and expertise. This allows concurrent research to be conducted on many distinct methods of processing coated conductors, all of which have the potential to present the idyllic blend of increased performance and reduced cost required to market HTS wire for widespread application.

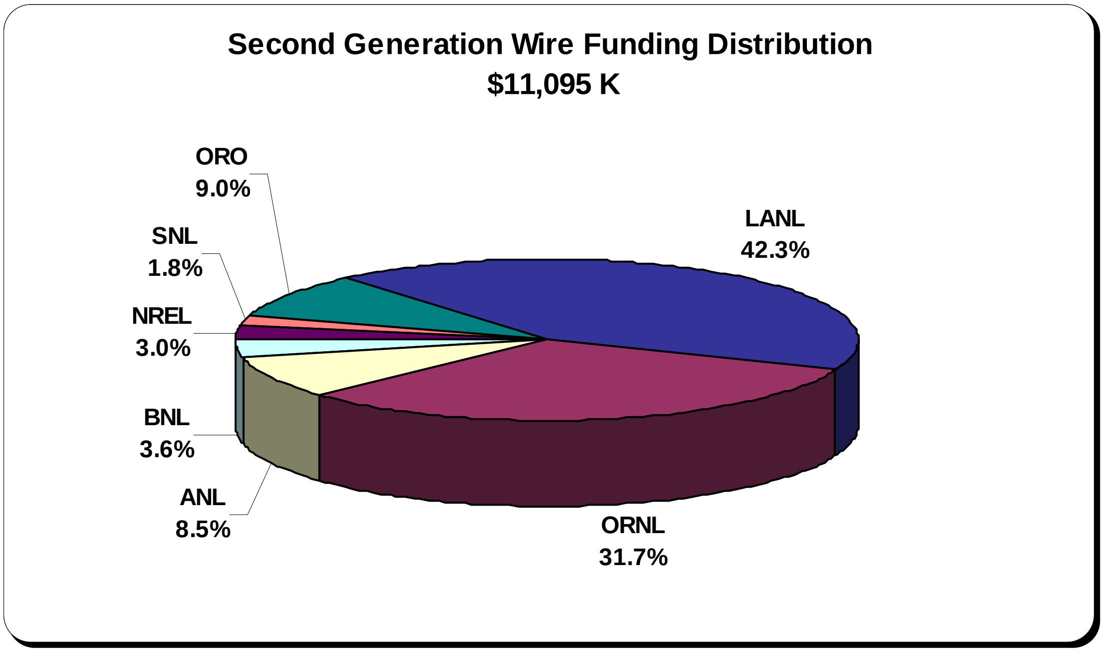
The performance-based, HTS Peer Review designed to assess the programs progress was held in August, 2003. Peer Reviewers provided the following comments about Second Generation Wire Development:

> "*More interaction with National Laboratories would be beneficial to SuperPowers effort, in particular as it relates to scaling-up IBAD and MOCVD." Improved collaboration is planned for FY-2004. The group efforts will include other DOE labs, AFRL, universities, and NIST.*
>
> *"The final goal to scale-up CC technology to pilot manufacturing was successfully approached by applying adequate polishing techniques and improved IBAD facilities (scale-up of 10 -100 m tape length). Both MOCVD and PLD yielded improved $I_c$ as compared to 2003. Complimented by (further) introduction of (continuous) on-line and off-line quality control tools. FY 2004 plans consequently continue the above efforts."*

## 3.2 Laboratory Research

Laboratory research of Second Generation Wire is aimed towards the development of new advances and coated conductor techniques, prior to their introduction to the private sector resulting in licenses and other intellectual property rights. Los Alamos National Laboratory (LANL) and Oak Ridge National Laboratory (ORNL) have dedicated a substantial portion of their research funding to the creation of research facilities dedicated to accelerate the development of second generation wire. Other laboratories dedicated to expanding second generation wire technology include National Renewable Energy Laboratory (NREL), Brookhaven National Laboratory (BNL), Sandia National Laboratory (SNL), and Argonne National Laboratory (ANL).

### Exhibit 4: FY - 2004 Second Generation Wire Funding Distribution




| ORGANIZATION | $ (K) |
|---|---|
| Los Alamos National Laboratory | $4,695 |
| Oak Ridge National Laboratory | $3,521 |
| Argonne National Laboratory | $944 |
| Brookhaven National Laboratory | $400 |
| National Renewable Energy Laboratory | $335 |
| Sandia National Laboratory | $200 |
| Title III Industrial Scale-up (ORO) | $1,000 |
| **Total** | **$11,095 K** |

### 3.2.1 Los Alamos National Laboratory (LANL)

**FY - 2004 Funding: $4,695,000**

| LOS ALAMOS NATIONAL LABORATORY SECOND GENERATION WIRE | |
|---|---|
| **Project Title** | **$ (K)** |
| YBCO Coated Conductor Tape Development with AMSC | $225 |
| Coated Conductor Tape Development with Superpower | $850 |
| Development of Coated Conductors Based on IBAD MgO | $1,500 |
| Coated Conductor Processing | $1,500 |
| Electron Beam Evaporation | $620 |
| **Total** | **$4,695 K** |

LANL will continue collaborations in scale-up processes in coated conductor technology with SuperPower, Argonne National Laboratory, American Superconductor Corporation, and Rockwell Automation. LANL will provide technical expertise and facilities in materials science, wire précising, characterization, design engineering, and analysis to advance coated conductor development.

FY-2004 Milestones:

1. Achieve 7,000 Amp-Meters in 100-Meter 2G HTS Wire
2. Enhance facilities to enable routine production of 100 meter lengths of 2G wire.
3. Demonstrate critical currents of 380 amperes in a short sample, and up to 250 amperes in 1 meter lengths of 2G wire.
4. Collaborate with Rockwell Automation Power Systems (RAPS) integrating 2G into a small demonstration HTS generator.
5. Transition to high-throughput buffer layer technologies developed at LANL to SuperPower's pilot production facility and fabricate several 100 amperes, 2 meter 2G wires using this high-throughput processing technology.
6. Demonstrate linear speed greater than 10 meters/hour in every processing step to produce 2G wire. High throughput is essential to commercial viability.
7. Develop slitting technology to produce 4 mm wide 2G wire, with at least 100 amperes/cm performance in lengths of several meters.
8. Develop patent-pending photolithography process, demonstrating up to 100 times lower AC losses.

### *3.2.2 Oak Ridge National Laboratory (ORNL)*

**FY - 2004 Funding: $3,521,000**

| OAK RIDGE NATIONAL LABORATORY SECOND GENERATION WIRE | |
|---|---|
| **Project Title** | **$ (K)** |
| RABiTS Template Research: Continuous Processing | $1135 |
| Ex-situ Continuous Processing of YBCO for Coated Conductors | $900 |
| Stability of 2G and 1G Wires and Tapes | $150 |
| Stability of 2G and 1G Wires and Tapes: funds out | $41 |
| American Superconductor 2G Scale-Up Research (competitive solicitation) | $845 |
| NIST Interagency Agreements – 2G Wire Research | $450 |
| **Total** | **$3,521 K** |

Several industry teams are working with ORNL staff members to develop the scientific basis for coated conductors and RABiTS technology. These teams represent American Superconductor Corporation, Oxford Superconducting Technology, Sandia National Laboratory, Neocera and Universities. Numerous publications and presentations help assure the transfer of information to industry. The challenge set by ORNL is to address the "R&D needs/knowledge gaps" identified in the DOE roadmap.

FY-2004 Milestones:

1. Develop robust buffers on ORNL Ni-3 at %W substrates in reel-to-reel configurations.
2. Utilize the ORNL rolling mill with clean room facility to develop substrates.
3. Support industrial partners with rolling activities. Develop with outside vendor's better starting coils.
3. Continue magnetization studies for a better understanding of ac loss contributions from the alloy substrates.
4. Fabricate long lengths of Cu-based substrates and develop fully-conductive buffer architectures.
5. Perform percolation calculations using experimentally achievable texture in RABiTS, both in self-field and applied field.
6. Resolve the in-plane and out-of-plane mis-orientations from the total mis-orientation angle and relate this to critical current density.
7. Develop further solution buffers and fabricate double-sided RABiTS.

### 3.2.3 Other National Labs

**FY – 2004 Funding: $1,879,000**

In 2004, collaboration with Argonne National Laboratory, Brookhaven National Laboratory, National Renewable Energy Laboratory, and Sandia National Laboratory will address critical issues in coated conductors process scale-up, characterization, electromechanical studies involving superconductors, and substrate deposition with ISD. ANL will be working with American Superconductor, SuperPower, and universities addressing Coordinated Characterization of Coated Conductors. NREL and SNL's primary focus will continue to further advance coated conductor technology.

Argonne National Laboratory (ANL)

| ARGONNE NATIONAL LABORATORY<br>SECOND GENERATION WIRE | |
|---|---|
| **Project Title** | **$ (K)** |
| Coordinated Characterization of 2G Wires with IGC-SuperPower | $450 |
| Phase Evolution & Characterization of 2G Wire with American Superconductor | $300 |
| In-House R&D in the Area of 2G Wire Fabrication by ISD Process | $194 |
| **Total** | **$944 K** |

FY – 2004 Milestones:

1. Understand and control fabrication parameters for reduced film surface roughness and enhanced biaxial texture.
2. Develop simplified buffer layer architecture for the fabrication of CC using ISD.
3. Optimize the inclination angle for ISD-MgO to be ≈35°
4. Achieve in-plane texture of ≈6° and out-of-plane texture ≈3° for YBCO on SRO Buffered ISD-MgO
5. Reduce surface roughness to ≈7nm
6. Reduce in-plane FWHM to ≈6° using SRO single buffer layer.
7. Fabricate 1.6 µm YBCO with $I_c$ >100 A/cm-width.

Brookhaven National Laboratory (BNL)

| **BROOKHAVEN NATIONAL LABORATORY<br>SECOND GENERATION WIRE** | |
|---|---|
| **Project Title** | **$ (K)** |
| Practical Conductor Development Utilizing High-$T_c$ Oxides: YBCO Tape Processing | $400 |
| **Total** | **$400 K** |

FY – 2004 Milestones:

1. Optimize the inclination angle for ISD-MgO to be ≈35°.
2. Achieve in-plane texture of ≈6° and out-of-plane texture of ≈3° for YBCO on SRO buffered ISD-MgO.
3. Fabricate 1.6 µm YBCO film with $I_c$ > 100 A/cm-width ($J_c \approx 0.7$ MA/cm$^2$) using SRO single-buffer-layer architecture.

National Renewable Energy Laboratory (NREL)

| **NATIONAL RENEWABLE ENERGY LABORATORY<br>SECOND GENERATION WIRE** | |
|---|---|
| **Project Title** | **$ (K)** |
| Electrodepostion of Biaxial Textured Ni Buffer Layer for Paramagnetic Ni-W Substrates | $60 |
| Electrodeposition of Non-Magnetic Ni-W on Textured Cu-Based Substrates | $60 |
| Quantify the Quality of the Substrate by Subsequent $CeO_2$/YSZ/$CeO_2$ and Superconducting YBCO Layer | $65 |
| Development of Electropolishing Technique to Improve the Base Textured Substrate Quality | $50 |
| Electrodeposition of Cu Stabilizer on YBCO-Coated Conductor in Collaboration with SuperPower Corporation | $50 |
| Developed a “Melt-Quench-Melt-Growth” Process, which Facilitated an Open Reaction and Eliminated Loss of Material During Processing | $50 |
| **Total** | **$335 K** |

FY – 2004 Milestones:

1. Prepare electrodeposited buffer layer for YBCO-coated conductors
2. Demonstrate current density (~$10^6$ A/cm$^2$) of YBCO using electrodeposited Ni film comparable with the reported literature value.
3. Explore techniques for improving Bi-2212 by nanoparticle additions (OST CRADA).
4. Prepare electrodeposited Cu stabilizer on YBCO-coated conductor.
5. Simplify and improve buffer architecture by developing non-magnetic electrodeposition metallic buffer layers.

Sandia National Laboratory

| SANDIA NATIONAL LABORATORY<br>SECOND GENERATION WIRE | |
|---|---|
| **Project Title** | **$ (K)** |
| Solution Deposition Processes for Coated Conductors | $200 |
| **Total** | **$200 K** |

FY – 2004 Milestones:

1. Replace vacuum buffer tri-layer with thin solution buffer.
2. Deposit on Ni-W or Cu-Fe substrates.
3. Increase YBCO film thickness toward 2µm single layers.
4. Decrease YBCO process time.

### 3.2.4 Title III Industrial Scale-up (ORO)

**FY – 2004 Funding: $1,000,000**

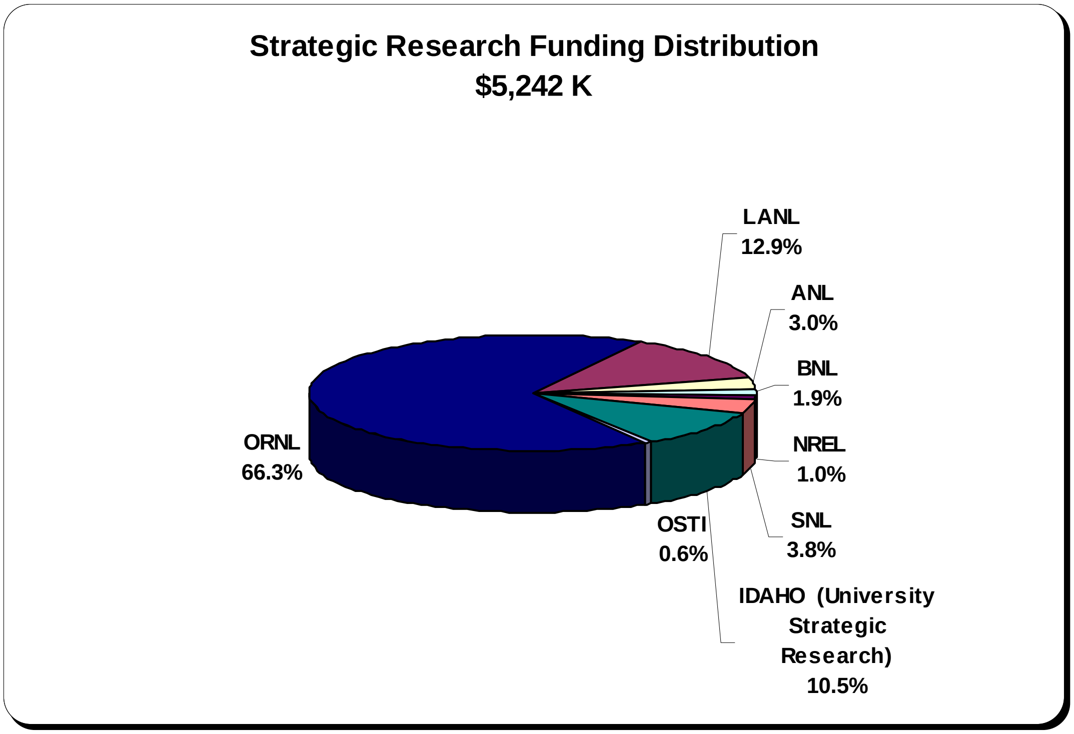
Oak Ridge Operations Office (ORO) will administer a competition for industry to investigate and develop the methods and expertise to begin scaling up coated conductor fabrication processes. Each process will be investigated for its potential to produce high quality, uniform conductors, acceptable economics, process limitations (including time constraints), and long term market potential. Some processes being researched in conjunction with national laboratories are “batch techniques” and questions how to configure their processes for continuous production need to be addressed.

## 3.3 Strategic Research

**FY – 2004 Funding: $5,242,000**

High Temperature Superconductivity Strategic Research involves investigating new approaches in producing or analyzing superconductors. This research focuses on high-risk concepts that have strong potential for increasing energy efficiency in the long-term, but which are unsuitable for commercial stakeholder involvement in the near-term. The focus on this research is on the characteristics and potential fabrication problems to be encountered in new coated conductors. A graphical representation of the distribution of funds for Strategic Research is shown in Exhibit 5.

**Exhibit 5: FY - 2004 Strategic Research Funding Distribution**




| ORGANIZATION | $ (K) |
|---|---|
| Oak Ridge National Laboratory | $3,476 |
| Los Alamos National Laboratory | $675 |
| Argonne National Laboratory | $156 |
| Brookhaven National Laboratory | $100 |
| National Renewable Energy Laboratory | $55 |
| Sandia National Laboratory | $200 |
| IDAHO (University Strategic Research) | $550 |
| OSTI | $30 |
| **Total** | **$5,242 K** |

### 3.3.1 Oak Ridge National Laboratory (ORNL)

**FY – 2004 Funding: $3,476,000**

| OAK RIDGE NATIONAL LABORATORY<br>STRATEGIC RESEARCH | |
|---|---|
| **Project Title** | **$ (K)** |
| ORNL-American Superconductor CRADA | $815 |
| RABiTS-Based Strategic Research | $528 |
| RABiTS-Based Strategic Research: funds out | $491 |
| Development of Ex *Situ* Processed, High $I_c$ Coated Conductors | $520 |
| Wire Development Group | $225 |
| Program Management | $444 |
| Planning and Analysis Activities | $503 |
| **Total** | **$3,526 K** |

In FY – 2004, the research and development effort will include a study of the dependence of the transverse stress effort (both static and dynamic fatigue) on new substrate materials, such as non-magnetic RABiTS. YBCO layer thickness is another parameter that will be studied as methods for producing these materials in length are developed. ORNL will also further explore YBCO quench and stability characterization in tapes and coils. Tapes will be investigated to quantify stability and quench propagation in bath – and conduction-cooled configurations. ORNL plans to collaborate with Los Alamos National Laboratory and University of Wisconsin to study the development of high $I_c$ ex-situ processes in RBCO coated conductors. Additional shared studies with University of Wisconsin will concentrate on buffer layer growth and thickness dependence of Jc in coated conductors and University of California, Santa Barbara will study the microstructure and mechanics of superconductor epitaxy via chemical solution deposition.

FY – 2004 Milestones:

1. Demonstrate uniformity and reproducibility in 10 m lengths with $I_c$ = 250-270 A/cm-w
2. Achieve uniform texture in 10 cm x 80 m RABiTS substrates.
3. Develop all solution buffer architectures that are compatible with MOD TFA YBCO
   -Achieve over 200 A/cm-w on solution LZO seeds
   -Extend to 4-cm-wide substrates
4. Continue fundamental studies of epitaxial growth of both PVD and solution buffers on textured substrates, including copper and copper alloys.
5. For copper-based substrates, develop a fully conductive architecture.
6. Achieve high-$I_c$ YBCO films on Cu or Cu-alloy templates by in-situ or ex-situ approach.
7. Enhance flux-pinning in YBCO films on RABiTS through growth-controlled pinning centers.
8. Investigate and develop the precursor chemistry for $LaMnO_3$ and MgO buffer-layers.
9. Investigate methods to increase critical thickness of $LaMnO_3$ and MgO buffer-layers.

### 3.3.2 Los Alamos National Laboratory (LANL)

**FY – 2004 Funding: $675,000**

| LOS ALAMOS NATIONAL LABORATORY STRATEGIC RESEARCH | |
|---|---|
| **Project Title** | **$ (K)** |
| BSCCO First Generation Wire (Wire Development Group) | $225 |
| Development of Magnesium Diboride Wires with Hypertech | $200 |
| AC Losses in HTS Conductors | $250 |
| **Total** | **$675 K** |

LANL continues to optimize the IBAD and PLD approaches for achieving outstanding properties in one-meter tape lengths. This work focuses on increasing deposition rates of both the IBAD and HTS films and extending film thickness to enable higher current carrying capacity. The transition in the IBAD process involving one-meter tapes from deposition of YSZ IBAD buffer to the faster MgO IBAD films will continue to be studied.

LANL plans to continue to focus on increasing deposition rates of both IBAD and HTS films along with extending film thickness and reducing ac losses to enable higher current carrying ability. Understanding and improving pinning with coated conductors will also be researched. A teaming effort with Stanford will address the process of in-situ scale-up transfers to metal tapes. Jay Switzer of University of Missouri-Rolla will work with LANL to determine the applicability of epitaxial electrodeposition of metal and metal oxide capping layers for RABiTS-based second generation coated conductors.

FY – 2004 Milestones:

1. Determine how the relative importance of the pinning mechanisms identified in PLD/IBAD MgO changes depending on the microstructure.
2. Assemble predictive equations for the losses in this temperature range.
3. Determine conductor temperature rise when exposed to large fluctuations in applied field (i.e. 1T increase in 1second).
4. Measure losses on various coated conductor samples with ac transport currents and ac magnetic fields.
5. Study conductor interaction (stacks, arrays) on ac losses.
6. Study cryo-stabilization of coated conductors under ac conditions.
7. Produce 400 A/cm-w ($J_c$ = 3.3 - 2.4 MA/cm$^2$) with film thickness 1.2-1.7 µm on an AMSC RABiTS™ template.
8. Study the growth of YBCO films on tape with respect to the growth rate, deposition temperature, and post-deposition treatment.
9. Explore the Phase Formation – FTIR.

### *3.3.3 Other National Laboratories*

**FY – 2004 Funding: $511,000**

| **ARGONNE NATIONAL LABORATORY STRATEGIC RESEARCH** | |
|---|---|
| **Project Title** | **$ (K)** |
| Processing of 1st Generation Wires with American Superconductor | $50 |
| IEA Research and Analysis | $45 |
| Management and Peer Review | $61 |
| **Total** | **$156 K** |

| **BROOKHAVEN NATIONAL LABORATORY STRATEGIC RESEARCH** | |
|---|---|
| **Project Title** | **$ (K)** |
| Practical Conductor Development Utilizing High-$T_c$ Oxides: AC Losses | $100 |
| **Total** | **$100 K** |

| **NATIONAL RENEWABLE ENERGY LABORATORY STRATEGIC RESEARCH** | |
|---|---|
| **Project Title** | **$ (K)** |
| Explore Techniques for Improving Bi-2212 by Nano-Particle Additions (Flux Pinning). Oxford Instrument CRADA | $50 |
| Technical Communications for the DOE Headquarters | $5 |
| **Total** | **$55 K** |

| **SANDIA NATIONAL LABORATORY STRATEGIC RESEARCH** | |
|---|---|
| **Project Title** | **$ (K)** |
| Ceramic Processing Capabilities for Assisting High-Rate Solution Deposition | $200 |
| **Total** | **$200 K** |

Other National Laboratories will perform research on the fabrication of biaxially-textured buffer layers on metallic substrates. Parameters such as ion flux, energy, the atom-to-ion flux ratio, beam-let divergence, and film thicknesses are studied to improve the texture of buffer layers. Electron-beam deposition, combined with assisting ion-gun deposition and thermal evaporation techniques, is explored for the deposition of textured buffers. Alternate buffer layer architectures are also investigated. Scientists are continuing to explore a metallo-organic chemical vapor deposition (MOCVD) technique for deposition of long-length YBCO conductors. The goal of this effort is to establish processing conditions to deposit buffer and superconducting layers on textured metallic substrates. Research includes texture development on metallic substrates and characterization of the textures of substrate and buffer layers. Researchers are undertaking the characterization of microstructural and superconducting properties of Second Generation Wire to improve understanding of $J_c$-limiting factors relating to formation and growth kinetics of high-temperature superconductors. The purpose of the project is to perform a detailed characterization of the microstructures in $YBa_2Cu_3O_7$ thick films to assist in understanding the formation mechanisms, as well as the factors controlling critical current densities.

Study is continuing to define the processing steps related to the development of a technologically useful $T_l$-oxide based wire or tape, i.e. substrate, precursor deposition, and heat treatment. In FY-2004, work will increase the deposition rates, film thicknesses, and $J_c$ values of solution-derived technology. Studies will be pursued to understand the atmosphere dependence of thick sol-gel YBCO crystallization kinetics, and means of speeding processing toward commercially important rates. Investigation will continue on economical, scalable, non-vacuum film deposition and processing techniques for use in coated conductor technologies. The emphasis is on developing solution methods (sol-gel) that produce textured buffer layers on technologically-important substrates (of sufficient quality to be of commercial interest), and on producing coated conductors by the solution method, with current carrying capabilities competitive with vacuum processed films.

FY – 2004 Milestones:

1. Construct sub-solidus phase diagrams of Ba-R-Cu-O in reduced oxygen partial pressure (R = Dy and Yb).
2. Study solid solution regions of Ba-R-Y-Cu-O (R=Nd, Eu, Sm, Gd).
3. Study low melting regions in the Ba-Y-Cu-O-F-OH system.
4. Study interactions of Y-213 with $CeO_2$ and with $SrTiO_3$.
5. Study *in-situ* Y-213 phase formation of the "$BaF_2$" Process (Ba-Y-Cu-O) system and subsystems using HTXRD.
6. Continue to study of $MgB_2$ thermo-chemistry.
7. Estimate physical parameters (e.g., interfacial energies) for use in model of nucleation and growth parameters.
8. Develop criteria for c-axis vs. a-axis nucleation.
9. Use the nucleation and growth model to estimate the effects of film dimensions and processing conditions leading to the onset of appreciable a-axis growth.

### 3.3.4 IDAHO (University Research)

**FY – 2004 Funding: $550,000**

University research is concentrated on innovative coated conductor technologies that are not being conducted in the DOE National Laboratories. DOE cooperative agreements are competitively awarded that provide strong interaction between the universities, DOE and Lab technical managers and will permit researchers to work in one of the National Laboratories for six months of the year. University of Wisconsin at Madison will conduct studies of buffer layer growth and thickness dependence of Jc in coated conductors. Massachusetts Institute of Technology (MIT) will work on conversion of oxyflouride-based coated conductors.

University of Wisconsin – Madison

| UNIVERSITY OF WISCONSIN - MADISON<br>UNIVERSITY STRATEGIC RESEARCH | |
|---|---|
| **Project Title** | **$ (K)** |
| Buffer Layer Growth and the Thickness Dependence of $J_c$ in Coated Conductors | $350 |
| **Total** | **$350 K** |

FY – 2004 Milestones:

1. Understand the mechanism of in plane texture improvement in SRO and $STO_2$.
2. Use MOD routes to deposit buffers on Ni-W RABiTS and understand role of and how to eliminate defects which propagate into the YBCO layer.
3. Develop "physics" model for $J_c$ showing additional effects of strong pins but still allowing to predicting lower $J_c$ associated with 2D to 3D vortex behavior
4. Research-thickness measurements on high current (>250A) films that do not fit the model
5. Develop new techniques (through-thickness EBSD) to follow grain boundary (GB) morphology.
6. Detail microstructural study of bimodal microstructure and YBCO overgrowth of template when much liquid present.
7. Investigate bi-crystal studies to check implications for GB critical current.

Massachusetts Institute of Technology

| MASSACHUSETTS INSTITUTE OF TECHNOLOGY<br>UNIVERSITY STRATEGIC RESEARCH | |
|---|---|
| **Project Title** | **$ (K)** |
| Conversion of Oxyflouride-Based Coated Conductors | $200 |
| **Total** | **$200 K** |

FY – 2004 Milestones:

1. Direct and quantitative measurement of the partial pressure of HF.
2. Clarification of relationship between the composition/time trajectory and film performance.
3. Quantitative measure of the degree of reaction between the YBCO film and the substrate buffer layer.
4. Compare between the results obtained from e-beam derived films with those of MOD derived films.
5. Understand/improve of YBCO coated conductor fabrication processing.

Five other competitively awarded university projects will be completed in FY – 2004. They are:

| UNIVERSITY STRATEGIC RESEARCH | |
|---|---|
| **Project Title** | **University** |
| Transfer to Metal Tapes and Process Scale-up of In-Situ High Rate YBCO | Stanford |
| Enhancing YBCO Performance through Fundamental Process Evaluation and Characterization | Albany-State University of New York |
| Epitaxial Electrodeposition of Metal and Metal Oxide Capping Layers for RABiTS-Based Second Generation Coated Conductors | University of Missouri-Rolla |
| Microstructure and Mechanics of Superconductor Epitaxy via the Chemical Solution Deposition Method | University of California, Santa Barbara |
| Systematic Decrease of $J_c$ Decrease in Thick Film Coated Conductors based on Micro-electrical and Micromechanical Properties | University of Houston |

# 4.0 Electric Applications

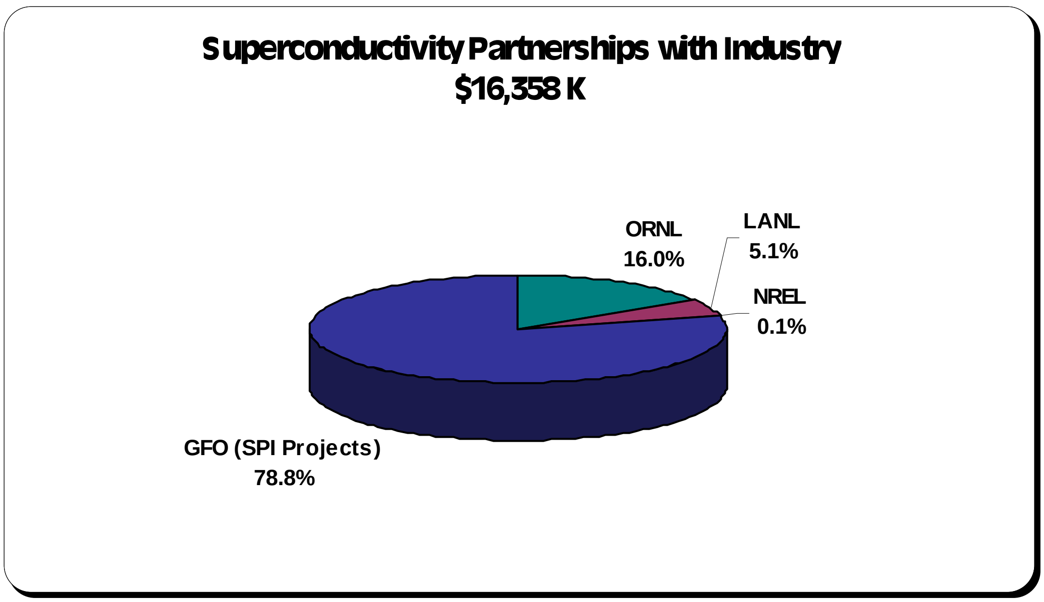
**FY – 2004 Funding: $16,358,000**

## 4.1 Superconductivity Partnerships with Industry

**FY – 2004 Funding: $16,358,000**

The Superconductivity Partnerships with Industry (SPI) fosters an integrated effort to accelerate the development of HTS application prototypes that can then be commercialized by U.S. industry. The competitive demonstration projects are co-funded by government and industry, and are accomplished by integrated teams of industry stakeholders, utilities, and national laboratories. Projects are funded primarily through cooperative agreements with the DOE Golden Field Office. The initiative has resulted in successful demonstration of a HTS transmission cable system, power equipment, electric motor, flywheel system, matrix fault current limiter, magnetic resonance imaging, and magnetic separation. All of the ongoing projects are nearing completion new projects will begin in FY – 2007. Exhibit 6 provides a distribution of the Superconductivity Partnerships with Industry breakdown.

**Exhibit 6: FY - 2004 SPI Funding Distribution**




| ORGANIZATION | $ (K) |
|---|---|
| Oak Ridge National Laboratory | $2,623 |
| Los Alamos National Laboratory | $830 |
| National Renewable Energy Laboratory | $10 |
| GFO (SPI Projects) | $12,895 |
| **Total** | **$16,358 K** |

The performance-based, HTS Peer Review to assess the program progress was held in July, 2003. Peer Reviewers provided the following comments about Superconductivity Partnerships with industry:

> *"The Southwire project is the poster project for DOE in terms of HTS success, and the success for the SPI program, an excellent example of the coordination and collaboration between industry, DOE and ORNL."* The number of cable projects will be expanded throughout the coming years.

> *"There is great potential for commercial development in magnetic separation. Help to environmental issues such as mercury removal from flue gas and/or from water and other pollutant removal. Extension of this project may require large magnets and thereby new development in the HTS areas."* In 2004, commercial applications will continue to be evaluated and a more broadened approach will be taken to industry needs.

## 4.2 Golden Filed Office Cooperative Agreements

**FY – 2004 Funding: $12,895,000**

The Golden Field Office (GFO) issued a solicitation in the spring of 2001 for new projects to supplement the suite of seven projects being completed that were awarded in the competitive selections of 1996 and 1994. The selected proposals were announced on September 24, 2001; new proposals will be accepted in 2006 for the 2007 fiscal year. About $12.9 million is set aside for the funding of these projects in FY - 2004. This foresight will enable accelerated startup and shorter timetables for the projects.

**FY – 2004 SPI Projects:**

***SPI Readiness Review Program:*** The focus of this project is on collaboration with the SPI team to identify potential failure modes; issues involving cryogenic temperatures, vacuum and high voltage dielectrics are a major concern. Expertise is obtained as needed from national laboratories, universities, and consultants. M. J. Gouge (ORNL) and Jim Daley (DOE) provided an overview of the proposed SPI oversight program at the January 2003 DOE Wire Development workshop and the program began in March 2003. The objective for 2004 is to provide at least one review of all active SPI projects.

***HTS Transformer: Waukesha/IGC-SuperPower Superconductivity Partnership Initiative Project*:** The objective in 2004 of the current Phase II Superconductivity Partnership Initiative (SPI) project with Waukesha Electric Systems (WES), SuperPower, Inc. (SP), and Energy East, is to demonstrate the technical and economic feasibility of HTS transformers of medium (30 MVA) to larger ratings. An alpha-prototype 5/10 MVA, 3-phase, HTS transformer, with primary/ secondary voltage ratings of 24.9/4.2 kV and 100-kV BIL has been designed, fabricated, and tested.

***Development of Ultra-Efficient HTS Motor Systems:*** The purpose of the project is to perform research in eight areas related to commercial viability of industrial motors with high temperature superconducting (HTS) windings. The eight areas were identified based upon the past work that

Rockwell Automation had conducted on development and testing of HTS based motors up to and including the laboratory test of a 1600 hp motor.

***Cost Effective, Open Geometry Superconducting Magnetic Resonance Imaging (MRI) System:*** The purpose in 2004 of this Phase II Superconductivity Partnership Initiative project is to build and operate a prototype Magnetic Resonance Imaging (MRI) system using HTS coils wound from low-cost, dip-coated BSCCO 2212 tape conductor. The planned milestones for FY 2004 were: (1) complete precursor powder manufacturing upgrades; (2) complete prototype conductor processing line; (3) begin conductor fabrication (4) complete design of cryogenics system and magnet.

***Design and Development of a 100 MVA HTS Generator:*** General Electric's Global Research in Niskayuna, N.Y., will design and develop a 100 MVA class high-temperature superconducting (HTS) generator, with designs through 250 MVA. The HTS rotor will be capable of retrofitting into existing generators. ORNL and LANL have entered into CRADAs with GE to provide assistance in several technology areas.

***Development Status of Flywheel Electricity System:*** The main purpose of this effort is to develop a 10-kWh flywheel energy system based on high-temperature superconducting (HTS) bearings. The first unit developed had a 3-kW motor/generator (M/G). The second unit developed has a 100-kW M/G. This effort started in FY1999. Due to DOE's funding limitations this year, the Boeing project received significantly lower funding than planned, and ANL didn't get any DOE funding at all. Specific objectives for FY 2004 were to complete the manufacturing of all components for the 100 kW/5 kWh UPS flywheel system, test all individual components at full speed, assemble the system, and fully test the UPS flywheel system at Boeing site with technical assistance from Southern California Edison's test personnel.

***High-Temperature Superconducting Power Cable:*** Southwire Company and ORNL have jointly developed, built, and demonstrated a series of cold-dielectric, high-temperature superconducting (HTS) power cables for this Superconductivity Partnership Initiative (SPI) project. The 30-m cable at Southwire's wire-manufacturing complex in Carrollton, GA, continues to run, accumulating over 26,000 hours at full load to date and running unattended over the last 36 months. This cable is rated at 12.4-kV, 1,250-A, 3-phase, 60-Hz, and 27-MVA. This cold dielectric cable was placed into full service in April 2000 for an extended testing period under actual industrial conditions.

***Waste Water Treatment with Magnetic Separation DuPont*** is leading the SPI development of a 500 mm HTS reciprocating magnetic separator. An HTS magnetic separator offers significant operational energy savings compared to conventional copper coil separators. The DuPont business plan calls for the development of new applications of magnetic separation that can benefit from the energy efficiency. DuPont and LANL established a CRADA in FY03 that capitalizes on LANL's experience in magnetic separation. DuPont has stationed a full-time employee, Jon Bernard, at the Los Alamos Research Park. After jointly assessing several potential market opportunities, DuPont and LANL agreed to focus on the removal of heavy metals in wastewater using high gradient magnetic separation (HGMS). LANL will work with

DuPont to develop an in-situ ferrite formation process that incorporates the heavy metals in a ferrite crystal lattice. The ferrites, having a high magnetic susceptibility, are then readily removed as they pass near a magnetized matrix material.

***Matrix Fault Current Limiter: SuperPower, Inc., CRADA:*** The purpose of this project is to conduct R&D on specified components and provide technical design support to a SuperPower, Inc. (SP) team developing high temperature superconducting (HTS) technology for a Matrix Fault Current Limiter (MFCL). This device incorporates a series-parallel array of bulk HTS elements and inductors in a sub-cooled liquid nitrogen (LN) bath. Transition of the HTS elements into the normal state during a fault drives most of the current into the inductors and leads to a sudden increase in impedance that limits the fault current

## 4.3 National Laboratory Support

**FY – 2004 Funding: $3,913,000**

### *4.3.1 Oak Ridge National Laboratory (ORNL)*

**FY – 2004 Funding: $2,623,000**

| SUPERCONDUCTIVITY PARTNERSHIPS WITH INDUSTRY RESEARCH ORNL | |
|---|---|
| **Project Title** | **$ (K)** |
| SPI Readiness Reviews | $104 |
| SPI Readiness Reviews: funds out | $24 |
| Southwire-ORNL HTS Power Cable Cooperative Research | $1760 |
| Southwire-ORNL HTS Power Cable Cooperative Research: funds out | $100 |
| Waukesha 5/10-MVA HTS Transformer Cooperative Research | $325 |
| GE 100-MVA HTS Generator Cooperative Research | $255 |
| SuperPower HTS Fault Current Limiter | $55 |
| **Total** | **$2,623 K** |

Oak Ridge National Laboratory will continue to support the Waukesha Electric Systems/IGC-SuperPower 5/10 MVA Transformer SPI project through design, specification, procurement and testing, including a nitrogen-based cryogenic cooling system. ORNL supports a second world-class SPI team, lead by Southwire Company for the development of high-voltage, transmission class HTS cables in the range from 138kV to 300kV. ORNL will work with Southwire to verify the operation of the terminations, instrumentation system, and cryogenic system of the cable installed at Southwire's headquarters.

FY – 2004 Milestones:

1. Measure thermal conductivity of Cryoflex™ on wrapped geometry.
2. Measure copper laminated HTS tapes for ac loss and fault tolerance.
3. Conduct design and initial testing of 3-m cable made with AMSC brass laminated HTS tapes.
4. Mitigation plans have been prepared that addresses the issues identified by the 2003 Readiness Review Team.
5. To complete measurements of the total hemispherical emissivity of specified surfaces at temperatures 20 K – 80 K including surface contamination.
6. Modify existing HTS test apparatus to support quench protection studies for HTS conductors down to 20 K.
7. Measure dielectric performance and partial discharge of prototype coil samples.
8. Conduct thermal and mechanical property measurements of sample coils as required.

### 4.3.2 Los Alamos National Laboratory (LANL)

**FY – 2004 Funding: $830,000**

| SUPERCONDUCTIVITY PARTNERSHIPS WITH INDUSTRY RESEARCH LANL | |
|---|---|
| **Project Title** | **$ (K)** |
| Waste Water Treatment with Magnetic Separation | $50 |
| Design and Development of a 100 MVA HTS Generator | $430 |
| HTS MRI System – Oxford Instruments | $200 |
| Current Controller – Superpower | $50 |
| Flywheel – Boeing | $50 |
| HTS Motor – Rockwell/Reliance Electric | $50 |
| **Total** | **$830 K** |

LANL leads a development team with SuperPower and Nexans to demonstrate a High Temperature Superconducting (HTS) Fault Current Limiter (FCL). They also play an integral role with DuPont in magnetic separation and cost effective, open geometry HTS MRI system.

FY – 2004 Milestones:

1. Powder processing upgrades complete and qualified by conductor performance: March 2004.
2. Reduce cost powder precursors in use: March 2004.
3. Prototype conductor processing line: July 2004.
4. Optimize ferrite & HGMS processes.
5. Determine controlling parameters and ranges
    - Particule concentrations (magnétite seed, Fe2+)
    - Type of stainless steel wool (extra-fine to coarse)

- Applied magnetic field strength
- Flow velocity in the separator
- Residence time in the separator

6. Determine scaling issues from laboratory to pilot plant.

### *4.3.3 National Renewable Energy Laboratory (NREL)*

**FY – 2004 Funding: $10,000**

| SUPERCONDUCTIVITY PARTNERSHIPS WITH INDUSTRY RESEARCH NREL | |
|---|---|
| **Project Title** | **$ (K)** |
| Assist Oxford Superconducting Technology on HTS MRI System (including characterization) | $10 |
| **Total** | **$10 K** |

NREL will provide characterization assistance to the MRI project. This is an essential aspect of the project enabling the primary team to understand various factors that can result in technological success.

# FY2004 Activities

The Superconductivity Program is dedicated to ensuring program success. This is accomplished through two primary program tools. Risk mitigation (Readiness Reviews) and the Annual Peer Review. The Superconductivity for Electric Systems Program has formulated risk mitigation practices that encompass sending out small independent teams of experts to the laboratories, in order to evaluate all possible failure modes of each project. Readiness Reviews focus on early detection of all possible failures regardless of probability. The result of each evaluation is then provided to the Superconductivity Partnerships with Industry Team and the Department of Energy. A copy of a presentation highlighting the Readiness Review teams intentions, goals, and results follow the SPI projects presented below. Appendix B provides an example of a risk probability report concerning a cryogenic system.

The other program tool focused on program success in this report is the Annual Peer Review (Agenda attached as Appendix C). This review was designed to provide peer evaluations. In FY2004, the review began with presentations of research overviews from the international panel. Progress reports in the system development activities were presented by all Project Leaders of the Superconductivity Partnerships with Industry (SPI). The systems development projects are carried out by vertically integrated teams composed of a technology user, an equipment manufacturer, and HTS wire supplier, and the project teams usually include a DOE National Laboratory. SPI projects receive quarterly reviews at field location in addition to this review. The following are summaries of the FY2004 SPI projects and Project Fact Sheets describing the goals and performances so far can be located in appendix A.

***SPI Readiness Review Program:*** The focus of this project is on collaboration with the SPI team to identify potential failure modes; issues involving cryogenic temperatures, vacuum and high voltage dielectrics are a major concern. Expertise is obtained as needed from national laboratories, universities, and consultants. M. J. Gouge (ORNL) and Jim Daley (DOE) provided an overview of the proposed SPI oversight program at the January 2003 DOE Wire Development workshop and the program began in March 2003. The objective for 2004 is to provide at least one review of all active SPI projects.

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# Superconducting Partnership with Industry: Readiness Review Update

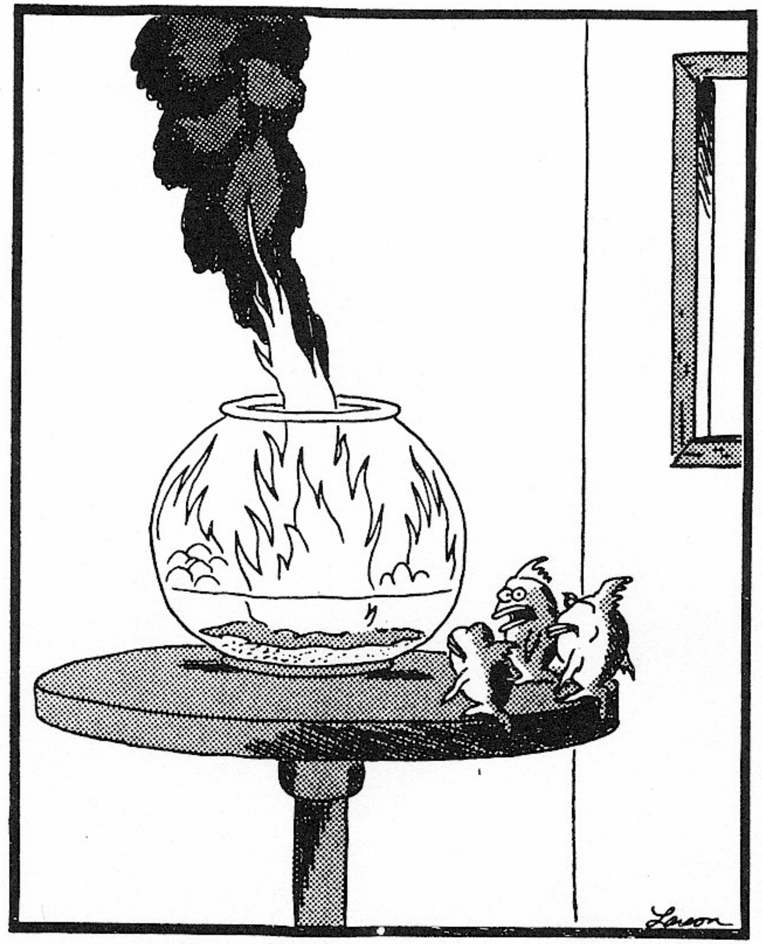
Mike Gouge, ORNL
Steve Ashworth, LANL
Paul Bakke, DOE-Golden

DOE 2004 Superconductivity Peer Review
July 27-29, 2004

SUPERCONDUCTIVITY FOR ELECTRIC SYSTEMS

# SPI Readiness Review Program

- **Goal: enhance the probability of successful completion of SPI projects.**
- **The major tool is phased readiness assessments:**
  - **Focus is on early identification and resolution of <u>technical</u> issues**
    - issues involving cryogenic temperatures + high voltage are a major concern
  - **Performed by a small group independent of the SPI team being reviewed (from national laboratories, universities, consultants).**
  - **Emphasis is on an objective technical review: in-depth but not an audit nor confrontational.**
  - **Report goes directly back to SPI team with a copy to DOE only.**



"Well, thank God we all made it out in time. ... 'Course, now we're equally screwed."

Budget: $140 K/year from DOE
$40 K-LANL (3 cable projects)
$100 K-ORNL (all other projects)

# Anticipate 3 reviews over an SPI time cycle

- **Phase 1**:
  - Shortly after the SPI award (typically during conceptual design), hold initial meeting to review the technical proposal and identify those system aspects potentially likely to repeat past problems or lead to new ones.
  - Identify resources and activities needed to address any potential problems.
    - Is the team organization/resources sufficient to address technical challenges?
    - Are incremental scaled-models and/or prototypes planned to reduce technical risks?
  - Meeting length – about 1 day.

# Anticipate 3 reviews over an SPI time cycle

- **Phase 2**:
  - Prior to hardware procurement/fabrication (in the final design phase), review those critical areas where redundancy or back-up systems may be needed or where team prior experience may be limited.
  - Potential problem areas are vacuum system integrity, high voltage details, partial discharge, heat loads, unanticipated heating sources, thermal stresses, transient mechanical loads, etc.
  - Would require 1-2 days on-site with discussion of:
    - plans to prevent potential problems and
    - component/subsystem testing to qualify system prior to assembly.
  - Non-disclosure agreements will be signed by reviewers if required.

# Anticipate 3 reviews over an SPI time cycle

- **Phase 3**:
  - Before system operation (for example, tie-in to the grid) do a final review to:
    - confirm that the phase-2 review concerns have been resolved
    - inspect the as-built hardware.
    - At this stage safety systems (to protect personnel and hardware) could be reviewed in some detail.
  - Look over project test plans to ensure completeness (for example, generation of data for technical standards for new technology).

*"'Be Careful'! All you can tell me is 'Be careful'?"*

# Peer Review Interface

- At the annual DOE peer review:
  - Each SPI team should present "readiness" preparation activities in accordance with the revised evaluation criteria.
  - Only non-proprietary information will be presented.
  - Have asked the two cable projects that not being reviewed in the SPI sessions to present status of risk mitigation in the Tuesday morning overview session
  - Peer reviewers provide feedback on readiness review program implementation.

# Relevant 2004 evaluation criteria

- **FY 2004 Performance/ FY 2005 Plans:** (SPI Panel: Included in this area for SPI projects is how the team is identifying, managing, and mitigating risks to a successful demonstration over the 2-year evaluation window.)

  **FY 2004 Results**: The presenter should identify major risks to a successful outcome, how they are mitigated (via a focused R&D program and/or redundancy, for example) and progress made during the last year on risk mitigation. (SPI Panel: Included in this area are results and recommendations from the phased SPI readiness reviews by the independent review team chartered by DOE.)

  **Research Integration**: Private sector presenters will describe how collaborations have accelerated their ability to overcome problems and mitigate risks in progressing towards commercial products and applications.

- **Bottom line**: How well is the team addressing technical risk mitigation?

# 2004 Results

- Four SPI readiness reviews in FY 2003
- Eight reviews to date in FY 2004
  - Four HTS cable project reviews
  - Two MFCL reviews (at SuperPower)
  - HTS Open Geometry MRI review
  - Flywheel electricity system with superconducting bearing review
- Reviews of the HTS motor project and 100 MVA Generator planned in August/September 2004

# SPI Readiness Review 2004 Results

| Project | Lead Company | Status (Jul 2004) | Reviews Done | Review Plans |
|---|---|---|---|---|
| HTS transformer 5/10 MVA | WES/ SuperPower | 5/10 MVA tests complete | Test program 6/2003 | Fall 2004: lessons learned |
| HTS motor 5000 HP | Rockwell | R&D | | August 2004 |
| Ultera long length HTS cable at AEP | Ultera (Southwire) | Design/ R&D/ prototypes | PDR: February 2004 | |
| Reciprocating magnetic separator | DuPont | Magnet complete/ assembly | HTS solenoid CDR: 3/2003 | TBD |
| Superconducting flywheel | Boeing | Testing @ 100 kW (Phase 2) | Oct 2003 | |
| HTS 100 MVA generator rotor | GE | Design/R&D/ fabrication | CDR July 2003 | PDR ~Sept 2004 |
| Open MRI | Oxford Inst. | Design/ fabrication | CDR: Nov 2003 | |
| Matrix fault current limiter | SuperPower | Design/R&D/ prototypes | CDR:Oct 2003 Tests: May 2004 | |
| Long length HTS cable at LIPA | AMSC/ Nexans | Design/R&D/ procurement | CDR Nov 2003 Termination March 2004 | |
| HTS cable at Albany (NYSERDA) | SuperPower/ SEI | Design/R&D / procurement | CDR Dec 2003 | |
| Follow-on transformer R&D | WES | Under discussion | | TBD |

# Cable Project Reviews

- LIPA AMSC-led cable project reviewed in November 2003 and March 2004 (termination only).
- Albany SuperPower-led cable project reviewed in December 2003
- AEP Ultera-led cable project reviewed in February 2004.

# The SPI Cable "Readiness Reviews"


## Steve Ashworth, LANL

Andreas Neuber, Texas Technical University

Joe Waynert, LANL

Roland George, DOE

Paul Bakke, DOE


SUPERCONDUCTIVITY FOR ELECTRIC SYSTEMS

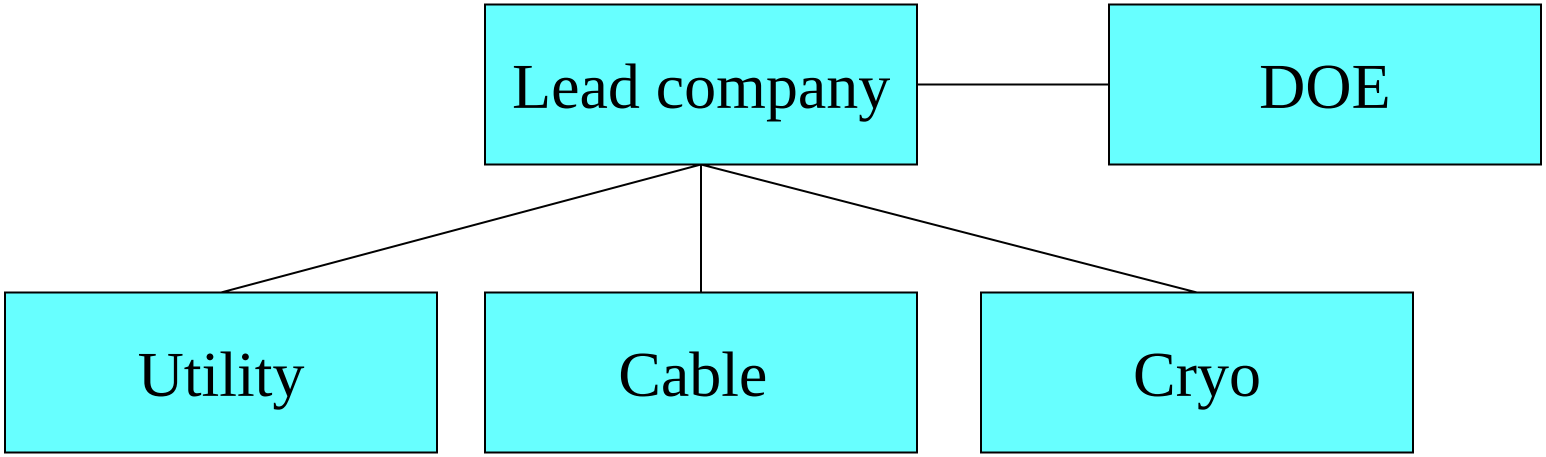
# Cable Readiness Reviews

- Project overviews
- Background – why do reviews?
- Review process
- Reviewers ‘philosophy’
- Examples of this philosophy
- The ‘big’problems
- NOT included: discussion of ‘specific’ risk items - confidential

# Why reviews? Past experience Detroit-Edison Cable

- Cable failed after installation
- Specific failure mode can be avoided in future
- This failure 'haunts' all SPI projects
- Learn from it and  change system
- We cannot allow this to happen again!

# Project structure not changed!




- How does DOE “see” into technical details of project
- Who questions technical details, requests further work
- Outside of company influence
- Review team can “see” everything

# Is this openness a problem for SPI team?

- Everybody is ‘haunted’ by Detroit-Edison cable
- All teams realize “we cannot fail” this time
- Failure is worse than losing ‘IP’
- This has presented fewer problems than expected
- Credit to SPI ‘lead’ companies
  - They’ve had to sell this to their partners
- Sometimes material is ‘eyes only’, but it has always been provided when requested

# The SPI Cable Projects

- Long Island Power Authority (LIPA) Project
  - American Superconductor
  - Nexans
  - LIPA
  - Air Liquide
- Albany Cable Project
  - Superpower
  - Sumitomo
  - Niagara Mohawk
  - BOC
- AEP Project
  - Ultera (NKT, Southwire)
  - AEP
  - Praxair
  - ORNL

# Review Process

- 1 – 2 days on site
- Presentations on all aspects of project
  - Presentations by technical people not ‘management’
  - Detailed technical questioning
- Encourage as many people to attend from SPI Team as possible
- Significant output from the review is that everybody in the SDPI team gets to see everybody elses work
- Communication (see later!)
- Nothing “off limits”, no question too sensitive

# Post-Review

- Project leader prepares “Risk management document”
- This is the most important ‘paper’ outcome of the review
- Captures all items raised by review panel
- Based on teams Internal Risk management procedure
- Emphasize review is only *part* of risk management
- Chair prepares report

# Risk documents are different but fulfill requirements

| Number | Requested by | Date submitted | Sub-system | Agreed response due date | Response by, Owner | | Close Date |
|---|---|---|---|---|---|---|---|
| 10/03-01 | Ashworth Neuber | 11/14/03 | Cable Terminatio n | January 28, 2004 | Nexans/ Schmidt | | |
| 10/03-02 | Ashworth Waynert Neuber | 11/14/03 | Cable | January 28, 2004 | Nexans/ Schmidt | | |
| 10/03-03 | Ashworth | 11/14/03 | Cable | January 28, 2004 | Nexans | Technical report on ** | |
| 10/03-04 | Ashworth Neuber | 11/14/03 | Cable | Febuary 20, 2004 | Nexans | Technical report on ** | |
| 10/03-05 | Ashworth | 11/14/03 | Cable | to be discussed with Swarn# | AMSC, Nexans | Three phase electrical ** | |
| 10/03-06 | Ashworth | 11/14/03 | Cable | March 31,2004 | Nexans | ** model | |
| 10/03-07 | Ashworth | 11/14/03 | Cable | January 28, 2004 | Nexans | Over Ic conditions ** | |
| 10/03-08 | Ashworth | 11/14/03 | Cable/Wire | June 30, 2004 | AMSC/Masur | The statistical sampling plan is **. | |
| 10/03-09 | Ashworth | 11/14/03 | Cable | March 31,2004 | Nexans | AC losses effect ** | |

- Small selection of risk items shown above from one review
- Comments are actually much more detailed, but confidential
- Document is updated by project leaders

# Another example….

| Tracking # | Code (see 'Key' sheet) | Reviewer | Comment | Assigned To | Priority/ Severity | 1st Response Date | Resolution Date | Comments |
|---|---|---|---|---|---|---|---|---|
| 12 | C | Weynert | There should have been a presentation on the analysis of ***** | SEI | B | 2/9/04 | Next RR meeting | |
| 18 | C | Weynert | Is there an issue with zero sequence network behavior ***** | SEI | B | 2/9/04 | 02/23/04 | |
| 27 | C | Ashworth | Forces during cable installation*** | SEI | C | 2/9/04 | Next RR meeting | |
| 6-d | C/TERM | Weynert | Would like to see more modeling/results on... **** | SEI | B | 2/9/04 | Next RR meeting | SP suggests combining with #27 |
| 31 | C | Ashworth | ** 2-D electromagnetic model of the cable detailing *** | SEI | B | 2/9/04 | 03/05/04 | |
| 51 | C | Neuber | Establish that the mechanical stress on the terminations **** | SEI | B | 2/16/04 | Next RR meeting | |
| 9 | C/TERM | Weynert | The differential thermal contraction of **** | SEI | B | 2/16/04 | Next RR meeting | SP suggests combining with #51 |
| 8 | FC | Weynert | ** there may be breakdown if ** | SEI | A | 2/16/04 | Next RR meeting | |
| 6-a | C/TERM | Weynert | Would like to see more modeling/results on ** | SEI | B | 2/16/04 | Next RR meeting | SP suggests combining with #8 |

# Reviewers Philosophy and Program Structure

- These companies know what they're doing
  - WHEN they're in their area of expertise
- Look for companies operating outside their area
- Look at the interface

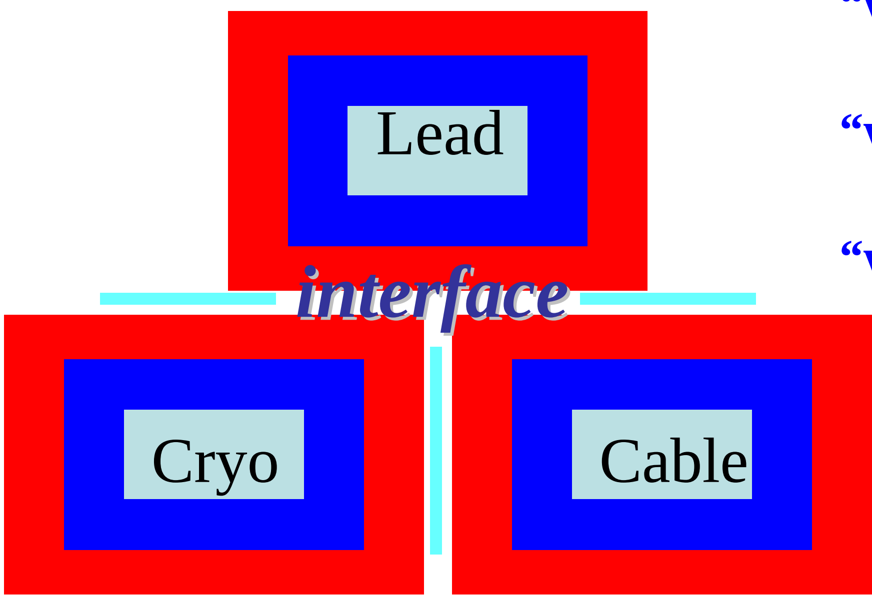
**"we have an expert in house who designed it"**

**"we've made one before and it worked"**

**"we have a person who knows something about this"**

**"we subcontracted it out, and they've done similar things"**

**"we have an acceptance / test plan**

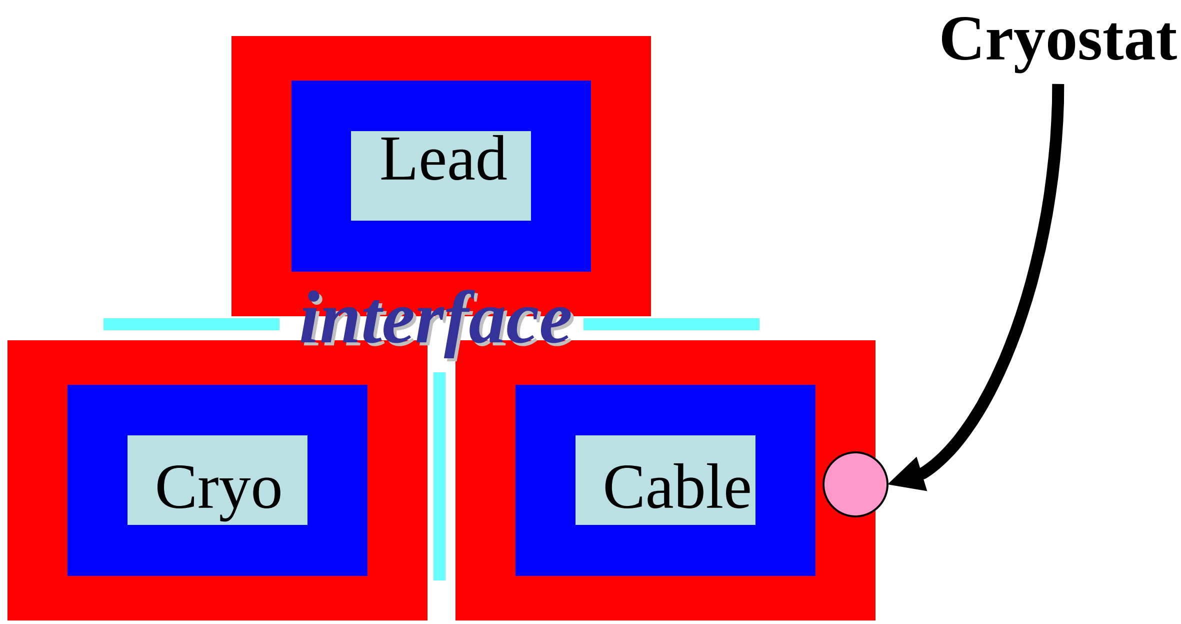



**"it's a new area for us"**

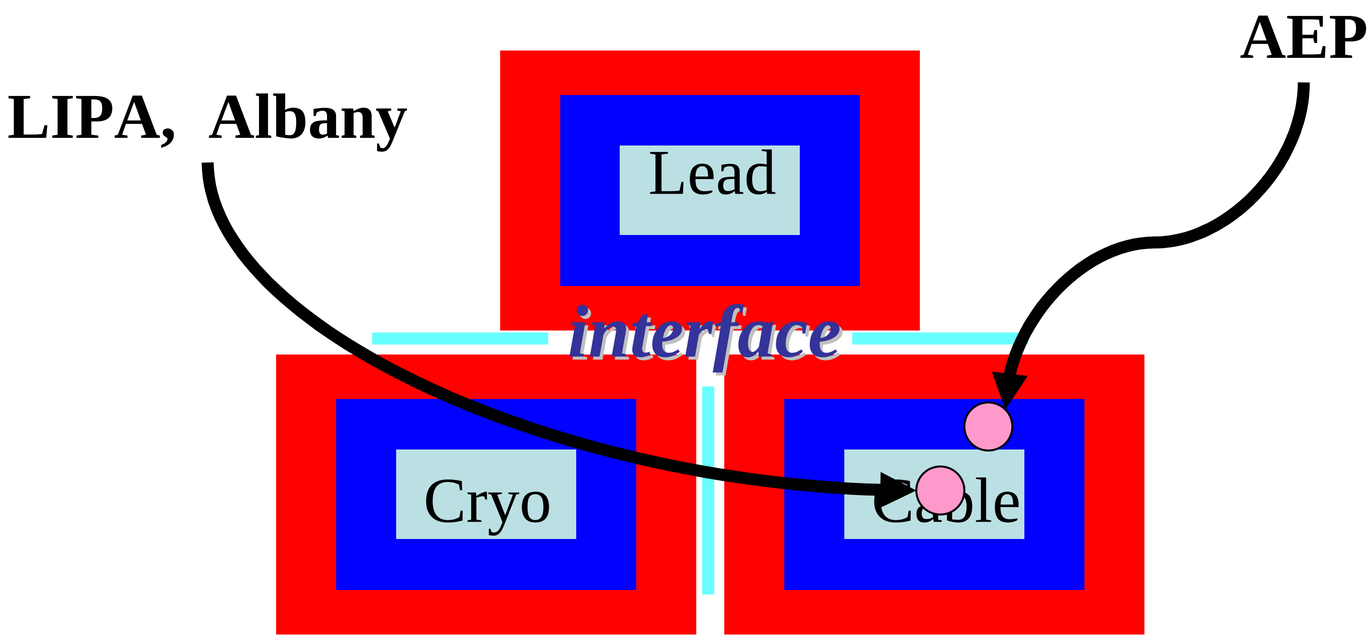
**"we don't have in-house expertise"**

**"we don't have a formal acceptance / test plan"**

# Failure item in Detroit-Edison was outside all 'cores' and visible only to one partner



That specific risk now reduced. Cryostats are being manufactured by Nexans and Sumitomo. Both have track record and experience




Partners now have more visibility into each others work.

Due in part to review process

# Examples of things that can go wrong at interfaces

Detroit-Edison Frisbee substation, August 03

- Trying to loosen bolt on bus bar system
- DE worker provides wrench
- ½" wrench fits 12mm bolt quite nicely
- Until you put force on it, then it slips
- Painful mashed knuckles into copper bus bar

**Teams have been told**

**"know where mm end and inches begin"**

# Example of things that *will not* go wrong at interface. #1

- Cryo company providing LN plant.
- Experienced in building, operating, maintaining complex LN system
- Sensors, computers, actuators – state of the art
- Reviewer: “have you ever operated a LN plant in multi-kV environment?”
  - Sensors mV?
  - Computers ???

**Review showed that this item was incorrectly assumed to be in ‘core’ of team member,**

**needed more thought**

# Example of things that *will not* go wrong at interface. #2

- Reviewer Question "LN dielectric integrity *after* a fault ? "
- Answer (Cable co:) "not important, breaker open, voltage goes away"
- Voice (Utility) "er…actually..we only disconnect at one end – cable can still have voltage"
- Discussion follows….
- "two breakers…linked, disconnect both ends…no voltage"
- Voice (Utility) "er…charging voltage stays until drained…"

**Review stimulated communication through interface within group**

# Where are the greatest risks?

- Fault Currents
  - These are driving cable designs
  - Outside limits of experience
  - Not able to test adequately
- Thermal contraction
  - LIPA cable will contract over 20 feet!
  - Companies being very creative in solutions
  - Philosophy: “solve for now” or “solve for ever”?
- Cryostat
  - Damage on installation
  - Lifetime?

# What's wrong with the process?

- Lots of common problems
  – sometimes 3 solutions!
  – Cannot all be the 'best' solution
  – All should work !
  – Reviewers CANNOT pass solutions along
  – Reviewers DO ensure that common concerns are passed along!
- Only three reviews in project lifetime
  – Perhaps too much is happening between reviews
  – We are trying to keep updated but..
  – Closer contact perhaps (short monthly update?)

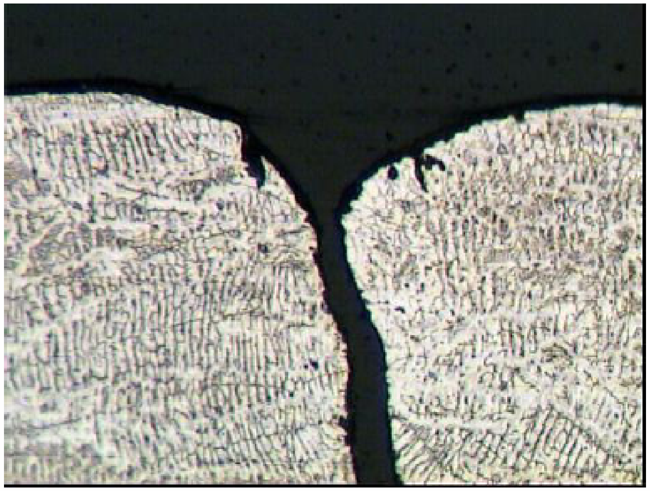
# Continuing concerns? Test Plans

- Approaching “Final design”
- Number of ‘risk items’ need resolving
- Teams all have test plans (short sections)
- Ask each team to ensure testing is integrated with ‘risk document’. Catch everything
- Will be discussing expanding testing
- Is “qualification” appropriate
  - Certainly for ‘voltage’ on cable and termination
  - How about ‘current’, bend?

# HV issues on past projects

- **Project 1** "…it would seem likely that the primary cause was a local increase in (vacuum) pressure which drove the operating conditions towards the minimum of the Paschen curve which resulted in a loss of dielectric integrity."
- **Project 2** "Flexible cryostat is manufactured with the in-line welding and corrugating technique. T.I.G. welds ensure leak proof welded tube."
  - *"Several micro-cracks detected in inner corrugated tube"*
  - *"Analysis also suggests material characteristics contributed to defect origins rather than solely welding process anomalies"*
  - *"Weak spots may have turned into complete fractures upon the further mechanical stress of installation"*

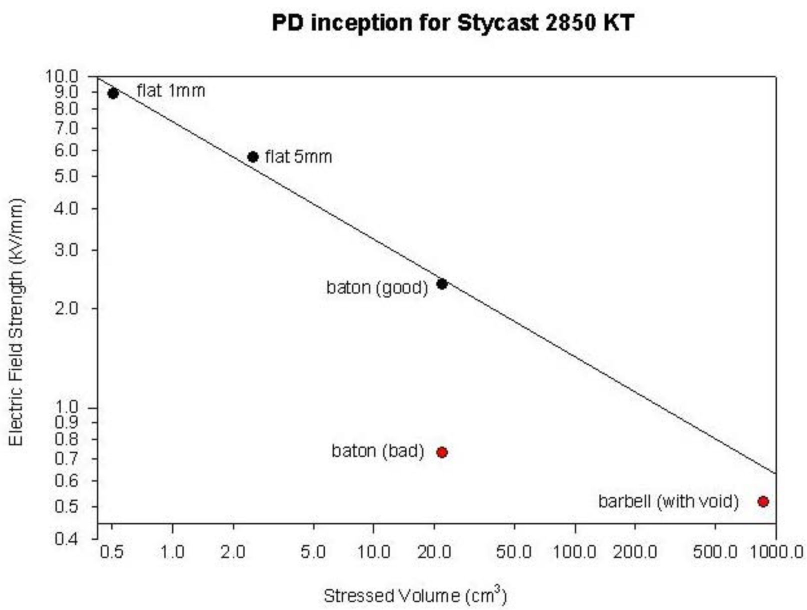
**Optical Microscope – Sample 1**

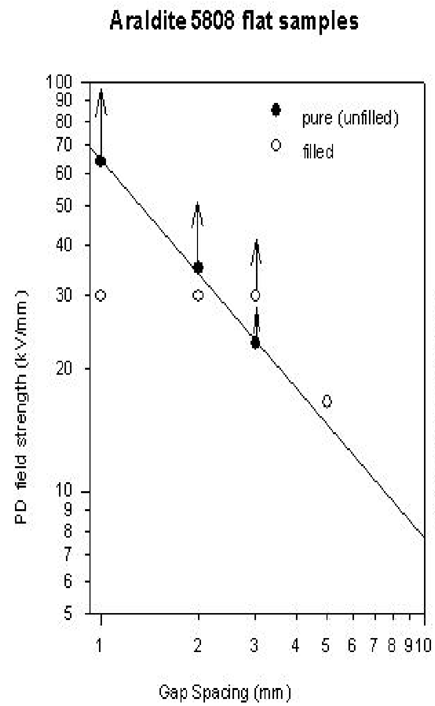


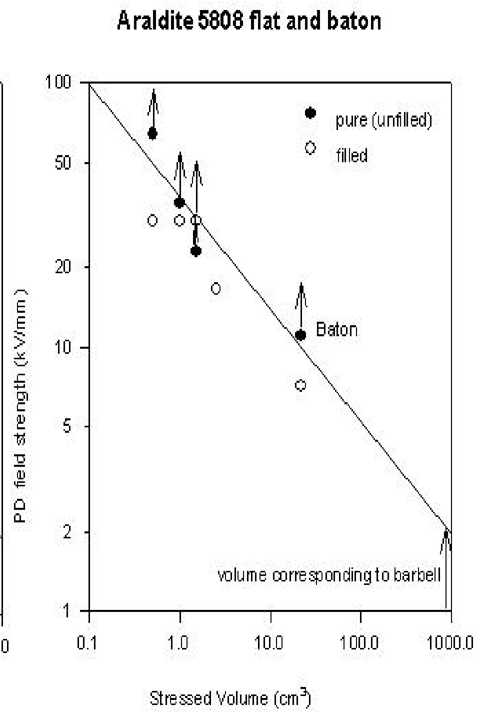
Crack detail on outer surface

# HV issues on present projects

- **Project 3**
  - "All 3 phases exhibited PD inception at very low voltages"
  - "Dielectric failure at less than rated voltage"
  - "All three phase sets failed in different places"
  - "Epoxies generally lose strength for large stressed volumes; problem is worse when defects such as bubbles are present; scaling with volume generally not known for most materials"
- Data from **Project 4**:




SUPERCONDUCTIVITY FOR ELECTRIC SYSTEMS

# 2005 Plans

- **All of the SPI projects will have been through at least one review cycle by August 2004. For 2005:**
  - At least one review per project is planned in 2005 and 2006 as the SPI projects proceed to initial commissioning.
- **We are encouraging all the SPI projects to develop risk identification and mitigation processes such as failure mode and effects analysis (FMEA) to manage risks.**
  - Will review each project's risk mitigation plans in 2005
- **In 2005 a web-site will be implemented that will have:**
  - lessons-learned from prior SPI projects
  - some general design guidance on high voltage, vacuum, etc. and
  - a place where SPI participants can post comments or questions and get feedback.

# 2005 Plans (continued)

- **Based on continuing issues with the performance of dielectric materials at cryogenic temperatures and at high voltage, more emphasis is needed on R&D and design guidelines in this area for the grid-based SPI projects.**
- **A High-Voltage Cryogenic Dielectric Workshop is being considered; it could be held just after the 2005 Wire Development Workshop.**
  - **Participation by each SPI team facing high voltage component qualification would be expected and the agenda could include some overview talks on liquid nitrogen dielectrics, solid dielectrics, HV design practices, etc.**

# Research Integration

- **Since the reviews contain a large amount of proprietary material, the results and recommendations are typically shared only between the project being reviewed, the reviewers and DOE.**
- **The reviewers, to the extent possible, highlight or flag potential problem areas that they have learned from other project reviews.**
- **The proposed web-site and workshop will be a way to share generic lessons-learned and design information.**
- **Have engaged review staff from 2 DOE labs, 1 DOD lab, a university and outside consultants to leverage expertise.**

# FY2004 Peer Review

Thirty-four reviewers on four panels (Second Generation Wire, Superconductivity Partnerships with Industry, University Research, and Strategic Research) reviewed a total of 36 projects over a three-day period. The titles and summaries of the projects presented during the review are available in Appendix A. The criteria used by the reviewers to evaluate the projects in this performance-based evaluation were:

Current year results (50% of the overall score) – comprises the bulk of the total score; this includes accomplishments made throughout the year and the relevance of the results to the program's stated mission.

Current year performance and next year's plans (30% of the overall score) – based on the researcher's ability to the objectives stated at the prior year's review and the continued direction of the project for the following year.

Research integration (20% of the overall score) – is how well the project team leveraged resources (i.e., funds, capabilities, facilities, etc…) by teaming with private companies and other organizations.

Reviewers are also asked to comment on project strengths and weaknesses, recommended additions or deletions, and give general impressions and other recommendations. A brief synopsis of the Reviewer findings for the research projects in each panel are summarized below.

**Jim Daley, Superconductivity Program Manager, welcomes the 2004 Peer Reviewers and presents the review guidelines**.

**During the open plenary session, the audience listens attentively to the International R&D panel.**

## Wire Panel

The 2004 Peer Review included eleven continuing projects. Overall it was generally agreed that the FY 2004 performance followed the plans outlined at last year's peer review and while most of the 2004 projects were logical, some requited a more quantitative milestone. Reviewers praised the FY-04 results, judging them as "good to excellent." Research Integration for all projects was rated "very good."

***2G Wire Session Reviewers*: (l to r) T. Haugan, A. Lauder, G. Deutscher, C. Park, H. Freyhardt, L. Fritzemeier K. Salama, and H. Weinstock. (not pictured H. Neumueller)**

## Superconductivity Partnerships with Industry (SPI) Panel

There were nine SPI projects in 2004. The reviewers indicated that the project plans were generally accomplished and the 2005 objectives are appropriate for the logical continuation of the work completed to date. FY -2004 results were slightly lower than 2003 scores. This shift in overall results indicates that the reviewers have places high expectations on the projects currently conducted.

***SPI-Related Research Session Reviewers*: (l to r) R. Eaton, M. Park, J. Cave, S-M. Hsu, S. Dale , E. Hahn, P. Duggan, S. Akita.**

## Strategic Research Panel

Nine projects were reviewed in 2004 with an emphasis being placed on characterization by the panelists. The projects performance and results ranked "very good" to "excellent." Research Integration scores indicate that some improvements can be made in FY 2005.

***Strategic Research Session Reviewers*: (l to r)**
**P. Grant, D. Gubser, S-W Chan, B. Strauss, F. Lange, B. McCallum, J. Wu, M. Cima, and D. Norton.**

## University Research

Seven University projects were reviewed, and determinations of "fair" to "excellent" were provided in relation to accomplishing the FY-2004 goals. The 2005 plans were considered appropriate, and the results also scored as "fair" to "excellent." Reviewers indicated that research integration should be improved in six of the seven projects. The outlier project earned a ranking of "very good."

***University Research Session Reviewers: (l to r)***
**K. Gray, H. Christen, D. Lee, T. Holesinger, L. Civale, V. Maroni, M. Paranthaman, and V. Matias.**

### Distribution of Review Scores

Each year, the Peer Reviewers are given a recommended rating scale to calculate by the weight of each criterion to determine an overall score for the project:

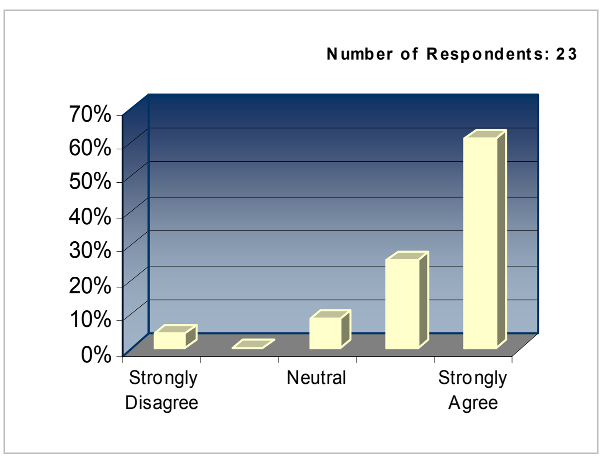
| | |
|---|---|
| 9 -10 | Excellent |
| 7 – 8 | Very Good |
| 5 – 6 | Good |
| 3 – 4 | Fair |
| 1 – 2 | Not Adequate |

The distribution of scores for all the projects show a general increase through the years in the percentage of projects rated as excellent and very good. This increase in review scores is the result of improving lower ranked projects or eliminating weak ones from the Superconductivity Program.

## FY2004 Program Evaluation

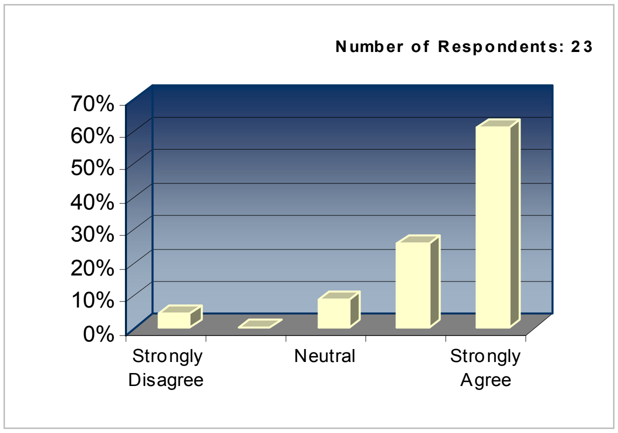
Peer Reviewers were asked to rate the overall Superconductivity Program by answering the subsequent set of six questions highlighted in the following section and to provide his or her perception of the DOE Superconductivity Program as a whole. Reviewers were then asked to comment on the programs mission and goals, productivity and accomplishments, technology transfer, the role of DOE, and new approaches. The following scores and comments were compiled from these evaluations

**I-A. MISSION AND GOALS:**
**Have the Program's research mission and goals been adequately defined and reflect the present status of science, technology, and needs of U.S. industry?**




*The program's mission and goals were viewed by 87% of the respondents to be adequately defined and reflects the needs of industry. This year, more respondents were either neutral or strongly disagreed with the majority. This trend may suggest that our mission and goals may need to be slightly revised or updated.*

### I-B. Is the program moving into applications at the proper pace to meet market needs?




*In 2003, 100% of the respondents either agreed or strongly agreed in the application pace of the program. This year there was more of a distribution of responses (4% disagreed, 18% neutral, 78% agreed and strongly agreed). The program may need to consider ways to accelerate development of SPI to meet market needs.*

### I-C. What would you add to, or delete from the program's mission and goals?

- The program goals should include not only prototype demonstrations, but also, demonstrations of feasibility in the actual power systems.
- Nothing.
- Fault current limiters are a critical enabling technology that needs to be accelerated (see detailed comments).
- Utility planners and modeling discussions and meetings/sessions at Peer Review.
- "Waste Water Treatment with Magnetic Separation" should be deleted, since this is not related to utility business. "Albany cable" and "LIPA cable" should be added.
- To my opinion the M&G include everything necessary for the introduction of a new technology. I would emphasize to use the wording "technical or practical" HTS conductors in the present stage of development. The time to meet market needs shrinks. We all know that we have a time window and this window is largely influenced by the materials and cryogenics – and – especially for electric power – by reliability and customer acceptance.

  Summarizing the results of the SPI projects up to now reveals that many problems exist for the combination of cryogenics, vacuum and high voltage. These problems should be generally solved within a platform project involving experienced electro engineers. This task could be headed by ONRL or LANL. Considering success in YBCO tape in reach it is highest time to promote the development of reliable, low service and low cost refrigerators especially for transformers, motors and generators (500W/77K, 100W/25K cold power). This task probably needs some rearrangement of the budget by reduction and focusing of the still broad material development.
- Rather than "Required" I would like to the DOE's mission "to enable" us companies . . . the goal should include the $/kA-m objectives deemed necessary for adoption.

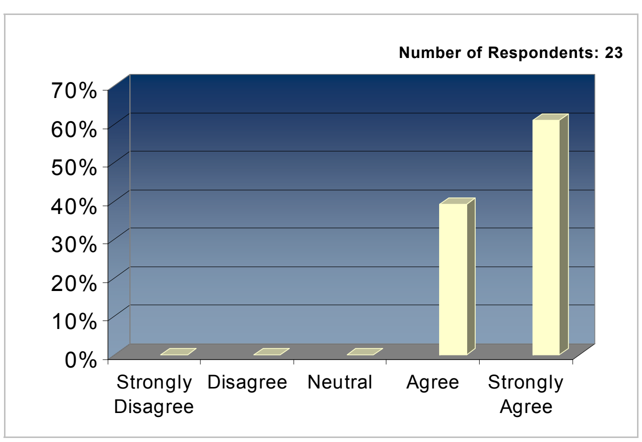
- This year in particular the program mission and goals are well defined since the scale-up processes are yielding good results. From now on, the mission should be focused on scaling up.
- The science of HTS materials has been well studied and documented. It is time to move to engineering conductors. It is clear to this reviewer from some of the SPI presentations on the first day that the needs of the equipment manufacturers need to be taken more seriously. Optimization of conductors is not just increasing $J_c$ and $T_c$. It is a multi-parametric optimization. AC losses need to be taken into account.
- Mission goals are forward thinking, and need no major change. In wire approaches, I would suggest that on YBCO be funded, and emphasis be place on MOD routes to, including the MgO coated wires produced by LANL. It is obvious that others abroad are attempting to learn MOD approach, at institutions and industry.
- Mission/goals are concise, precise and clear – no changes. Structure of the Peer Review is a model that other Departments should follow. Although it is not without risk of criticism to turn “outsiders” loose to critique performance.
- The program goals are visionary.
- Some applications are highly dependent on AC losses being minimized. One of the strategic colas should be to “develop HTS wires with acceptable AC losses for their application.”
- I would put more emphasis on understanding the basic science components (grain boundaries, thickness dependence, etc.) in the university and strategic programs. Gen 1 and 2 far enough along that industry can work on the "mechanics" of long length robots and plug in the "basic" findings later.
- I am concerned that the CRADA’s are too focused on manufacturing problems and are not a two-way transfer of fundamental information.
- Add 1; High-voltage cryogenic dielectric technology analysis program (over 100kV). In case of the real application for power utility, it is the most critical point. Needs to establish a project “Development of the over 100kV class high-voltage cryogenic dielectric technology”

**Comments**

- The Program Goals will be shifted according to the changes of electric power systems environment.
- The HTS electric power equipment needs to be cost effective as compared with conventional equipment.
- Well defined program mission and goals.
- The program appears extremely cost effective with major activities proceeding at cost and many, many cases of commercial support for additional activities to assure thoroughness and good results and progress. Energy storage is also a critical enabling technology (see detail flywheel project comments).
- Very good program addressing todays and the near future needs. Key element – the conductors!
- In the SPI project area, DOE should be cautious to not fund projects that are only modifications of past projects. These types of projects should be left to the industry and not DOE.

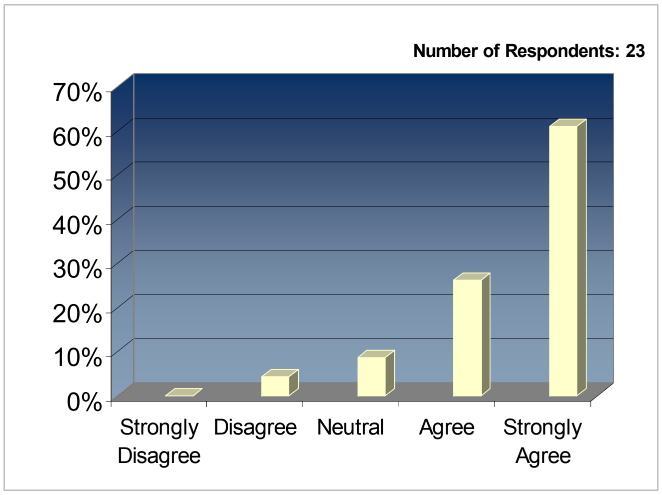
- The progress in YBCO tape development is remarkable. On the other hand it is time now to focus the broad approach to push 2 (AMSC, Superpower) or 3 main routes which scope the market penetration phase within next 5 years. There is strong need to assist the development of a HTS market by more customer lead device projects which underline the benefits and reliability of the HTS technology. The National labs assist the technical conductor development (AC-loss, stability…), the component development and part of the systems integration. More DOE engagement is necessary to involve utilities and big industries (world-wide) in demonstration and pilot projects.
- This is the top program world-wide for the implementation of HTS science and technology in the power sector. It is both focused and broad-based.
- We should always be striving for faster market availability. Windows of opportunity will/could be closing.
- This year in particular the program mission and goals are well defined since the scale-up processes are yielding good results. From now on, the mission should be focused on scaling up.
- The program is driving applications at a pace that can be met by the better performers. The emerging market needs and national needs are critical. Greater funding should be expended on those organizations that would use it to move forward even faster.
- Many new technologies are developed and as many not-that-new technologies are further improved inside this program. To find ways to adopt these technologies to other fields of science and technology can be pursued to the extent that it is not holding back the progress of HTS technology.
- It is proper for the program to expand into industrial applications for HTS. Some of this is now starting and should be expanded.
- This year, all the programs I reviewed were in the 8-10 categories (unlike some in previous years!). The problem is that a few programs were clumsily presented and probably were not rated highly; against the far, more practiced national labs and the WDG.
- Needs to more focus on the power application. In case of magnetic application, LTS is much more advantage than that of HTS.

## II-A. PRODUCTIVITY/ACCOMPLISHMENTS
## Is the program's research productivity remarkable and world class?



*Reviewers unanimously agreed for the second consecutive year that the program's research productivity is remarkable and outstanding (100% agreed and strongly agreed). In 2002, 90% supported this conclusion. This shows that the overall support for the program remains consistently positive.*

## II-B. Have the Program's accomplishments provided a strong technology base for power applications?



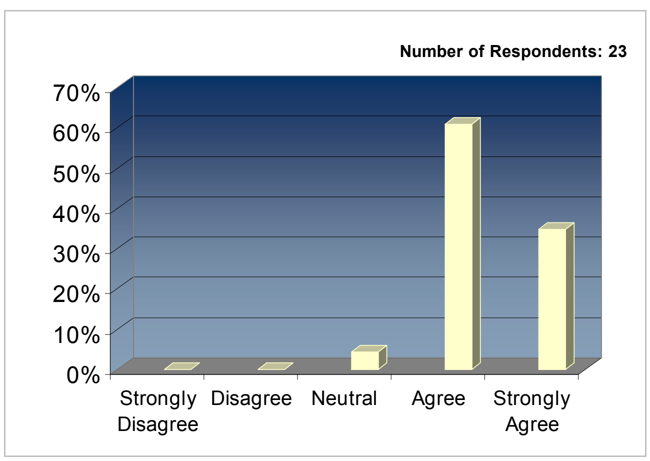

*Reviewers predominantly supported the programs accomplishments (87% agreed and strongly agreed. This strong opinion increased from 2003.*

**Comments**

- More power system study should be added to the program if we want to supply strong technology base for power applications.
- Early termination of SPI project (open MRI) should be prevented for future Projects. The failures of 5/10 MVA HTS transfer should be avoided by adding some appropriate actions.
- Outstanding R&D productivity over many years.
- It is clear that DOE is striving to increase and listen to utility inputs.
- This program has tried and succeeded in transferring information and enabling communication between utilities/national labs/universities and private industry.
- "Generator Project" achieved a lot of important research objectives. I was very impressed.
- Strengthen the technical and product oriented R&D. Recommendation: Focus on the main production lines (TFA, MOCD), Labs and Universities should work with priority 1 on solutions which can be integrated in the existing infrastructure without many changes (buffers, substrates…). Priority 2 should have new (additional) deposition methods or the race for new $I_c$/ width. 300A/cm-w is a good level.
- In the applications, more attention should be paid to cryogenic support systems which have been a weak point in high visibility applications.
- The research productivity is very good. However, there are some duplication among labs.
- Present conductors and conductor configurations have AC losses that seriously limit the competitiveness of HTS applications with respect to efficiency.

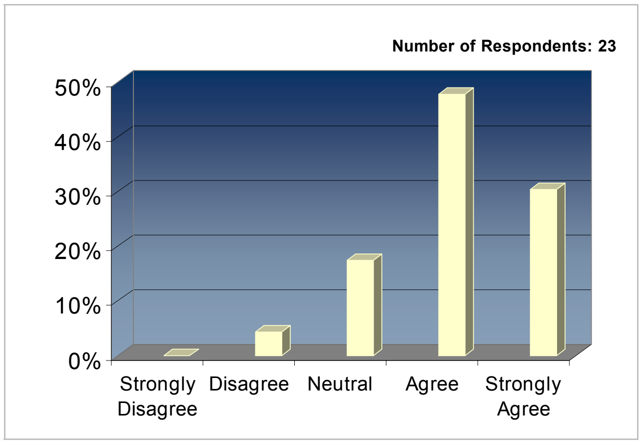
- The major accomplishment this year has been the demonstration that flux pinning will dramatically increase $J_c$ and allow thicker films, with much higher $I_c$, when produced as a multi-layer film (LANL) and with included nanoparticles such as BaZrO3. These flux pinning methods now have to be commercialized.
- Productivity in the past year has been unbelievably high. Disagree only with the verb tense – it should read “are providing” – the job is not yet complete. This in no way detracts from the productivity and accomplishments.
- The program has been streamlined and is nearing minimal level of activity at this crucial stage toward market insertion.
- Outstanding accomplishments so far.
- Developments of HTS based power applications are multidisciplinary. The SPI program should therefore include cryogenic dielectric materials and applications. The SPI program should not include basic development of HTS conductors, but focus on the applications to drive wire development and demonstration of wire capability.
- This year's productivity has been OK. However, the work on meandering and BG overlap has been outstanding (but not all results were at that level), and the cooperation between the national labs has been the best I've ever seen. The integrated technology base established over the last 14 years has been unparalleled.
- SPI is the world lead program of applied superconductivity power application. Always SPI gives the outstanding results of the applied superconductivity power application, this year is also unchanged.

## III-A. R&D PLANNING
**Is the quality of the proposed FY 2004 R&D activities impressive and ambitious?**



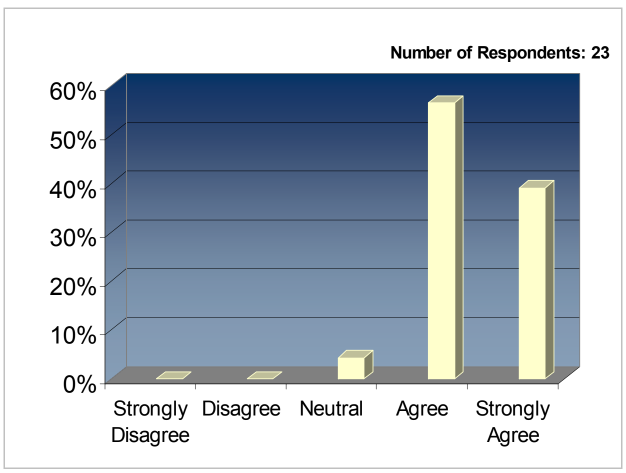

*Only, two reviewers responded neutral to the quality of the FY 2005 R&D activities, while 90% agreed or strongly agreed. In 2003, 100% of the reviewers endorsed the activities whereas in 2002 only 80% did. This is strong evidence that the program has been benefiting from continuous incremental improvements.*

### III-B. Are key research areas receiving sufficient emphasis that will enable the achievement of program goals?




*This year there was a fundamental shift in responses regarding that key research areas are being provided sufficient emphasis to meet program goals (4% disagreed, 17% neutral, 48% agreed, 31% strongly agreed). In 2003, 68% agreed and 27% strongly agreed. This "shift" is most likely do to the FY 2004 budget situation.*

### III-C. Are the R&D milestones realistic and achievable?




*Reviewers agreed that the R&D milestones are realistic and achievable. Overall, 95% agreed and strongly agreed. This is up 13% from 2002 but down 4% from 2003. The reviewers' expectations are higher as the program matures and more successes are achieved.*

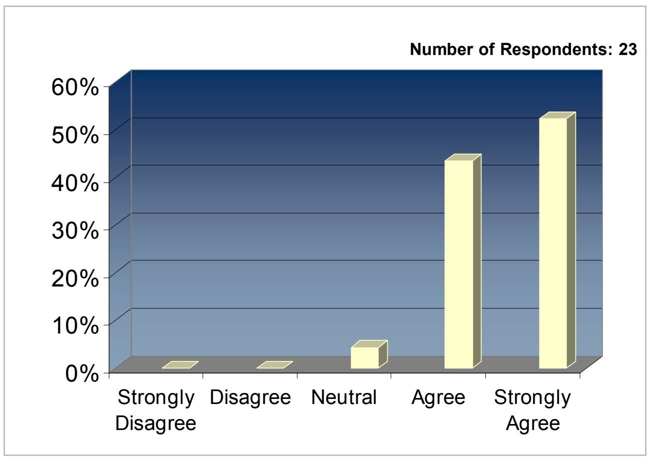
### Comments

- Key technologies in the electric power systems are moving slowly with the deregulation of electric power markets.
- Funding uncertainties facing the program make R&D planning difficult.  In spite of that handicap, the program R&D planning is strong.
- Model sharing (e.g., topography with other applications such as Simulations, Planning, Transmission PRA, and Asset Management), improved cable diagnostics and wireless sensors to support conditions based maintenance.

- This year (2004) has seen an upturn in YBCO progress, due is large part to this program's focus.
- Now I see many "utility engineers" in the review panel (SPI). It is very important. I think we are heading in the right direction.
- To the milestones. The milestones so far have been presented to the reviewers clearly and are becoming realistic earlier than expected. 10 m length, homogeneous, above 1 MA/cm² has been achieved in FY 2003. Remark: the FY 2005 next years plans are tending to more general formulations as, "Further develop high rate processes…", " Scale up IBAD MgO processes to 100m length…" without specifying the Ic in A /cm- w and the homogeneity (< 10%). Remembering the last Peer Reviews there was the dream of all the solution (buffer + YBCO) buffers. Now we are mixing PVD (which was a stopgap solution) and CSD (Chemical solution deposition). This needs a general strategic decision which would involve a new evaluation of the different methods used up to now and their specific impact to a marketable production. This evaluation has to be done by an independent evaluator, as it was the case for the market estimation of HTS grid applications performed by RAND (Richard Silberglitt). Strengthen the technological aspects of CC- wires. Besides electromechanical and AC loss properties a technical conductor also needs an reliable, low cost insulation of high electrical strength which does not waste the current density in the windings (especially in case of motors and generators)
- Some of the programs do not spell out sufficiently their FY 2005 plans. DOE should insist that grantees should spell out their plans in more detail. MOCVD is not sufficiently funded.
- Achievement of 100% of goals is not necessarily positive. I would like to see goals stretched.
- Remaining technological tasks may make it difficult to know whether R&D milestones can be met. One must be careful not to oversell the expected outcomes.
- Cost analysis could be increased as a guiding mechanism for planning. IGC-SuperPowers used this to mostly stop efforts internally on long-length YBCO by PLD.
- Key research areas are not always addressing industry scale-up needs. While ORNL already developed MOD and transferred to AMSC, other labs are still working on it.
- The wire program is now more than 10 years old. The initial period looked promising, but tedious. Today, the end is clearly in sight, with processing details needed to reduce AC loss, make wires cheaper and then to go on to Cu substrates for greater reliability and further cost reduction. If there has been a need for a large government program, this was the proper choice. Without the government (our tax $$), industry could never have substained this effort, which, in the end, will produce much income, and much more tax revenue for the USA relative to most other energy related programs. Obviously, industry, and governments have nearly given up in other countries.
- Largely agree with prepared activities: a) but depends on individual programs, b) the programs are under funded. Considerably more could be achieved with increase. c) The R&D milestones are largely realistic and the historical "sandbagging" to ensure success is rapidly disappearing. The programs need stretch goals and knowledge/understanding on the part of the reviewers (and DOE).
- Areas critical to industry and market insertion must be addressed. "Some" market successes are crucial to the program.

- Key research areas are receiving sufficient emphasis, and it should continue. Further down-selection and more focused funding can lead to better results of the program.
- It's really hard to judge a prior "quality" of proposed research, especially whether it's "excellent" or not. What has been proposed for FY2005 is "reasonable" and in line with what needs to be done, at least for now. I suggest in the future that question III-A be eliminated or re-worded.
- The milestone of the HTS power application is strongly dependent on the development result of 2G wire.

## IV-A. TECHNOLOGY TRANSFER
**Teaming between industry, universities, and the national laboratories is an important element of the program. Are present arrangements appropriate for success and future commercialization?**



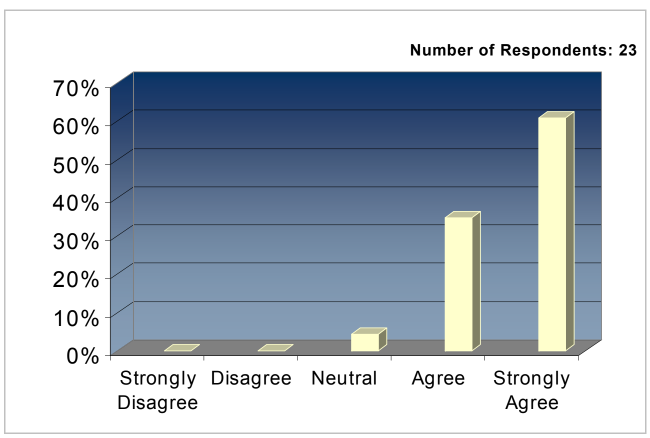

*Reviewers agreed and strongly agreed (95%) that teaming between industry, universities, and national labs are essential. This percentage is reminiscent of last year where 95% of the reviewers also agreed or strongly agreed.*

### Comments
- Power system aspects should be included into the transferred technology and information.
- May consider some level of participation from international entities.
- Very strong component of the program.
- More use of “historically” expert retirees (those who know why not just how) to assure superconductive applications are aware of issues conventional equivalents have already evolved through.
- The new “risk mitigation” approach is essential for success.
- Knowledge obtained during DOE funded R&D should be shared with utility engineers.
- Generally the teaming is very good and nearly in all cases and there is efficient cooperation. The partnerships should include more small companies who could very efficiently do more or less conventional or established tasks (electro polishing, substrate fabrication). On the other hand there are partners which are not very well integrated within the coated conductor

community such as NREL!  There is still room for improvement in cooperation between the different partners. There is still room for the labs to further improve collaborations.

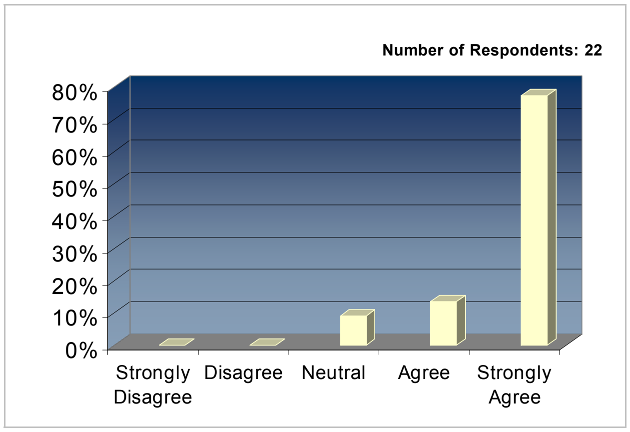
- It can never be strong enough but this program is an exemplar for collaboration!
- The transfer of IBAD to SuperPower and MOD to AMSC is excellent.
- There has been excellent teaming between conductor manufacturers (industry) and the national laboratories and universities.  Based on comments from equipment manufactures in the first morning SPI session, the program needs work on integrating their needs into the conductor development program.
- Several companies are now making 2G wire.  This grew from the program.
- Teaming is essential.  The vertical integration and cross-communication is a model on how to optimize the synergy in complex technological programs.
- Direct involvement with industry is essential.  Those efforts that do this must be well funded.
- The collaboration between national labs and private companies is excellent.  This certainly is a model to be followed by many other fields of science and other countries.  There are teams consisting of private companies and national labs.  Closer collaboration between these teams including the companies (the private companies may not like this) could accelerate the accomplishment of the goals of this program.
- I've commented a number of times that the labs play the role of "corporate" R&D labs for the companies that cannot afford such facilities (AMSC, IGC-SP) or who were never in that business (utilities). Universities need to be more strongly integrated using the model of the WDG.

## V-A. DOE ROLE
## Has DOE performed the proper planning for the success of the Program?




Once again, there was milder agreement concerning the DOE planning and success of the superconductivity program (4% neutral, 35% agreed, 61% strongly agree). In 2003, the reviewers unanimously agree or strongly agreed.

## V-B. Is the role DOE plays in the Superconductivity Program entirely appropriate?




*The role of DOE in the Superconductivity Program was almost entirely endorsed (9% neutral, 13% agreed, 78% strongly agreed. The percentage for strongly agreed is up 10% from 2003. This shows that the program is supporting the appropriate R&D activities and is encouraging collaborations and partnerships with the private sector while leveraging resources and mitigating risks.*

### Comments

- I hope continuous DOE support to the Superconductivity Program directed to the future realization of superconductive power technology.
- More emphasis should be given to transmission applications as what President Bush said "…it's clear that the power grid needs an overhaul. It needs to be modernized. As we go into an exciting new period of American history, we want the most modern electricity grid for our people… we need more investment; we need research and development…"
- This technology could not move forward without the funding and equally important collaboration base that DOE provides on technical issues across projects.
- The DOE has provided the framework for these very valuable collaborations.
- DOE did a wonderful job in timely manner. "SPI Readiness Review Program" is an example.
- The DOE program has proven flexibility over years maintaining always a sustainable R&D thereby. There has been a broad support to promising coating technologies in the first demonstration phase. The continuous support to CSD technologies seem to pay off now and should consequently promote more budgets spending for infrastructure and manpower. Continued effort is still necessary in case of the development of reliable key technologies (refrigeration, cryogenic technology) indispensable for success of the HTS technology and customers acceptance (see platform concept above).
- The annual review is a great venue for helping to refine approaches and stimulating excellence.
- Based on the disappointments with the Detroit Edison cable project and the challenges at Waukesha with the transformer DOE should consider taking a much more active role in production oversight. Challenges with these two projects have resulted from lack of detailed

engineering as well as engineering and fabrication experience with cryogenic systems and could have been prevented.

- Within the limits (fiscal) imposed by Congress.
- One suggestion: Could DOE work with other federal agencies to garner further support for the field? Joint agency funding for joint projects. If this can be worked on, it would strengthen the development and encourage insertion to a broader market.
- This was my first time participating in the peer review. I was impressed by the way DOE is handling this program. DOE is definitely steering the HTS community in the right direction.
- In fact, it is essential for DOE to be the driver for the type of R&D needed in order to reduce the risk of entry by the private sector, both in conductor development and the early development of prototypes and demonstration of the technology in several areas.
- a) In fact, it is essential for DOE to be the driver for the type of R&D needed in order to reduce the risk of entry by the private sector, both in conductor development and the early development of prototypes and demonstration of the technology in several areas. I give this a "5" for the OETD program management, and a "2" for policy management at the under secretary level, given the inability or unwillingness to alleviate the "earmark blitz."

  b) The "Readiness Reviews" are a step in the right direction, but I would go further. DOE should require in-depth closed session technical reviews of each SPI project by commercially disinterested experts from government labs and consultants that probe methods as well as results. Willingness to undergo such reviews should be a requirement for an SPI award contract. There are numerous ways to structure non-disclosure agreements to protect corporate proprietary interests. If I were running such a company, I would welcome the opportunity to get expert advice and oversight...for free,
- The 1st gen program is improving a commercial product. The CRADA's focus is on manufacturing problems.
- DOE plays a significant role in developing applied superconductivity power application technologies. I strongly believe that this is an appropriate role for DOE.

## VI. NEW APPROACHES

**Please suggest any new approaches the Program could pursue to accelerate the development of HTS wire and the development of wire products such as: coils, current limiters, transformers, generators, transmission cables, and motors.**

- International collaboration might accelerate the development.
- More funding needs to be given to SPI project in a timely manner. Some SPI Projects were not performed as planned because of the lower funding than expected.
- More use of expert "historical" retirees. Continue and expand risk review formal process. Lessons learned and web pages are good initiatives. Model more workshops on issues like 2nd Gen Cable Roadmap.
- Utility planners need to be further involved as well as utility network modeling, for example, meetings and/or Peer Review Sessions dedicated to network architectures and modeling.
- "Power Cable" and "Transformer" should also be investigated for aging by conducting an accelerating life-time test. This is very important for utility engineers.

- The progress of 2nd generation conductor allows first steps toward marketable HTS fault current limiters. A major European power equipment manufacturer has already verified prototypes and a lot of experience in such devices. Unfortunately the plate technology used up to now cannot reduce the cost of the switching elements to the level necessary for future commercial products. This company is very interested in the technology and would probably be interested in further collaborations. A first step of such a project is to realize practical basic switching coils which clearly demonstrate the successful approach.
- There should be a better collaboration between the labs. For instance, the group at ANL working on ISD lost in my opinion a good part of this year's work because they used bad hastealloy substitutes. It turned out that excellent substrates are unavailable from LANL.
- The development of wire is excellent, but applications are not as successful. Hopefully by next year, more demonstrations will be available.
- There is no program component to invent/develop small s/c devices that utilize HTS 2nd Gen wire. This would be ideal for a STIR program. The two U.S. companies could sell 2nd Gen conductor to participants or program.
- This program has provided an excellent scientific basis for many issues in high temperature superconductors (HTS). However, if the goal is to provide materials of transformers and motors there must be provision for the design and engineering of conductors with acceptable AC losses. The science for minimizing these losses in superconductors is over three decades old. The program must face the task of optimizing HTS conductors for these applications. The highest $J_c$ or $T_c$ materials may not be optimum and these two parameters should not be the Holy Grail in materials development. For real engineering applications conductor optimization is multi-parametric.
- Once flux pinning positions have been introduced commercially with MOD processing on either IBAD MgO seed layers or Ni (alloy foils, direction should turn to how to make twisted wires by patterning and using both sides of the metal foils.
- Additional competitive programs, e.g., current limiters (need higher DOE funding). Further encouragement through new program starts to reduce commercial power consumption (improve efficiency), e.g., motors and magnetic separations, i.e., reduce demand, reduce manufacturing costs for wire. Greater, more open, discussion of product costs and anticipated savings.
- One suggestion: Could DOE work with other federal agencies to garner further support for the field? Joint agency funding for joint projects. If this can be worked on, it would strengthen the development and encourage insertion to a broader market.
- Down-selection of the number of approaches and more focused funding.
- The program should have a focused effort on understanding and reducing AC losses. This is a driver for several important applications, such as transformers and motor stators. The program must also include a focused effort on cryogenic dielectric materials and application design. Dielectrics and electrical insulation are critical for development of the application technologies such as transformers, motors, cables, and cable accessories (bushings and splices).
- One of the toughest issues to assess is the market draw for superconductivity in an industry that historically has shown little appetite for advanced technology. The only idea I have is to "do it for free...or almost free." The model would be that which jump started the nuclear power industry, that is, the first 10 or so nuclear plants were "cost shared," the utility paying

for what would have been the cost of an equivalent fossil plant and DOE (really AEC) picking up the rest. If a utility needs to put in a new transformer, cables, generators, let's subsidize them accordingly to use superconductivity.

- Establish a program or project which decides the precise specification of 2G wire for each application (transformer, generator, power cables and motors). AC loss of 2G wire, it is hot potato.

## VII. Any Additional Comments

- Thank you for inviting me as a SPI reviewer. This is very exciting work.
- When evaluating future SPI projects, more attention should be given:

  (1) To prevent early terminations;

  (2) To ensure the urgent needs for the transmission applications are taking care; and

  (3) To prevent failures before they actually occur.
- Within the Agency, the overall importance of the superconductivity is relatively unappreciated and that is part of the problem with adequately funding the program. Eliminating that problem is nearly impossible.
- Keep up the good work, but focus on early enablers and start now to work on broad justification of benefits of these technologies just in case government emphasis shifts to renewables. Energy storage (8 hours) to act as "replacement power" is critical to improve industry asset utilization and to create viable economics for renewables that might not be available during peak demands.
- If you can arrange a session for "2G wire status and direction" for SPI panel on the third day, it would be great. SPI reviewers cannot attend any of 2G wire sessions, so we are not aware of any important milestones or current status. For SPI panel, most of them were new members. On Thursday, we did not meet to discuss SPI program. Actually nobody showed up in the reviewer's room. If DOE designates one guy as "captain" he will direct the panel more effectively. (Ed. Note: SPI session was completed on Wednesday and it was up to individual SPI reviewers to meet in the available room. Some SPI reviewers left Wednesday night or Thursday morning. Also, only 3/8 were new reviewers.)
- a) Regarding presentations: very excellent – but again, because of the limited "brain" capacity of the evaluators and the very tight time schedule – please concentrate on main facts, explain the "why" and the "how" you expect to measure. The Sandia presentation was a good example how one can enjoy the reviewers.

  b) Thanks to Jim Daley, to the Energetics staff and all others who have contributed to make this 2004 Peer Review a success. I hope my suggestions can be valuable for your further project planning and HTS technology can demonstrate its power which will be the key for the expected market penetration.

  c) Unfortunately because of the time passed more and more customers gave up and new projects are currently hard to stimulate – especially in Europe and Japan. In my opinion there is still a good chance for success of HTS technology if the wire manufacturers can offer convincing wire performance: 300-400 A/cm-w, homogeneous reliable properties at high production rate and the perspective of low cost wire enabling a cost down to 25 €/kAm in 2008 and down to 10 €/kAm to a least 2012.

- Source of key issues such as thickness dependence of $J_c$ and AC losses were not presented at the 2G wire session, but in a parallel one (University Research Strategic research). This has prevented reviewers from focusing on opinions as to whether these issues that are very important for the future of 2G wire were properly addressed. May I suggest that presenters are not completely free to select the session they want to present their work.
- I would like to see more "industrially" oriented (2G) review panel members to provide a more balanced perspective on the value of activities such as SPI and robust process development.
- While the distinction between performance and results is clear to the reviewers, but most project summaries lump these under a single category. Project leaders should stick to the defined categories. Many presenters ignore the scoring categories until the end of their presentations. They should integrate these into their entire presentation. Generally, Research Integration is highly rated for all projects.
- Technical problems still exist that are best studied by the national labs. Problems with coated conductors are not completely solved: AMSC has achieved good long lengths but there might be cost issues, and they have only started to work on applications that might require IBAD templates. IGC-Superpower has achieved long lengths, but can MOCVD be used for long length processing? The next year should help to clarify issues with both of the companies. Adding risk mitigation analysis/management is a good step.
- Presentations are too long and contain too many details. It could be enough to focus on main points and major achievements. Two days may be adequate. Evaluations by reviewers need more time to reach a better understanding.
- Amazing amount of programs for a tough funding year. Really spectacular.
- This program has provided an excellent scientific basis for many issue sin high temperature superconductors (HTS). However, if the goal is to provide materials of transformers and motors there must be provision for the design and engineering of conductors with acceptable AC losses. The science for minimizing these losses in superconductors is over three decades old. The program must face the task of optimizing HTS conductors for these applications. The highest $J_c$ or $T_c$ materials may not be optimum and these two parameters should not be the Holy Grail in materials development. For real engineering applications conductor optimization is multi-parametric.
- Weed out the weak; bring in new blood and fresh ideas. The competitive approach, e.g., three cable teams, is beneficial, effective, and will lead to lower costs on commercialization. DOE is getting outstanding value for money through the cost share aspect from corporations and other departments, e.g., NIST. Programs seem to start up faster and move forward faster in an industrial vs. laboratory setting. Why? Vertically integrated teams are working well. There is a high level of communication and cooperation between team members.

  Program cut-backs due to budget reduction was applied selectively and not through a uniform percentage across the board. DOE should encourage leadership by taking action (not an easy solution). How can we get a better assessment of value and practicality when process cost data is so proprietary – this could influence program selection considerably. Is there a way to assess industrial contribution/interaction quantitatively for each program? (This is not a job for the reviewers, just DOE.)
- I had to sit in the 2nd gen wire session all day, and had no chance to hear presentations in the strategic research session. Some presentations in strategic research session seem to be

closely related to the 2nd gen wire development. Rather than putting these sessions in parallel, why not putting them in serial? I would not care whether the sessions go into late night. Otherwise, the presentation time for each group can be shorter. Some presentations include so many detailed materials which would not make a lot of difference in the evaluation. The presentation should stick to the scoring criteria rather than showing everything they did in the past year.

- Over the 12 or 13 years the program has existed, certain institutions (e.g., national laboratories, the WDG, AMSC, IGC-SP) have polished their review presentations to an extremely high degree, one might even say approaching a "high theater, glaze their eyes over" performance. The presentations are too long with too much detail. I say this with a high degree of technical experience, competence and personal conceit. If I can't absorb it all, neither can anyone else.

  Let me suggest a different approach. Once the reviewers have been selected and on board, send them the technical presentations beforehand to go over. Then, at the PR, allow only presentations of goals and benchmarks achieved, and leave an hour for an in-depth grilling, an "oral exam," if you will. Choose reviewers known to throw hard balls. A number of other institutions and some industries do not have the experience and "PR skills (PR can be read two ways!)." Having a chance to see the data first and then a long period of inquiry by the panel following the presentation would help a lot.

  There should be a way to better score the "loose cannons" and "bearers of bad news" who don't stay with the program. One presenter who said he'd have to be paid to use Gen 1 tape got excoriated in "hall talk" that followed, but that's exactly the way a competitive company assesses internal technical projects...would people buy it if it were free?

  Finally, in the "I don't get no respect" category, the wonderful work of NIST on phase stability reported yearly goes largely unappreciated, or at best underappreciated. Physicists and engineers should be banned from the review panel or asked to leave the room. Ternary and tertiary (including oxygen) phase diagrams provide the "dictionary" for materials synthesis, but have you ever heard a writer acknowledging a dictionary (or Google) for helping him (or her) construct a novel?

# 2004 Post-Review Meeting
# Key Results

At the conclusion of the Peer Review, it is the practice of program management to conduct a meeting recognizing "world-class" advancements relevant to the superconductivity program. All of the reviewer's scores were tabulated and their comments compiled. Prior to this meeting, the results were distributed to DOE's, Superconductivity for Electric Systems program management team without attribution to individual reviewers. The project managers were also provided with the results and comments for only the projects they were responsible.

The post review meeting was then held on October 19, 2004, to provide the project managers and industry partners with an overview of the peer review results for all projects presented. This meeting was an opportunity for program management to discuss an interpretation of the reviewer's findings concerning the program as a whole.

This year the key thrusts compiled from the scoring of the reviewers are:

- Maintain emphasis on 2G wire research
- Maintain thrusts on supporting technologies and longer, high performance 2G wires
- Continue "Readiness Reviews" on SPI projects to mitigate prototype testing success
- Explore the formation of 2G Conductor Design development and engineering group
- Dielectrics Workshop

During the 2-hour meeting, presentations and discussions covered analytical activities that need to be accomplished on order to recognize opportunities for applications of superconductivity as a solution to transmission congestion, bottlenecks, and delivery problems. The meeting was structured in two sessions. The first session focused on the 2004 results with a presentation given by Jim Daley, Lead, Superconductivity for Electric Systems, followed with an awards ceremony. The second session focused on the concepts and expectations that were plainly stated by the results of the Peer Review. Attendees were primarily members from the National Laboratories, Universities, and DOE. The key results for FY2004 are shown in the following table below.

# FY 2004 Projects – Key Results

| Second Generation Wire | | |
|---|---|---|
| **Project Title** | **Lab** | **Key Results** |
| YBCO Coated Conductor Tape Development with AMSC | LANL | **R&D systems successfully upgraded for longer length**<br>♦ Process confirmation with 1 cm x 34 m @ 186 A/cm-w<br>**Key Equipment designed, ordered and built**<br>♦ Pilot PVD system – installed, qualified at 4 cm width<br>♦ Industrial reaction furnace – in acceptance testing<br>♦ Pilot scale slitting line – in acceptance testing |
| Coated Conductor Tape Development with Superpower | LANL | ♦ Transitions to high-throughput buffer layer technologies developed at LANL to SuperPower's pilot production facility and fabricate several 100 amperes, 2 meter 2G wires using this high-throughput processing technology.<br>♦ Demonstrated 8 m lengths of 4 mm wide conductors slit from 1 cm wide tape with only 1% loss in Ic (sum of Ic of both 4 mm tapes) even though slit without any copper stabilizer.<br>♦ 100 A/cm performance in all 61 m of tapes slit to 4 mm widths for Albany Cable project. |
| Development of Coated Conductors Based on IBAD MgO | LANL | ♦ IBAD demonstrated at 100 meters/hour<br>♦ PLD producing CC meters |
| RABiTS Template Research: Continuous Processing | ORNL | ♦ A major cause for delamination in PM derived NiW substrates was identified, understood and delamination has been eliminated<br>♦ Installation of rolling mill facility with a class 1000 clean room was completed and made the mill was made fully operational<br>♦ American Superconductor Corporation has used this facility on a routine basis for fabrication of wide substrates – materials from this facility are used for scale-up research on wide web processing<br>♦ Long lengths of sharply textured substrates have been fabricated |
| Ex-situ Continuous Processing of YBCO for Coated Conductors | ORNL | ♦ Identified pinning centers and processing parameters responsible for different field dependencies in samples converted in different systems.<br>♦ Investigate differences in solution and PVD precursors responsible for different reaction rates, and increase the reaction rate of PVD precursors. |
| American Superconductor 2G Scale-Up Research (competitive solicitation) | ORNL | ♦ Substrate rolling in 4 cm width at ORNL<br>♦ $Y_2O_3$ seed by reactive sputtering in 4 cm width<br>♦ YSZ barrier in development against benchmarks<br>♦ Mechanical testing of slit wire |

# FY 2004 Projects – Key Results Cont.

| Second Generation Wire | | |
|---|---|---|
| **Project Title** | **Lab** | **Key Results** |
| Coordinated Characterization of 2G Wires with IGC-SuperPower | ANL | ♦ Demonstrated ability to detect localized regions of poor superconductivity, extract representative specimens, and perform detailed TEM analyses<br>♦ Identified impurity phases and isolated local defect structures at the YBCO/buffer layer interface in sections of a 50 m SuperPower tape |
| Phase Evolution & Characterization of 2G Wire with American Superconductor | ANL | ♦ Substrate Rolling in 4 cm width at ORNL<br>♦ Y2O3 seed by reactive sputtering in 4 cm width |
| In-House R&D in the Area of 2G Wire Fabrication by ISD Process | ANL | ♦ Develop simplified buffer layer architecture for the fabrication of CC using ISD.<br>♦ Optimize the inclination angle for ISD-MgO to be ≈35°<br>♦ Achieve in-plane texture of ≈6° and out-of-plane texture ≈3° for YBCO on SRO Buffered ISD-MgO |
| Practical Conductor Development Utilizing High-$T_c$ Oxides: YBCO Tape Processing | BNL | ♦ Optimize the inclination angle for ISD-MgO to be ≈35°.<br>♦ Achieve in-plane texture of ≈6° and out-of-plane texture of ≈3° for YBCO on SRO buffered ISD-MgO.<br>♦ Fabricate 1.6 µm YBCO film with $I_c$ > 100 A/cm-width ($J_c$ ≈ 0.7 MA/$cm^2$) using SRO single-buffer-layer architecture. |
| Non Vacuum Techniques for HTS Coated Conductors | NREL | ♦ Prepare electrodeposited buffer layer for YBCO-coated conductors<br>♦ Demonstrate current density (~$10^6$ A/$cm^2$) of YBCO using electrodeposited Ni film comparable with the reported literature value.<br>♦ Explore techniques for improving Bi-2212 by nanoparticle additions (OST CRADA).<br>♦ Prepare electrodeposited Cu stabilizer on YBCO-coated conductor.<br>♦ Simplify and improve buffer architecture by developing non-magnetic electrodeposition metallic buffer layers. |
| Solution Deposition Processes for Coated Conductors | SNL | ♦ Replace vacuum buffer tri-layer with thin solution buffer.<br>♦ Deposit on Ni-W or Cu-Fe substrates.<br>♦ Increase YBCO film thickness toward 2µm single layers.<br>♦ Decrease YBCO process time. |

# FY 2004 PROJECTS – KEY RESULTS CONT.

| STRATEGIC RESEARCH | | |
|---|---|---|
| **Project Title** | **Lab** | **Key Results** |
| ORNL-American Superconductor CRADA | ORNL | ♦ Textured RABiTS substrates in 10 cm x 80 m were fabricated<br>♦ FM loss at Ipeak ≈ Ic reduced by a factor of 2-3 with Ni-Cr-W substrate. AC loss contribution from Ni-Cr-W substrates is significantly lower than YBCO hysteretic loss<br>♦ Scalability demonstrated for substrate production, PVD deposition and lamination |
| RABiTS-Based Strategic Research | ORNL | ♦ High quality LZO and CeO2 films were produced using solution deposition<br>♦ Nucleation and growth kinetics of solution processed LZO and CeO2 layers were studied<br>♦ Achieved Ic of 213 A/cm-w on LZO seed layers using MOD YBCO |
| Development of Ex *Situ* Processed, High $I_c$ Coated Conductors | ORNL | ♦ New processing has been developed for PVD-BaF2 precursors conversion rates > 10 Å/s (duration < 17 min / μm-thickness) fast conversion provides a vehicle for improving I<br>♦ Performed studies to improve processing of 1-2 μm thick YBCO coatings on RABiTS<br>♦ Established a linear relation between Ic and YBCO thickness in fast processed films<br>♦ Applied results from flux pinning study to further improve Ic<br>o Ic □ 410 A/cm (1.25 μm YBCO)<br>o Ic ≅ 390 A/cm (1.7 μm YBCO) |
| Wire Development Group | ORNL | ♦ Initiate 2G pinning characterization work<br>♦ Field-angle Ic characterization and TEM at LANL on AMSC 2G wire reveals correlated pinning from planar grain structures dominating.<br>♦ Reduced field angle dependence with Y-doping and short processing in AMSC and ORNL 2G ex-situ films; nanodot pinning effect identified |
| AC Losses in HTS Conductors | LANL | ♦ Develop lower loss conductors<br>♦ Study cryo-stabilization of coated conductors under ac conditions |
| BSCCO First Generation Wire (Wire Development Group) | LANL | ♦ Heat treat quenching and characterization at UW on AMSC precursor<br>♦ Identify new enhancement mechanisms to achieve new short-length 1G record without OP: 190 A (77 K) |
| Nucleation and Growth of YBCO by the $BaF_2$ Process and AC Losses of YBCO Films | BNL | ♦ Estimate physical parameters (e.g., interfacial energies) for use in model of nucleation and growth parameters.<br>♦ Develop criteria for c-axis vs. a-axis nucleation.<br>♦ Use the nucleation and growth model to estimate the effects of film dimensions and processing conditions leading to the onset of appreciable a-axis growth. |

# FY 2004 Projects – Key Results Cont.

| University Strategic Research | | |
|---|---|---|
| **Project Title** | **Lab** | **Key Results** |
| Buffer Layer Growth and the Thickness Dependence of Jc in Coated Conductors | UW | ♦ Develop new techniques (through-thickness EBSD) to follow grain boundary (GB) morphology.<br>♦ Detail microstructural study of bimodal microstructure and YBCO overgrowth of template when much liquid present.<br>♦ Investigate bi-crystal studies to check implications for GB critical current. |
| Conversion of Oxyflouride-Based Coated Conductors | MIT | ♦ Quantitative measure of the degree of reaction between the YBCO film and the substrate buffer layer.<br>♦ Compare between the results obtained from e-beam derived films with those of MOD derived films.<br>♦ Understand/improve of YBCO coated conductor fabrication processing |
| Transfer to Metal Tapes and Process Scale-up of In-Situ High Rate YBCO | Stanford | ♦ Study the growth of YBCO films on tape with respect to the growth rate, deposition temperature, and post-deposition treatment.<br>♦ Characterized by XRD and R - T. |
| Enhancing YBCO Performance through Fundamental Process Evaluation and Characterization | Albany-State University of New York | ♦ Working with AMSC on Microstructural optimization of processing parameters for MOD-TFA route for YBCO films confirmed fluorine content to be less than 1.5 at% in their fully processed films which carried a current of 200 A, and Jc ~ 2.5 MA/cm2.<br>♦ Collaboration with IGC-SuperPower on Microstructural investigation of reduction in Jc with increasing YBCO thickness in PLD and MOCVD films. One of the first visual demonstration by FIB of electrically dead layer on top of the films. Identified the composition and nature of the defects in these films.<br>♦ Partnership with UES Inc. to evaluate the quality of their ISD buffer deposition process for long length tapes. Performance evaluation and correlation of properties with growth morphology of buffer layer. |
| Epitaxial Electrodeposition of Metal and Metal Oxide Capping Layers for RABiTS-Based Second Generation Coated Conductors | University of Missouri-Rolla | ♦ Cu2O on Cu RABiTS<br>o Lactate, pH 9= (001); pH 12= (001), (111), (011), and (211) orientations<br>o Tartrate, pH 13= (001) orientation, smooth film: 1.6 nm mean roughness<br>♦ Chiral CuO on Cu RABiTS (tartrate)<br>o L= (0-10), D= (010), DL = (100)<br>♦ $90^{o}$ grain boundaries may limit $J_c$ |
| Microstructure and Mechanics of Superconductor Epitaxy via the Chemical Solution Deposition Method | University of California, Santa Barbara | ♦ Investigate and develop the precursor chemistry for LaMnO3 and MgO buffer-layers<br>♦ Investigate methods to increase critical thickness of LaMnO3 and MgO buffer-layers. |

# FY 2004 Projects – Key Results Cont.

| University Strategic Research | | |
|---|---|---|
| **Project Title** | **Lab** | **Key Results** |
| Systematic Decrease of $J_c$ Decrease in Thick Film Coated Conductors based on Micro-electrical and Micromechanical Properties | University of Houston | ♦ YBCO Film Thicknesses to 15 μm with High Growth Rates Demonstrated<br>♦ Pinning Center Generation Increases Jc |

# FY 2004 Projects – Key Results Cont.

| Superconductivity Partnerships with Industry Research | | |
|---|---|---|
| **Project Title** | **Lab** | **Key Results** |
| SPI Readiness Reviews | ORNL | ♦ Eight reviews in FY 2004<br>♦ Four HTS cable project reviews<br>♦ Two MFCL reviews (at SuperPower)<br>♦ HTS Open Geometry MRI review<br>♦ Flywheel electricity system with superconducting bearing review |
| Southwire-ORNL HTS Power Cable Cooperative Research | ORNL | ♦ Over 26,000 hours of operation<br>♦ Critical current measurements show robust superconductor<br>♦ Unattended operation (since 6/01)<br>♦ Development of a 3 kA tri-axial termination continued.<br>♦ Developing dielectric materials to eliminate PD and 15 kV breakdown. |
| Waukesha 5/10-MVA HTS Transformer Cooperative Research | ORNL | ♦ Focused on repair and testing of the 5/10-MVA transformer.<br>♦ ORNL personnel made 8 extended visits to WES.<br>♦ External short around “C” phase was found & repaired w/ G10 shim.<br>♦ LN system leaks were found and repaired.<br>♦ ORNL participated in cooldown and further testing of the transformer.<br>♦ Extensive short-circuit testing up to 2X overcurrent.<br>♦ High-voltage breakdowns prevented testing to full voltage.<br>♦ After tests, the transformer was untanked and inspected for damage.<br>♦ Coil failure prevents installation in WES substation. |
| GE 100-MVA HTS Generator Cooperative Research | ORNL | ♦ New, superior BSCCO wire insulation methods<br>♦ Full-size transfer coupling design, tests, and improvements, including brush seals HTS coil support method. Additional verification/risk reduction in progress.<br>♦ BSCCO joint UT test developed.<br>♦ Rotor dynamics "coupled oscillator" problem addressed for first time.<br>♦ HTS coil winding methodology backed by several small coil windings HTS coil inductance managed with exciter needs in mind. |

# FY 2004 PROJECTS – KEY RESULTS CONT.

| SUPERCONDUCTIVITY PARTNERSHIPS WITH INDUSTRY RESEARCH | | |
|---|---|---|
| **Project Title** | **Lab** | **Key Results** |
| SuperPower HTS Fault Current Limiter | ORNL | ♦ Finalized design and procured long lead items<br>♦ Fabricate components and subassemblies<br>♦ Completed subassembly tests–Open LN2 bath tests of matrix<br>♦ Completed component integration, final assembly and proof-of-concept test |
| Waste Water Treatment with Magnetic Separation | LANL | ♦ Determined controlling parameters and ranges for<br>♦ ferrite process<br>♦ Parameter sensitivity evaluation and optimization<br>♦ Optimized ferrite & HGMS processes optimized process for specific application/site determined how process variables might change for different conditions/application<br>♦ Determined scaling issues from laboratory to pilot plant quantities of chemicals, processing times<br>♦ Established a pilot plant partner with LIST<br>♦ Achieved initial penetration of a new market |
| Design and Development of a 100 MVA HTS Generator | LANL | ♦ HTS coil ac loss analyzed<br>♦ HTS quench protection analysis for future implementation<br>♦ Generator response in grid verified to be acceptable by analysis<br>♦ Cryo-refrigeration options developed, compared, optimized for present technology<br>♦ EM shield options developed and investigated for manufacturability<br>♦ Full-size rotor vacuum retention analysis done, outgassing tested, and getter designed<br>♦ Full-size rotor emissivity control estimated with Ag coating and manufacturability |
| HTS MRI System – Oxford Instruments | LANL | ♦ Powder processing upgrades complete and qualified by conductor performance.<br>♦ Reduced cost powder precursors in use.<br>♦ Prototype conductor processing line completed and the process qualified by test coil results.<br>♦ Conductor fabrication complete<br>♦ Cryogenics and magnet designs complete |

# FY 2004 PROJECTS – KEY RESULTS CONT.

| SUPERCONDUCTIVITY PARTNERSHIPS WITH INDUSTRY RESEARCH | | |
|---|---|---|
| **Project Title** | **Lab** | **Key Results** |
| Flywheel – Boeing | LANL | ♦ All components of the 100 kW / 5 kWh Flywheel UPS systems were manufactured<br>♦ All flywheel components were spin tested up to 102% of the operating speed (22,900 rpm)<br>♦ The redesigned metal Hub/Composite Rim assembly was balanced and quill tested to 22,900 RPM (102% MEOS)<br>♦ Stainless steel cryostat for HTS stability bearing was manufactured, sealed, and tested at liquid nitrogen temperatures with no leaks on first seal attempt<br>♦ The cryogenic system including thermosyphon, GM cryocooler, and bearing cryostat was assembled and tested |
| HTS Motor – Rockwell/Reliance Electric | LANL | ♦ Motor has successfully been operated as a generator producing 900 watts to a resistive load (900 Watts output at 1800 rpm and 81 K)<br>♦ First 2nd generation HTS conductor rotating machine demonstration |

# FY2005 Funding

An Annual Operating Plan has been developed for the FY2005 identifying the funding and activities that will take place throughout the year. In 2004, $33,649,000 million was awarded for the Superconductivity for Electric Systems Program, whereas, in 2005 the funding will be increased to $36,000,000 million. This spend plan was designed to help fund and promote superconductivity technologies to commercialization. The Second Generation Wire, Superconductivity Partnerships with Industry, Strategic Research, and University Research funding are discussed in detail. The following two documents are the FY2005 budget and the FY2005 Annual Operating Plan.

Three new cable projects will begin during FY2005. The projects have been designed to focus on different aspects of superconducting technologies. Each project is a sponsored project involving utility, industry, and national laboratories. The MRI project has reached completion and will not continue through the FY2005. Superconducting Partnerships with Industry will continue to be 50% cost shared. The project thrusts will center on researching and testing products designed that will be commercialized in the near future. All other projects will continue to move forward in research and development with a primary focus placed on coated conductor technology, characterization, and risk mitigation.

The Annual Peer Review will commence during the last week of July 2005. All projects within the program will be reviewed and analyzed by experts within the field of Superconductivity. The reviewers will be evaluating the projects performance, results, and research integration qualities.

# FY2005 Financial Report with Project Prioritization

| Peer Review Ranking | Total Score (#/100) | Priority (#) | Project Title/ Description/ Comments (text) | Contact Name | Field Office or Laboratory Name | Large Subcontracts | $45M FY-2005 Funding (K$) | $36M FY-2005 Funding (K$) | FY 2004 Funding (K$) |
|---|---|---|---|---|---|---|---|---|---|
| **Office of Electric Transmission and Distribution** | | | | | | | | | |
| **High Temperature Superconductivity R&D** | | | | | | | | | |
| 9/11 | 76.0 | 3 | Applied R&D of 1st and 2nd Generation HTS Conductors | Gouge | ORNL | | | $ 200 | $ 200 |
| 3/11 | 88.1 | 1 | RABiTS Substrates R&D | Goyal, List, Paranthaman | ORNL | | | $ 900 | $ 950 |
| 8/11 | 79.0 | 3 | Ex-Situ Processing of YBCO Precursors | Christen, Lee, List | ORNL | | | $ 850 | $ 950 |
| 4/9 | 85.4 | 2 | Phase Relations of High Tc Superconductors | Wong-Ng, Cook | ORNL | NIST | | $ 250 | $ 250 |
| 6/11 | 84.8 | 2 | Electromechanical Studies for Superconductor Development | Ekin, Cheggour | ORNL | NIST | | $ 200 | $ 200 |
| 1/11 | 89.6 | 1 | Scale-Up of Coated Conductor (2G) Technology at AMSC | Malozemoff, Rupich, Schoop | ORNL | AMSC (SB) | | $ 900 | $ 950 |
| | | 2 | Conductor Design and Engineering for Low AC Loss | Lee, List | ORNL | | | $ 500 | $ - |
| | | 2 | Flux Pinning and Microstructural Characterization of 2G Wires | Goyal, Christen | ORNL | | | $ 400 | $ - |
| 2/9 | 88.3 | 1 | RABiTS-Based Strategic Research | Goyal, Sathyamurthy, Aytug | ORNL | | | $ 900 | $ 1,050 |
| 6/9 | 85.7 | 2 | Development of High Ic Ex-Situ Processed RBCO Coated Conductors | Feenstra | ORNL | | | $ 350 | $ 350 |
| 3/9 | 87.8 | 1 | ORNL-American Superconductor Strategic Research CRADA | Goyal, Paranthaman, Schoop (AMSC) | ORNL | | | $ 1,050 | $ 1,050 |
| 7/9 | 80.8 | 3 | Wire Development Group | | ORNL | | | | $ 300 |
| 4/9 | 77.6 | 2 | SPI Readiness Review Program | Gouge | ORNL | | | $ 200 | $ 200 |
| 8/9 | 69.3 | 4 | HTS Transformer CRADA | Schwenterly | ORNL | | | $ 300 | $ 325 |
| 3/9 | 80.9 | 1 | 100 MVA HTS Generator CRADA | Duckworth | ORNL | | | $ 250 | $ 325 |
| 1/9 | 85.6 | 1 | HTS Power Cable CRADA | Demko | ORNL | | | $ 1,200 | $ 1,700 |
| 2/9 | 84.4 | 1 | Matrix Fault Current Limiter CRADA | Schwenterly | ORNL | | | $ 650 | $ 400 |
| | | | Planning and Analysis Activities | | ORNL | | | $ 400 | $ 400 |
| | | | | | | | **$ 10,500** | **$ 9,500** | **$ 9,600** |
| | | | | | | | | | |
| 1/11 | 88.7 | 1 | Scale Up of Coated Conductor Technology at SuperPower CRADA | Selvamanickam, Reeves, Peterson | LANL | | | $ 500 | $ 434 |
| | | 2 | Scale Up of Coated Conductor Technology at American Superconductor CRADA | | LANL | | | $ 250 | $ 225 |
| | | 3 | Coated Conductor Technology at ITN - CRADA | | LANL | | | $ - | $ - |
| | | 3 | Coated Conductor Technology at MetOx - CRADA | | LANL | | | $ - | $ - |
| | | 3 | Coated Conductor Technology at Oxford - CRADA | | LANL | | | $ - | $ - |
| | | 4 | Development of Magnesium Diboride Wires with Hypertech | | LANL | | | $ - | $ 200 |
| 7/11 | 81.3 | 3 | Coated Conductor Development | Matias, Gibbons, Civale | LANL | | | $ 1,900 | $ 2,100 |
| 1/9 | 91.2 | 1 | Understanding and Improving Pinning in Coated Conductors | Civale, Driscoll | LANL | | | $ 350 | $ 550 |

# FY2005 Financial Report with Project Prioritization Continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6/9 | 85.7 | 2 | Development of High Ic Ex-Situ Processed RBCO Coated Conductors | Holesinger | LANL | | | $ 250 | $ 250 |
| 5/9 | 85.2 | 2 | Research on IBAD MgO-Based Coated Conductors | Arendt, Foltyn | LANL | | | $ 1,400 | $ 1,400 |
| 8/9 | 78.9 | 3 | AC Loss Studies in Coated Conductors | Ashworth | LANL | | | $ 300 | $ 300 |
| 2/9 | 84.4 | 1 | Matrix Fault Current Limiter CRADA | | LANL | | | $ 100 | $ 20 |
| 7/9 | 80.8 | 3 | Wire Development Group CRADA | Civale | LANL | | | $ 200 | $ 375 |
| 4/9 | 77.6 | 2 | SPI Readiness Review Program | Ashworth | LANL | | | $ 70 | $ 35 |
| 9/9 | 60.5 | 5 | HTS Open Geometry MRI System CRADA | Holesinger | LANL | | | $ - | $ 200 |
| 3/9 | 80.9 | 1 | 100 MVA HTS Generator CRADA | Waynert | LANL | | | $ 480 | $ 330 |
| 5/9 | 69.9 | 2 | Waste Water Treatment with Magnetic Separation CRADA | Waynert | LANL | | | $ 200 | $ 60 |
| | | 3 | Reliance HTS Motor CRADA | | LANL | | | $ - | $ - |
| | | 3 | Boeing HTS Flywheel CRADA | | LANL | | | $ - | $ - |
| | | | | | | | **$ 8,000** | **$ 6,000** | **$ 6,479** |
| | | | | | | | | | |
| 10/11 | 61.8 | 5 | Inclined Substrate Deposition | Balachandran, Ma, Miller | ANL | | $ - | $ - | $ 470 |
| 4/11 | 85.6 | 1 | Characterization of Coated Conductors | Gray, Miller, Maroni | ANL | | $ 1,375 | $ 1,375 | $ 520 |
| 7/9 | 80.8 | 3 | Wire Development Group CRADA | | ANL | | $ 80 | $ 80 | $ 80 |
| | | | Research and Analysis for IEA | Wolsky | ANL | | $ 45 | $ 45 | $ 45 |
| | | | | | | | **$ 1,500** | **$ 1,500** | **$ 1,115** |
| | | | | | | | | | |
| 9/9 | 75.9 | 3 | Nucleation and Growth of YBCO by the BaF2 Process | Suenaga, Welch | BNL | | $ 300 | $ 300 | $ 400 |
| 9/9 | 75.9 | 3 | AC Losses of YBCO Films | Suenaga | BNL | | $ 100 | $ 100 | $ 100 |
| | | | | | | | **$ 400** | **$ 400** | **$ 500** |
| | | | | | | | | | |
| 11/11 | 60.8 | 4 | Non-Vacuum Techniques for HTS Coated Conductors | R. Bhattacharya | NREL | | $ 250 | $ 250 | $ 250 |
| 11/11 | 60.8 | 4 | Substrate preparation by electropolishing and electrodeposition | | NREL | | $ 150 | $ 150 | $ 150 |
| | | | | | | | **$ 400** | **$ 400** | **$ 400** |
| | | | | | | | | | |
| 5/11 | 83.6 | 2 | All Solution Deposited Buffers and YBCO Development | Clem, Voigt | SNL | | $ 200 | $ 200 | $ 200 |
| 5/11 | 83.6 | 2 | Vacuum Conversion and CRADA | Clem, Voigt | SNL | | $ 200 | $ 200 | $ 200 |
| | | | | | | | **$ 400** | **$ 400** | **$ 400** |

# FY2005 Financial Report with Project Prioritization Continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 7/9 | 68.9 | 4 | Rockwell Motor | Schiferl | GO | | | | $ - |
| 8/9 | 69.3 | 4 | Waukesha Transformer | Pleva (WES), Hazelton (SP) | GO | | | | $ 200 |
| 6/9 | 69.9 | 3 | Boeing Flywheel | Strasik | GO | | | | $ 215 |
| 3/9 | 80.9 | 1 | General Electric Generator | Fogarty | GO | | | | $ 1,855 |
| 1/9 | 85.6 | 1 | Southwire Cable | Lindsay | GO | | | | $ - |
| 5/9 | 69.9 | 2 | Dupont Separator (Waste Water) | Bernard | GO | | | | $ 500 |
| | | 1 | SuperPower Cable | | GO | | | | $ 4,050 |
| | | 1 | American Superconductor Cable | | GO | | | | $ 4,700 |
| 2/9 | 84.4 | 1 | SuperPower Fault Current Limiter | Kovalsky (SuperPower), Bock | GO | | | | $ 1,250 |
| 9/9 | 60.5 | 5 | Oxford MRI System | Marken, Gilgrass | GO | | | | $ - |
| | | | | | | | **$ 19,500** | **$ 16,000** | **$ 12,770** |
| | | | | | | | | | |
| 1/7 | 88.4 | 2 | Conversion of Oxy-Fluoride Based Coated Conductors | Cima, Suenaga (BNL) | MIT, BNL | | | | $ 200 |
| 2/7 | 87.0 | 2 | Buffer Layer Growth and the Thickness Dependence of Jc in Coated Conductors | Eom, Gurevich, Larbalestier | UW-Madison | | | | $ 350 |
| 3/7 | 66.8 | 3 | In-Situ High Rate YBCO Process | Ahai, Huh, Storer (LANL) | Stanford, LANL | | | | $ 100 |
| 4/7 | 63.1 | 3 | Enhancing YBCO Performance Through Fundamental Process Evaluation and Characterization | Rane, Dunn | SUNY Albany | | | | $ 75 |
| 5/7 | 59.0 | 4 | Epitaxial Electrodeposition of Metal and Metal Oxide Capping Layers for RABiTS-Based Coated Conductors | Switzer | U Missouri - Rolla | | | | $ 150 |
| 6/7 | 57.9 | 4 | Microstructure and Mechanics of Superconductor Epitaxy via the Chemical Solution Deposition Method | Lange | UC - Santa Barbara | | | | $ 150 |
| 7/7 | 49.3 | 4 | Systematic Decrease of Jc in Thick Film Coated Conductors | Ignatiev | U Houston | | | | $ 75 |
| | | | | | | | **$ 1,280** | **$ 1,280** | **$ 1,100** |

# SUPERCONDUCTIVITY FOR ELECTRIC SYSTEMS

## ANNUAL OPERATING PLAN
## FY 2005

**U.S. Department of Energy**

**William Parks, Acting Director, Office of Electric Transmission and Distribution**
**Joanna Livengood, Acting Director, Office of Electric Power Systems Research and Development**

**James Daley, Lead, Superconductivity for Electric Systems,**

**Managers**
**Roland George**
**Harbans Chhabra**

**November 2004**

## About This Document

This document is the 2005 Annual Operating Plan (AOP) for the Superconductivity for Electric Systems program of the U.S. Department of Energy (DOE), Office of Electric Transmission and Distribution (OETD). It is primarily an internal DOE document that provides information for the reader on the program mission, organization, and specific project oriented milestones and goals. Many of the activities described are undertaken in collaboration with partners from the national laboratories, industry, and universities. Any questions about this document can be directed to Dr. James Daley, Superconductivity for Electric Systems, at 202-586-1165, or via e-mail at james.daley@doe.hq.gov

US Department of Energy
Office of Electric Transmission and Distribution
Electric Power Systems Research and Development, TD-2
1000 Independence Avenue, SW
Washington, DC 20585

# Table of Contents

# 1.0 INTRODUCTION

This document is the FY-2005 Annual Operating Plan (AOP) for the Superconductivity Program for Electric Systems. The plan details the research and development activities needed in order to advance the superconductivity technology towards a commercial marketplace for electric power applications. The Second Generation Wire Development, Strategic Research, and Superconductivity Partnerships with Industry (SPI) will be the three primary programmatic areas discussed. The Superconductivity Program for Electric Systems is a major program within the DOE Office of Electric Transmission and Distribution.

## 1.1 OFFICE OF ELECTRIC TRANSMISSION AND DISTRIBUTION

The Office of Electric Transmission and Distribution (OETD) is organized to help ensure a robust and reliable U.S. transmission grid for the 21st century. The department's mission is: *to lead a national effort to modernize and expand America's electricity delivery system to ensure a more reliable and robust electricity supply, as well as economic and national security. This effort is accomplished through research and development, demonstration, technology transfer, and educational outreach activities.* Three program goals have been developed to attain the OETD mission: reliability, efficiency, and affordability.

**Reliability:**
Increasing the dependability of the national transmission grid will decrease bottlenecks and reduce the risks of electrical blackouts or outages.

**Efficiency:**
Reduce energy losses by 10% by 2020 throughout the United States.

**Affordability:**
Reduce electricity costs by 2% by 2015.

## 1.2 MISSION

This AOP addresses the Superconductivity Program Mission: "*To work in partnership with industry to develop high-temperature superconducting wire and perform other research and development activities leading to the commercialization of high-temperature superconductivity (HTS) electric power applications by U.S. companies.*" The primary outcomes that are targeted in order to achieve the Superconductivity Program mission are to help facilitate in the development of:

1. HTS wire that will carry 100 times the current without the resistance losses of comparable diameter copper wire; and

2. HTS equipment will be half the size of conventional alternative with the same power rating and will have only half the energy losses.

In order to achieve the goals set forth, the program has been organized into three research and development (R&D) areas: Second Generation Wire, Superconductivity Partnerships with Industry and Strategic Research. The Superconductivity Program is implementing the necessary R&D efforts that will have a significant impact on the way electricity is produced, delivered, and used by utilities and industry in the future. The Superconductivity Program mission also satisfies the OETD goal of leading the national effort to modernize the electricity delivery system. As a result of this coordinated effort, the mission and goals of this program also insures the primary objectives of the OETD program.

The time period in which these objectives are based on the *Program Planning Level* funding and involve DOE leading the efforts that requires participation of the National Laboratories, industry, and universities. Analysis of the steps that are necessary to achieve the goals has resulted in a priority ranking system for the Superconductivity Program for Electric Systems projects that addresses the most important fundamental breakthroughs needed. The ranking system is based on a scale from 1-5, one being most important and five the least.

## 1.3 Superconductivity Program for Electric Systems

The High Temperature Superconductivity Program for Electric Systems is currently in a technological field that does not exist as a commercial market. Due to this, extensive planning and marketing research for the technology is closely evaluated. The economics and reliability of the HTS first-of-a-kind systems will remain a primary thrust of the program's prototype field testing activity. The Superconductivity Program bases this AOP and its long-range research on strategic planning conducted by Oak Ridge National Laboratory and several subcontractors. The strategic planning is subjected to analysis by the contractors and by informed industrial reviewers. Continual review is conducted by the industrial partners in the Superconductivity Partnerships with Industry projects as they develop the prototypes for new HTS electrical systems. Likewise, second generation wire development is also subject to scrutinized reviews. The program incorporates a project readiness review process to ensure that design concepts and demonstration procedures will meet the operating expectations and rigors under real-world conditions. This process will reduce the risk of failures and enhance market acceptance. This practice will continue throughout the next fiscal year.

## 1.4 Performance Based Peer Review

The Oak Ridge National Laboratory (ORNL) coordinates a yearly, public program review and peer evaluation of research projects funded by the Superconductivity Program for Electric Systems. An international panel of experts evaluates the research management and accomplishments of the projects conducted by the participants in the Superconductivity program. The panel then provides comments to ORNL on the strengths and weaknesses exhibited by the projects. The results of the Peer Review are communicated to DOE - HQ for use in the management of the program. The July 2004 Peer Reviewers were asked the following set of five questions and their responses follow:

*Are the program's research mission and goals adequately defined and reflect the present status of science, technology, and needs of the industry? Is the program moving into applications at a sufficient pace?*

> Reviewer's agreed that the mission and goals are adequately defined. "*Mission/goals are concise, precise, and clear – no changes. Structure of the Peer Review is a model that other departments should follow." "This is the top program world-wide for the implementation of HTS science and technology in the power sector. It is both focused and broad-based."*

*Has the Program's research productivity been remarkable and world class? Have the Program's accomplishments provided a strong technology base fro power applications?*

> Reviewers unanimously agreed for the second consecutive year that the program's research productivity and accomplishments are remarkable and outstanding. *"Productivity in the past year has been unbelievably high." "SPI is the world leader program of applied superconductivity power applications. Always SPI gives the outstanding results in applied superconductivity, this year is no different."*

*Do you feel that the quality of the proposed FY 2004 R&D activities is impressive and ambitious? Are the key research areas receiving the proper emphasis to achieve program goals? Are the R&D milestones realistic and achievable?*

> Reviewers agreed the quality of the activities and milestones are obtainable and realistic, but there was a fundamental shift from last year's agreement regarding the proper emphasis being placed on key research areas. "*Largely, agree with prepared activities but it does depend on the individual program, some of the programs are under funded. Considerably more could be achieved with funding increase."*

*Is the teaming between industry, universities, and the national laboratories an important element of the program? Are the present arrangements appropriate for success and future commercialization?*

> Reviewers unanimously agreed that the teaming efforts are essential to the program and future commercialization of HTS technology. *"The collaboration between national labs and private companies is excellent. This certainly is a model to be followed by many other fields of science and other countries. There are teams consisting of private companies and national labs. Closer collaboration between these teams including the companies (the private companies may not like this) could accelerate the accomplishment of the goals of this program." "I've commented a number of times that the labs play the role of "corporate" R&D labs*

> *for the companies that cannot afford such facilities (AMSC, IGC-SP) or who were never in that business (utilities). Universities need to be more strongly integrated using the model of the WDG."*

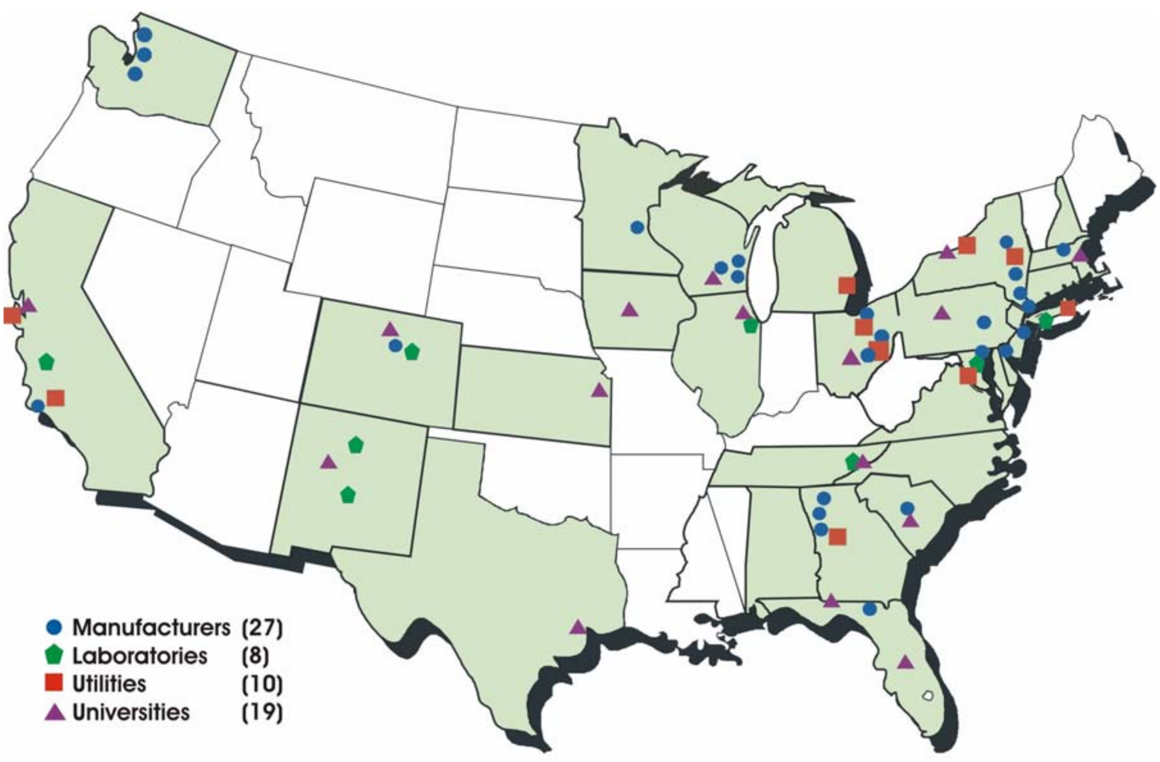
*Has DOE performed the proper planning ensuring the success of the program and is DOE's role appropriate?*

> The final question posed to the reviewer's indicated an overall agreement regarding the planning and DOE role. The reviewer's stated, *"The annual review is a great venue for helping to refine approaches and stimulate excellence of the R&D program." "It is essential for DOE to be the driver for the type of R&D needed in order to reduce the risk of entry by the private sector, both in conductor development and the early development of prototypes and demonstration of the technology in several areas."*

## 1.5 PUBLIC – PRIVATE PARTNERSHIPS

The Superconductivity Program for Electric Systems is a national program in support of national energy, economic, environmental, and educational interests throughout the Unites States. The program participants range from manufacturers, laboratories, utilities, and universities. The scope of this program and its stakeholders throughout the United States is presented in Exhibit 1.

**Exhibit 1: Superconductivity National Program Participants and Performers**



The Superconductivity Program for Electric Systems works in partnership with industry to perform the wire research and technology development required for U.S. companies to commercialize High Temperature Superconductivity (HTS) in electric power applications. To achieve commercialization, the Superconductivity Program engages in research and development which aims to:

1. Improve the performance of HTS superconducting wire while reducing manufacturing costs (Second Generation Wire Development)
2. Demonstrate the applicability and the potential benefits of superconductivity in electric power systems (Superconductivity Partnerships with Industry).
3. Conduct alternative research in superconducting processes and characterization that may further improve technological advances and performance of conductors (Strategic Research).

Second Generation Wire research seeks methods to produce wire that has higher current carrying capacity, reduced manufacturing costs, and better industrial application characteristics, such as durability, flexibility, and tensile strength. Near-term research in this area focuses on conquering scale-up issues of more developed HTS wire technologies like that of the Southwire cable project. Longer-lengths wire research activities concentrate on next generation superconducting wire, which include research on YBCO (yttrium barium copper oxide), BSCCO (barium calcium copper oxide), and other compounds for coated conductors.

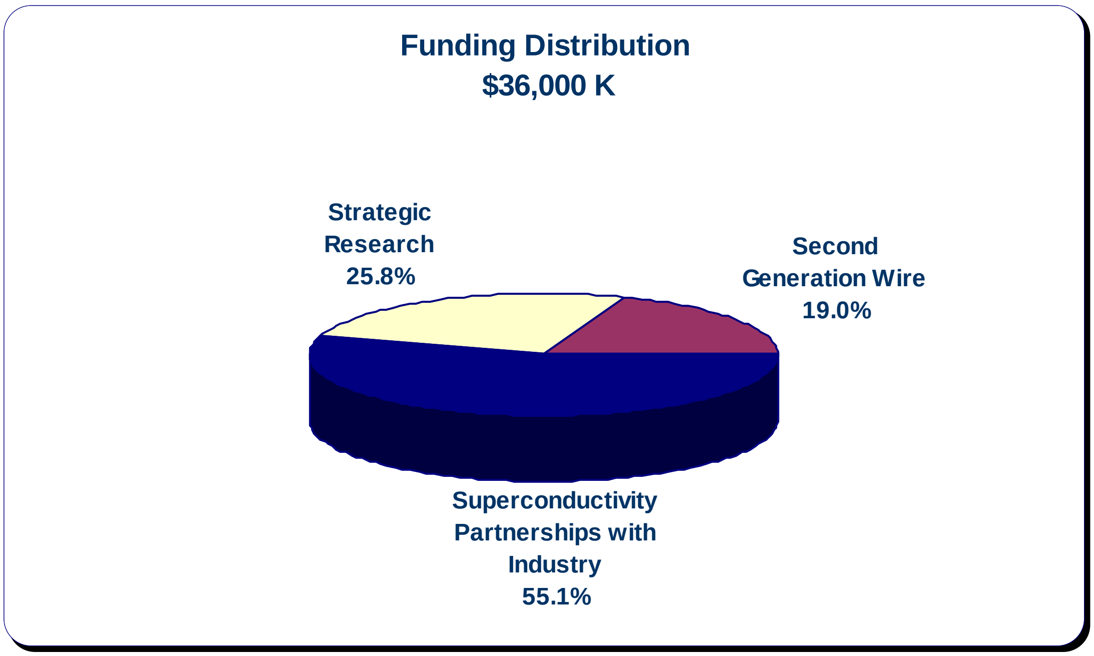
Superconductivity Partnerships with Industry (SPI) research activities center on electric power system applications of HTS technology and involve industry-led cooperative projects. Researchers investigate adaptability issues for using superconducting wire in power system applications, which include power cables, transformers, fault current limiters, generators, and flywheel electricity systems. In addition, program efforts target end-user applications in energy-intensive industries, including large electric motors and magnetic separators. Application issues include the development of efficient cryogenic systems, power cables, and magnetic field research. The public - private partnerships philosophy is needed in HTS systems development to encourage private investment in research by reducing the financial risk. The Superconductivity Partnerships with Industry research is cost shared 50-50.

The Strategic Research activities focus on chemical characterization, stability, and normal zone propagation properties of second-generation wires. Accompanying R&D in this area works to develop dielectric materials and investigate alternate processes and wire geometries that may lead to an improved performance ratio for second generation conductors. This is achieved by laboratory, industry, and university research focused on the program and its activities which additionally include close communication, systems analysis, and outreach with stakeholders.

## 1.6 FY – 2005 PLANNED ACTIVITIES

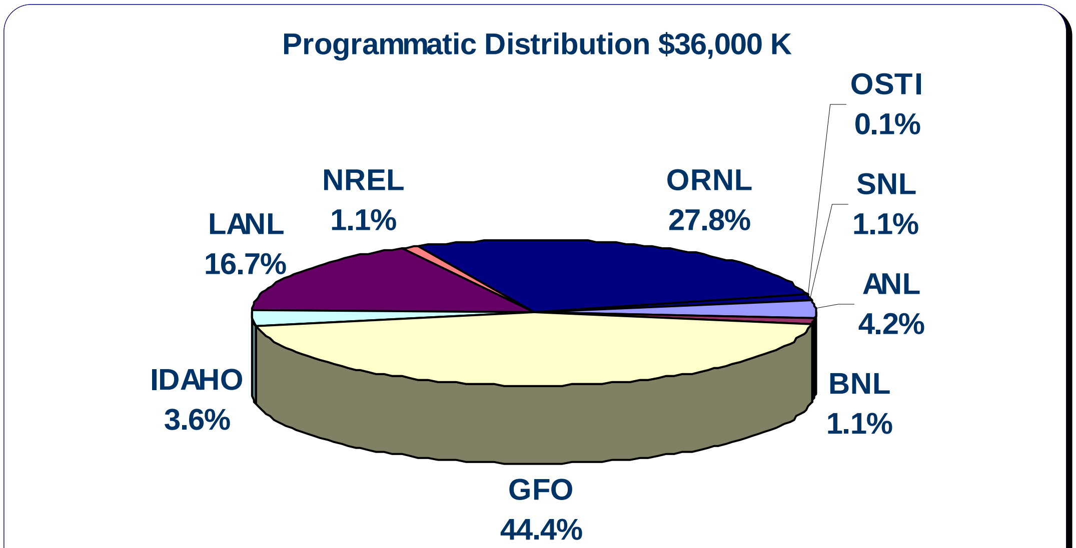
Superconductivity R&D activities are described in relation to the three program elements: Second Generation Wire Development; Superconductivity Partnerships with Industry; and Strategic Research. Second Generation Wire Development consists of R&D projects which are industry-led in cooperation with the national laboratories, and have the potential to increase efficiency and performance of superconductivity applications by improving the new types of high temperature superconducting (HTS) wire. Superconductivity Partnerships with Industry (SPI) efforts are driven by the needs of the electric utility industry and electrical equipment manufacturers who participate in vertically integrated teams that are competitively awarded project funding. SPI projects include the most advanced HTS wire technology available for applications nearing commercialization. Strategic Research leads to further development of HTS wires and applications. Strategic Research focuses on understanding the underlying principles and mechanisms of HTS and on enabling technologies such as dielectric materials and cryogenic systems. The programmatic funding by area and lead organization are shown in the following two Exhibits.

**Exhibit 2: FY – 2005 Superconductivity Program Funding by Area**




| FUNDING DISTRIBUTION | $ (K) |
|---|---|
| Second Generation Wire | $6,850 K |
| Superconductivity Partnerships with Industry | $19,850 K |
| Strategic Research | $9,300 K |
| **Total** | **$36,000 K** |

### Exhibit 3: FY – 2005 Superconductivity Program Funding Distribution




| ORGANIZATION | $ (K) |
|---|---|
| Los Alamos National Laboratory | $6,000 K |
| Oak Ridge National Laboratory | $10,000 K |
| Argonne National Laboratory | $1,500 K |
| Brookhaven National Laboratory | $400 K |
| National Renewable Energy Laboratory | $400 K |
| Sandia National Laboratory | $400 K |
| Golden Field Office (GFO) | $16,000 K |
| IDAHO (University Strategic Research) | $1,280 K |
| OSTI | $20 K |
| **Total** | **$36,000 K** |

# 2.0 PROGRAM MANAGEMENT

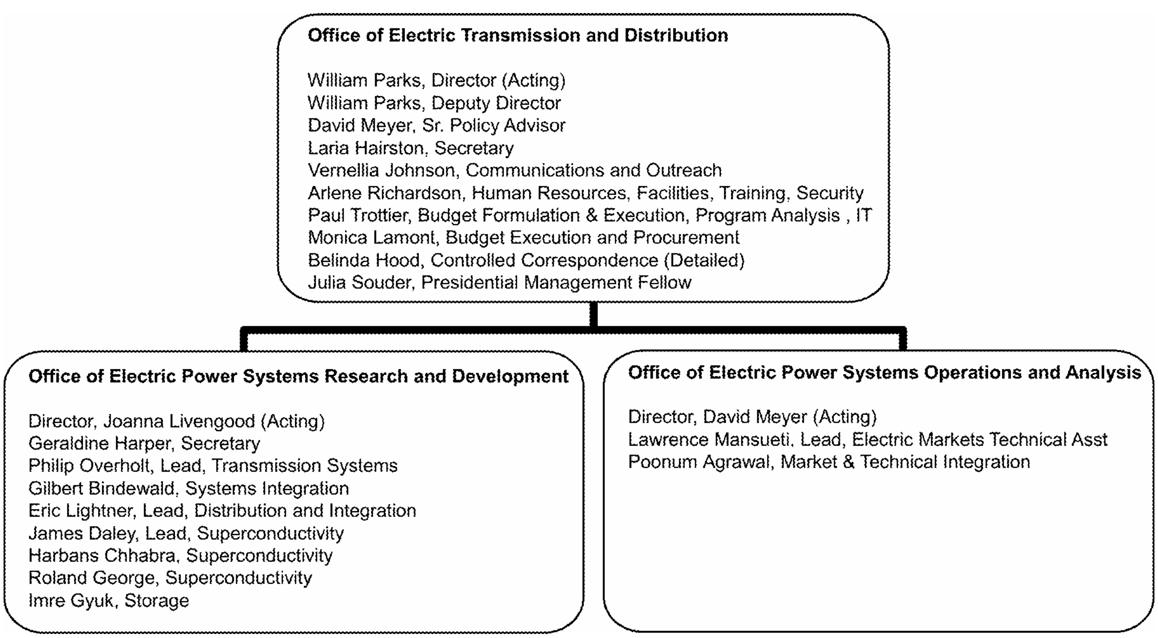
## 2.1 DOE – HQ

The responsibility of the Superconductivity Program for the Office of Electric Transmission and Distribution has been assigned to three staff members at the Department of Energy Headquarters (DOE-HQ). These individuals are responsible for planning, organizing, and managing the national program. The fundamental goals of the headquarters office are to uphold the mission and objectives created for the program formulate and justify the annual budget, and to provide overall program guidance and direction. Funding the Superconductivity for Electric Systems activities i.e. salary, travel, training, and support comes from the Program Direction Budget of the Office of Electric Transmission and Distribution. The names of the Superconductivity for Electric Systems headquarters staff are listed below along with the organizational chart of the Office of Electric Transmission and Distribution:

**James Daley, Program Director, Superconductivity for Electric Systems, 202-586-1165, james.daley@hq.doe.gov**

**Program Managers**
**Harbans Chhabra, 202-586-7471, harbans.chhabra@hq.doe.gov**
**Roland George, 202-586-9398, roland.george@hq.doe.gov**

**Exhibit 4: Office of Electric Transmission and Distribution Organizational Chart**



## 2.2 Field Management

The DOE Golden Field Office, Superconductivity Project Manager, Paul Bakke, issues solicitations requesting proposals for projects to be cost shared under the Superconductivity Partnerships with Industry (SPI) program element. These proposals are competitively evaluated by a panel of experts, and funding for successful proposals is awarded as DOE cooperative agreements with industry teams.

Each DOE National Laboratory receiving funding from the Superconductivity Program for Electric Systems has an internal management team to direct the individual researchers, to administer cooperative research and development agreements (CRADAs) work with industry, and to solicit proposals and execute subcontracts. These laboratories, along with principal contacts for the superconductivity program, are listed below.

***Argonne National Laboratory***
**George Crabtree**
**crabtree@anl.gov**

***Brookhaven National Laboratory***
**David Welch**
**welch@sun2.bnl.gov**

***Los Alamos National Laboratory***
**Dean Peterson**
**dpeterson@lanl.gov**

***National Renewable Energy Laboratory***
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# 3.0 ELECTRICAL WIRES
## *(SECOND GENERATION WIRE DEVELOPMENT)*

## 3.1 SECOND GENERATION WIRE DEVELOPMENT

**FY – 2005 Funding: $6,850,000**

Second Generation Wire Development projects are designed to research and develop cost-effective, material synthesis and fabrication processes that can be scaled-up by industry to manufacture long (kilometer) lengths of high performance HTS wire. The research is conducted at six Department of Energy National Laboratories throughout the United States and each of the labs investigate increasing engineering current density, improved flux pinning properties in strong magnetic fields, and reducing alternating current losses through materials processing. This HTS research is also being conducted at various universities as well as private industrial laboratories. The extensive array of participants is privy to an abundance of resources and each contains distinctive knowledge and expertise. This allows concurrent research to be conducted on many distinct methods of processing coated conductors, all of which have the potential to present the best possible formulation of increased performance and reduced cost required to market HTS wire for widespread commercialization.

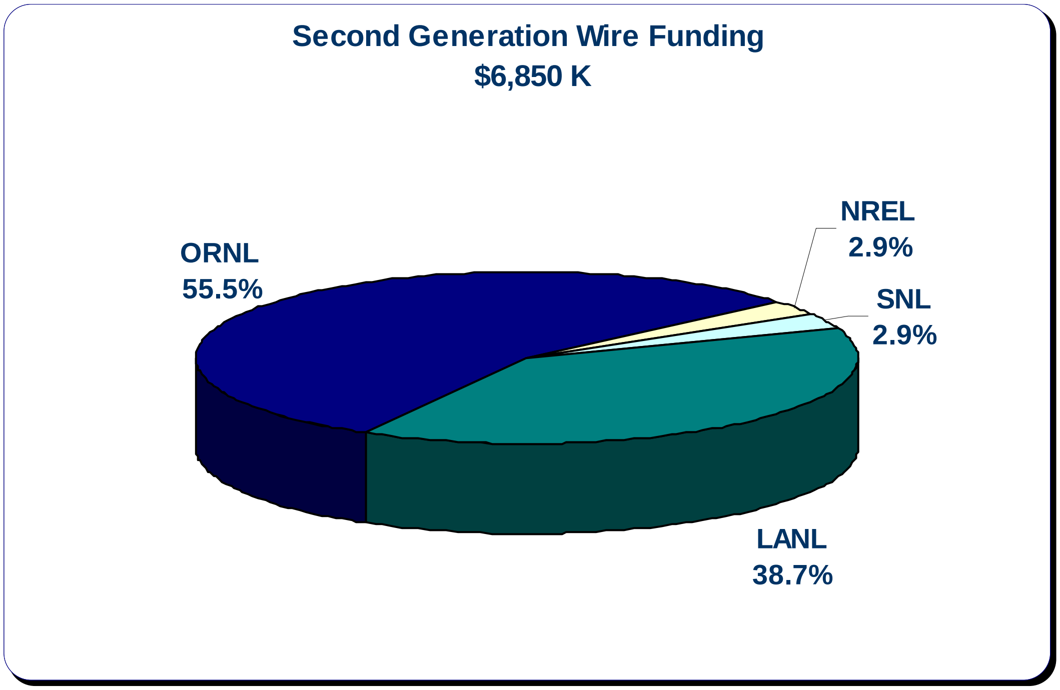
The performance-based, HTS Peer Review designed to assess the programs progress was held in July, 2004. Peer Reviewers provided the following comments about Second Generation Wire Development:

> *"A remarkable year of achievements, difficult to expect more, the multiple aspects of the program was individually demonstrated and well integrated ranging from critical characterization to fabrication, e.g., major progress in electro polishing."* In 2005, the projects will continue to strive for further breakthroughs within the various aspects of coated conductor technology and work in collaboration with partners, national laboratories, and universities in order to reach their goals.
>
> *"All national laboratories should start a PC-based catalog of the most critical defects (depends in deposition method) which could help laboratory people or technician with less expertise at external labs and industries to help in identifying the "bad buys" out of a heap of analysis data. This catalog could also be a future basis for a continuous control (Raman) and for a feedback loop in a continuous process."* Future implementation of information technologies are added as needed further improving upon Second Generation Wire Development resources aimed towards collaboration.
>
> *"Funding level should not go down."* In 2004, many national laboratories suffered from decreased funding. Funding levels have stabilized for 2005.

## 3.2 LABORATORY RESEARCH

Laboratory research of Second Generation Wire is primarily aimed towards the development in new advancements in coated conductor techniques, prior to introduction to the private sector resulting in licenses and other intellectual property rights. Los Alamos National Laboratories (LANL) and Oak Ridge National Laboratory (ORNL) have dedicated a substantial portion of their research funding to the creation of research facilities dedicated to accelerating the development of second generation wire. Other laboratories dedicated to expanding second generation wire technology include the National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL).

**Exhibit 5: FY – 2005 Second Generation Wire Funding Distribution**




| ORGANIZATION | $ (K) |
|---|---|
| Los Alamos National Laboratories | $2,650 K |
| Oak Ridge National Laboratory | $3,800 K |
| National Renewable Energy Laboratory | $200 K |
| Sandia National Laboratories | $200 K |
| **TOTAL** | **$6,850 K** |

### 3.2.1 Los Alamos National Laboratory (LANL)

**FY – 2004 Funding: $2,650,000**

| SECOND GENERATION WIRE<br>LANL | | |
|---|---|---|
| **PRIORITY** | **PROJECT** | **$ (K)** |
| 1 | Scale Up of Coated Conductor Technology at SuperPower CRADA | $500 K |
| 2 | Scale Up of Coated Conductor Technology at American Superconductor CRADA | $250 K |
| 3 | Coated Conductor Development | $1,900 K |
| | **Total** | **$2,650 K** |

In 2005, Los Alamos National Laboratory will continue collaborations in scale-up processes in coated conductor technology with SuperPower, Argonne National Laboratory, American Superconductor Corporations, and Rockwell Automation. LANL will provide technical expertise and facilities in materials science, wire précising, characterization, design engineering, and analysis to advance coated conductor development.

**FY – 2005 Milestones:**

*Substrates and Buffers*

1. Add sputtering capability for barrier layer in reel-to-reel system.
2. Scale up Buffer sputtering processes for IBAD MgO to 100 m lengths with texture ~ 6 degrees

*High Rate Deposition*

3. Develop reactive sputtering processes for high rate buffer deposition on IBAD MgO
4. Demonstrate 10 m/h in every process step to produce 10 - 100 m tapes with $I_c$ > 100 A

*Improved YBCO Layer Quality*

5. Reduce $I_c$ variation to < 2% on a 2-cm measurement length over > 1 m; understand the cause of variation.
6. PLD: Fabricate CC with $I_c$ >500 A @ 75 K (5 m, $J_c$ >1 MA/cm$^2$).
7. Reactive co-evaporation: Fabricate CC with $I_c$ > 200 A @ 75 K (5 m, $J_c$ > 1 MA/cm$^2$).
8. Scale up IBAD MgO process to 100 m lengths with uniform texture of ~ 6 degrees
9. Demonstrate 100 A over 100 m using our new Pilot MOCVD facility.
10. Scale up slitting & electroplating processes to 100 m lengths of 4 mm wide conductor
11. Improve field dependence of $I_c$ to achieve 100 A @ 1 T, 77 K (B || c-axis)

*Conductor Design and Architecture*

12. Develop robust CC IBAD architectures needed for the different YBCO processes by working with industry.
13. Reduce ac losses in the CC wire by one order of magnitude; examine transition from 2D to 3D geometry.
14. Scale up photolithography process to long lengths & evaluate ac loss reduction in long lengths.

*Process Monitoring and Control*

15. Employ Raman Spectroscopy as an active on-line monitoring tool for long runs in Pilot MOCVD facility.
16. Add more & enhance existing QC tools to support 100 m conductor fabrication

*HTS Components*

17. Deliver 250 m of 4 mm wide conductor with "Surround Cu Stabilizer" & 50 micron thick substrates with $I_c$ of at least 100 A/cm to SEI for Albany Cable Project.
18. Work with Rockwell Automation to improve 2-G generator/motor
19. Fabricate HTS coil that can generate fields of 1 - 2 T @ 65 – 77 K

### 3.2.2 Oak Ridge National Laboratory (ORNL)

**FY – 2005 Funding: $3,800,000**

| SECOND GENERATION WIRE<br>ORNL | | |
|---|---|---|
| **Priority** | **Project** | **$ (K)** |
| 1 | RABiTS Substrates R&D | $900 K |
| 1 | Scale-Up of Coated Conductor (2G) Technology at AMSC | $900 K |
| 2 | Electromechanical Studies for Superconductor Development | $200 K |
| 2 | Phase Relations of High $T_c$ Superconductors | $250 K |
| 3 | Applied R&D of 1st and 2nd Generation HTS Conductors | $200 K |
| 3 | Ex-Situ Processing of YBCO Precursors | $850 K |
| N/P | Capital Equipment | $500 K |
| | **Total** | **$3,800 K** |

*N/P Not Prioritized

In 2005, industry teams will be working together with ORNL in order to increase the development of coated conductors using RABiTS technology. These teams include American Superconductor, Sandia National Laboratories, Neocera, Argonne National Laboratory, NIST-Boulder, Ametek, MetOX, Oxford Superconducting Technology (OMT), and Universities. In 2005, ORNL will also be continuing to investigate YBCO precursors and superconductor development.

**FY – 2005 Milestones:**

*Precursor Materials*

1. Further develop R2R PED as a routine precursor deposition tool.
2. Optimize precursor to enable fast $G_p$ with high $J_c$ to the performance level of modified e-beam precursor.
3. Increase $I_c$ performance of 1 cm-wide precursor to that of small samples.
4. Collaborate with NIST and ANL on the phase development of ex-situ precursors.
5. Collaborate with SNL to develop solution precursor suitable for R2R slot-die coater.

*Substrates and Buffers*

6. Research and develop long lengths of powder metallurgy derived Ni-(5-9.5) at %W substrates and transfer of technology to industry.
7. Study texture development of non-magnetic Ni-W substrates via vacuum casting derived coils.
8. Research and develop strengthened and conductive Cu-based substrates with good texture.
9. Develop conditions for standard buffer layer deposition in reel-to-reel configurations for higher W containing Ni-based substrates.
10. Use thermal desorption spectroscopy to study evolution of gases from higher W containing Ni-based substrates for prevention of buffer delaminating.
11. Develop improved buffer architectures which reduce oxygen diffusion to the metal/alloy substrate.
12. Transfer the deposition conditions to reel to reel (R2R) evaporation system.

*High Rate Deposition*

13. Jointly with Neocera, develop a high repetition rate PED source (>50Hz).
14. Develop R2R low pressure system.
15. Transfer the deposition conditions to reel to reel (R2R) evaporation system.
16. Further develop high rate processes for buffer layer depositions, such as solution or reactive sputtering.

*Improved YBCO Layer Quality*

17. Increase intra-granular $J_c$ and pinning thru modifications such as composition variation, RE substitution or doping.
18. Develop methods aimed at separating the a-axis and c-axis tilt components from the total misorientation measured in EBKP for materials with lower symmetry such as YBCO.
19. Relate $J_c$ to measured grain boundary maps in laser-scribed samples and experimentally demonstrate filament sub-division to reduce hysteretic losses.

*Conductor Design and Architecture*

20. Impact of various YBCO conductor substrates and stabilization layers on ac losses and over-current tolerance will continue to be studied (in collaboration with AMSC).
21. In addition, normal zone propagation and stability margins will be measured in a series of copper-stabilized, YBCO coated conductors –with different copper thicknesses and joining techniques.
22. Further develop conductive architectures for Cu-based which can support a high-$J_c$, thick YBCO.

*HTS Components*

23. A 1-Tesla HTS coil will be made with YBCO conductor and tested to determine operating envelope and stability margins. –similar to a study with a BSCCO coil in 1994: "Stability measurements of a 1-T HTS magnet," J. W. Lue, R. E. Schwall, et al.
24. Plan to make an YBCO cable with ~ 4-mm wide 2G tape.
25. Work with outside vendors to obtain improved coils with reduced defects.

### 3.2.3 Other National Laboratories

**FY – 2004 Funding: $400,000**

In 2005, there will be increased collaboration with National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL). Their primary focus will address various scale-up aspects of coated conductor's vacuum and non-vacuum techniques, along with coordinated characterization technologies. NREL will be working in collaboration with SuperPower, Los Alamos National Laboratory, Oak Ridge National Laboratory, Brookhaven National Laboratory, and Oxford Superconducting Instruments. SNL partnerships with Oak Ridge National Laboratory, Los Alamos National Laboratory, and Air Force Research labs will concentrate on substrate deposition. University involvement is proposed.

**National Renewable Energy Laboratory (NREL)**

| SECOND GENERATION WIRE (NREL) | | |
|---|---|---|
| **PRIORITY** | **PROJECT** | **$ (K)** |
| 4 | Non-Vacuum Techniques for HTS Coated Conductors | $200 K |
| | **Total** | **$200 K** |

**FY – 2005 Milestones:**

1. Continuation of electrodeposition to obtain bi-axially textured buffer layer for YBCO.
2. Investigate non-vacuum techniques for producing YBCO superconductor.
3. Demonstrate state of the art critical current density (>$10^6$ A/$cm^2$) for HTS YBCO superconductor using newly developed electrodeposited Ni-W, Ni-Ir, and Ir buffer layer.
4. Continue preparation and evaluation of electrodeposited Cu stabilizer on YBCO-coated conductor in collaboration with SuperPower.

**Sandia National Laboratories (SNL)**

| SECOND GENERATION WIRE (SNL) | | |
|---|---|---|
| PRIORITY | PROJECT | $ (K) |
| 2 | All Solution Deposited Buffers and YBCO Development | $200 K |
| | **Total** | **$200 K** |

**FY – 2005 Milestones:**

*All Solution Deposited Buffers:*

1. Improve SrTiO3Δφto <6°, roughness <5nm to replace vapor buffer.
2. Develop AMSC YBCO conversion parameters for STO/NiW.
3. Investigate better NiW#lattice-matched single buffer layers, i.e. $Y_2Ti_2O_7$ YBCO vacuum conversion, scale-up, and interactions.
4. Develop 1 Torr vacuum conversion for 1.5 -2.25 µm TFA/DEA YBCO $I_c$> 200A/cm SanDEA YBCO films on buffer/Ni-W (1.7 MA/$cm^2$, 1.5µm).

*YBCO Development:*

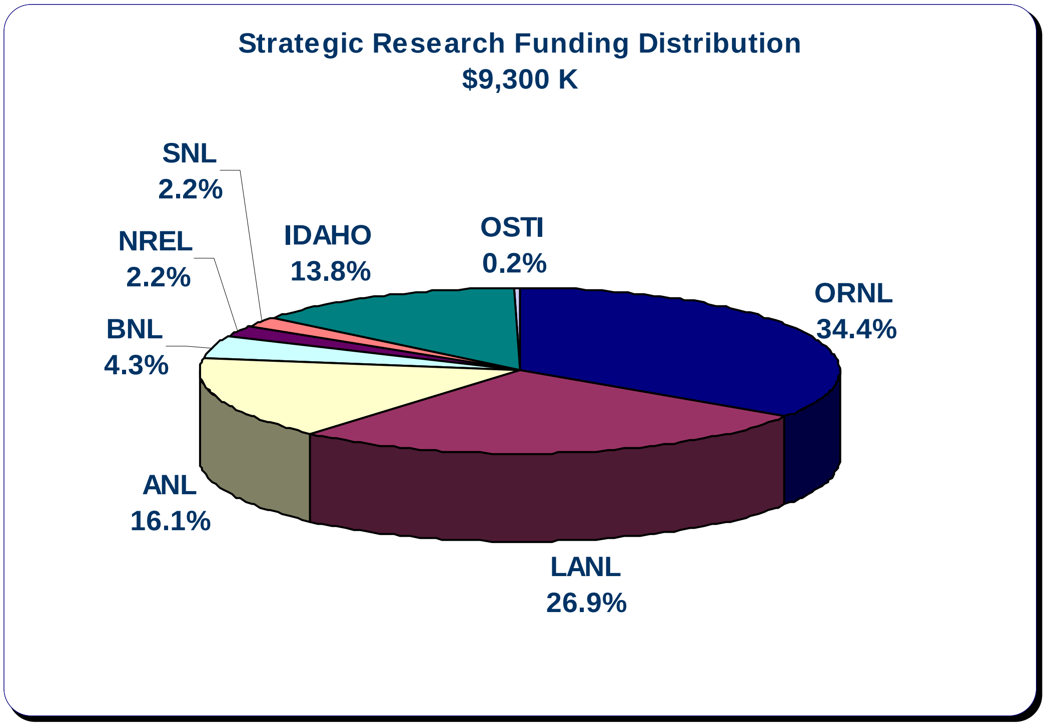
5. Deposit meter lengths of 1.5µm (2L) YBCO films w/ORNL AMSC CRADA: solution buffers, >1µm YBCO, process characterization.
6. Develop small scale pilot production for rapid conversion of YBCO films on buffer-coated substrates for coated conductor fabrication in meter lengths.

## 3.3 STRATEGIC RESEARCH

**FY – 2004 Funding: $9,300,000**

Strategic Research involves investigating new approaches in producing or analyzing superconductivity and HTS applications. This research focuses on high-risk concepts that show promise in the long-term, but additional research is needed before such concepts could interest the private sector. The focus is on solving potential fabrication problems to be encountered in new coated conductors and in HTS application subsystems. The funding distribution of this area of research is found in Exhibit 6.

**Exhibit 6: Strategic Research Funding Distribution**




| ORGANIZATION | $ (K) |
|---|---|
| Oak Ridge National Laboratory | $3,200 K |
| Los Alamos National Laboratory | $2,500 K |
| Argonne National Laboratory | $1,500 K |
| Brookhaven National Laboratory | $400 K |
| National Renewable Energy Laboratory | $200 K |
| Sandia National Laboratories | $200 K |
| IDAHO (University Strategic Research) | $1,280 K |
| OSTI | $20 K |
| **Total** | **$9,300 K** |

### 3.3.1 Oak Ridge National Laboratory

**FY – 2005 Funding: $3,200,000**

| STRATEGIC RESEARCH<br>ORNL | | |
|---|---|---|
| PRIORITY | PROJECT | $ (K) |
| 1 | RABiTS-Based Strategic Research | $900 K |
| 1 | ORNL-American Superconductor Strategic Research CRADA | $1,050 K |
| 2 | Conductor Design and Engineering for Low AC Loss | $500 K |
| 2 | Flux Pinning and Microstructural Characterization of 2G Wires | $400 K |
| 2 | Development of High $I_c$ Ex-Situ Processed RBCO Coated Conductors | $350 K |
| 2 | Phase Relations of High $T_c$ Superconductors | $250 K |
| | **Total** | **$3,200 K** |

In 2005, Oak Ridge National Laboratory plans to increase their effort in design and engineering for low ac loss, flux pinning, and reasons behind the dependence of the transverse stress on RABiTS substrate materials. ORNL will continue to partner with American Superconductor using clean room techniques to further advance substrate manufacturing reliability and rare earth substitutions. ORNL also intends to collaborate with Los Alamos National Laboratory and University of Wisconsin to study the development of high $I_c$ ex-situ processes rare earth substitutions of coated conductors. Additionally, shared studies with University of Wisconsin will concentrate on buffer layer growth and thickness dependence in $J_c$ in coated conductors and University of California, Santa Barbara will address the microstructure and mechanics of superconductor epitaxy via chemical solution deposition.

**FY -2005 Milestones:**

*Substrates and Buffers*

1. Improvement of RABiTS template manufacturing process reliability through fundamental characterization of the buffer layer properties.
2. Reduction of the substrate/buffer manufacturing cost through improved understanding of the interactions of buffer deposition rates and intrinsic properties.
3. Detailed analysis of the role of RABiTS template texture and manufacturing defects as current limiting mechanisms in long length, 4 mm wide YBCO wires.

4. Analysis of the uniformity and reproducibility of long length, 4cm wide RABiTS templates produced in a high-rate reel-to-reel manufacturing process.
5. Continue development of functional buffer layers on textured non-magnetic substrates, including copper and copper alloys.
6. Determine feasibility cube-textured Cu-alloys with a yield strength of over 100 MP and a conductivity of at least 50% IACS.
7. Further develop all-solution buffers and demonstrate $J_c$ performance similar to that possible on vapor-deposited buffers.

*High Rate Deposition*

8. Study effects of rare-earth (R) substitutions for Y using the newly developed fast process

   Focus will be on:
   - Exploration of new opportunities to modify the mediated growth to optimize the GB network/structure, improve $J_c$, flux pinning
   - WDG related task.
   - Initial studies: 100% substitution → RBCO (several R elements)
   - Desired direction: partial substitution → (Y,R)BCO or (R1R2)BCO
   - Capital investment is needed to install a fourth evaporation source in precursor deposition chamber (deferred from FY2004)
   - Properties will be compared to YBCO to evaluate benefits

*Improved YBCO Layer Quality*

9. Continue optimization of flux pinning in YBCO in-situ and ex-situ films on RABiTS:
   - Incorporation of second-phase pinning centers
   - Development of growth defects from substrate surface modifications
10. Study how the liquid-mediated growth can be controlled to improve the structure and properties of grain boundaries (GB) in 1-2 µm ex situ YBCO coatings on RABiTS and IBAD templates.
11. Optimize $J_c$ by variation of conversion and precursor parameters.
12. Perform bi-crystal studies to relate $J_c$ (GB) to 3-dimensional variations in the GB structure.
13. Identify the composition of transient liquids in the conversion of PVD-BaF2 precursors
    - Trap liquids by quenching
    - Use analytical TEM to study structure-chemistry-processing relations

*Conductor Design and Architecture*

14. Development of new, low-cost template architectures that are applicable to Ni-5at%W as well as non-magnetic Ni-9at%W and NiCrW substrates.
15. Establish viability of a fully conductive buffer architecture that is compatible with ex situ YBCO.

*Process Monitoring and Control*

16. Use transmission electron microscopy (TEM) and EBSD at various levels within a film to study grain boundaries (GB) structure and meandering.

*Production Scale-up*

17. Begin pilot line production of high quality (4 cm wide by 100 m long) alloy substrates using the ORNL rolling mill facility with clean room.

### 3.3.2 Los Alamos National Laboratory (LANL)

**FY – 2004 Funding: $2,500,000**

| STRATEGIC RESEARCH<br>LANL | | |
|---|---|---|
| **PRIORITY** | **PROJECT** | **$ (K)** |
| 1 | Understanding and Improving Pinning in Coated Conductors | $350 K |
| 2 | Development of High $I_c$ Ex-Situ Processed RBCO Coated Conductors | $250 K |
| 2 | Research on IBAD MgO-Based Coated Conductors | $1,400 K |
| 3 | AC Loss Studies in Coated Conductors | $300 K |
| 3 | Wire Development Group | $200 K |
| | **Total** | **$ 2,500 K** |

In 2005, Los Alamos National Laboratory plans (LANL) to further enhance its understanding of pinning in coated conductors. LANL will continue in the research areas of IBAD and PLD approaches to achieve outstanding properties in one-meter tape lengths. This work focuses on increasing deposition rates of both the IBAD and YBCO films and extending film thickness to enable higher current carrying capacity.

LANL also intends on increasing deposition rates of both IBAD and HTS films with extending film thickness and reducing ac losses to enable higher current carrying ability. A teaming effort with Stanford University will address the process of in-situ scale-up transfers to metal tapes. Collaborations with partners will proceed in 2005 in order to investigate methods that will increase performance and reduce costs of IBAD technology.

**FY -2005 Milestones:**

*High Rate Deposition*

1. Modify IBAD assist gun to expand deposition zone length to improve process efficiency.
    - Double window to 90% of gun length

*Improved YBCO Layer Quality*

2. Study how the liquid-mediated growth can be controlled to improve the structure and properties of grain boundaries (GB) in 1-2 µm ex situ YBCO coatings on RABiTS and IBAD templates.
3. Optimize $J_c$ by variation of conversion and precursor parameters.
4. Perform bi-crystal studies to relate $J_c$ (GB) to 3-dimensional variations in the GB structure.
5. Improve IBAD MgO texture by reducing divergence of SuperPower's ion-assist gun.
    - Routinely obtain $\Delta\Phi < 5°$ FWHM.
6. Expand upon our data of how YBCO superconducting properties ($T_c$, $J_c$) are affected by transition metal impurities.
    - Determine tolerance limits for substrate elements in YBCO films.

*Conductor Design and Architecture*

7. Continue to refine multi-layers to exploit very high $J_c$ for thinner YBCO.
    - Reproducible 1000 A/cm-width in 2.5 µm.
8. Assist industrial partners in implementing multilayer designs appropriate to their deposition technologies.
9. Develop and test conductor architecture
    - Capable of carrying 100A/cm width ac current in 100m T ac field without quenching (present limit is 10m T)
    - Capable of carrying 100A/cm width ac current in 10m T ac field with ac losses TWO orders of magnitude below present values.
    - "3D" CC (1mm wide, 10um thick)
    - Double layer technology

*Process Monitoring and Control*

10. Use TEM and EBSD at various levels within a film to study grain boundaries (GB) structure and meandering.

*Production Scale-up*

11. Develop and test a conductor production technique (lengths > 10cm)
    - Capable of carrying 100A/cm width ac current in greater than 10m T ac field without quenching.
    - Capable of carrying 100A/cm width ac current in 10m T ac field with ac losses one order of magnitude below present values.
12. Priorities
    - High $J_c$, 1mm wide tapes ($J_c$>3MA/cm$^2$)

### 3.3.3 Other National Laboratories

**FY – 2005 Funding: $2,300,000**

| Strategic Research (ANL) | | |
|---|---|---|
| **Priority** | **Project** | **$ (K)** |
| N/P | Research and Analysis for IEA | $45 K |
| 1 | Characterization of Coated Conductors | $1,375 K |
| 3 | Wire Development Group CRADA | $80 K |
| | **Total** | **$1,500 K** |

| Strategic Research (BNL) | | |
|---|---|---|
| **Priority** | **Project** | **$ (K)** |
| 3 | AC Losses of YBCO Films | $400 K |
| | **Total** | **$400 K** |

| Strategic Research (NREL) | | |
|---|---|---|
| **Priority** | **Project** | **$ (K)** |
| 4 | Substrate preparation by electro-polishing and electrodeposition | $200 K |
| | **Total** | **$200 K** |

| Strategic Research (SNL) | | |
|---|---|---|
| **Priority** | **Project** | **$ (K)** |
| 2 | Vacuum Conversion and CRADA | $200 K |
| | **Total** | **$200 K** |

*N/P not prioritized

Other National Laboratories will perform research on the fabrication of bi-axially-textured buffer layers on metallic substrates. Parameters such as ion flux, energy, the atom-to-ion flux ratio, beam-let divergence, and film thicknesses are studied to improve the texture of buffer layers. Electron-beam deposition, combined with assisting ion-gun deposition and thermal evaporation techniques, is explored for the deposition of textured buffers. Alternate buffer layer architectures will also be investigated.

Scientists are continuing to explore a metallo-organic chemical vapor deposition (MOCVD) technique for deposition of long-length YBCO conductors. The goal of this effort is to establish processing conditions to deposit buffer and superconducting layers on textured metallic substrates. Research includes texture development on metallic substrates and characterization of the textures of substrate and buffer layers. Researchers are undertaking the characterization of microstructural and superconducting properties of second generation wire to improve understanding of $J_c$-limiting factors relating to formation and growth kinetics of high-temperature superconductors.

In FY-2005, work will persist in the deposition rates, film thicknesses, and $J_c$ values of solution-derived technology. Studies will be pursued to understand the atmosphere dependence of thick sol-gel YBCO crystallization kinetics, and means of speeding processing toward commercially important rates. The emphasis will be placed on developing solution methods (sol-gel) that produce textured buffer layers on technologically-important substrates (of sufficient quality to be of commercial interest), and on producing coated conductors by the solution method, with current carrying capabilities competitive with vacuum processed films.

**FY -2005 Milestones:**

*Argonne National Laboratory*

1. Fully characterize the microstructure and electrical properties of Y-based coated conductors.
2. Enhance our understanding and control of BSCCO-2223 phase formation in 1G wires to further improve phase purity, eliminate CLMs and open new paths to increase $I_c$, including optimized OP processing.
3. Combine detailed $J_c$-anistropy and microstructure measurements with new processing to introduce pinning and improved grain boundary structure to optimize 2G wire performance at the operating conditions of temperature, field and field orientation for targeted applications.
4. Implement and refine new analytical techniques such as LTSLM for probing current flow and dissipation in 1G and 2G conductors, identifying CLMs and opening new paths for $J_c$ enhancement.

*Brookhaven National Laboratory*

1. Investigation of nucleation energetics will be extended to include other substrates, nucleation in defects, nucleation in defects, and nucleation in interfaces with Cu segregation.
2. The nucleation and growth kinetic model will be further developed to incorporate finite rates of HF diffusion, and developed to incorporate finite rates of HF diffusion. The model will be utilized to investigate the effects of various process

conditions on process conditions on c-axis, a-axis, a-axis, and general nucleation axis, and general nucleation and growth.
3. The effects of stacking YBCO tapes on ac losses
4. The effects of magnetic substrates and $J_c$ in homogeneity on ac losses of YBCO films.
5. The role of the defects (nucleation sites) on the substrates. (single crystals and metallic substrates).
6. Similar study on different substrates.
7. The effects of sub-atmospheric pressure processing.

*National Renewable Energy Laboratory*
1. Prepare electrodeposited biaxially textured buffer layer for YBCO HTS.
2. Prepare electrodeposited Cu stabilizer on YBCO-coated conductors.

*Sandia National Laboratories*
1. CRADA to spin-off solution buffer technology.

### 3.3.4 Idaho (University Research)

**FY – 2005 Funding: $1,280,000**

University research is concentrated on innovative coated conductor and characterization technologies that are not being conducted in the DOE National Laboratories. DOE cooperative agreements are competitively awarded that provide strong interaction between the universities, DOE and Lab technical managers, this approach will permit researchers to work in one of the National Laboratories for six months of the year. In 2005, the projects and the prioritization universities intend to investigate are found in the tables below.

| IDAHO<br>UNIVERSITY RESEARCH PROJECTS | | |
|---|---|---|
| **Priority** | **Project** | |
| 2 | Conversion of Oxy-Fluoride Based Coated Conductors | MIT, BNL |

**FY -2005 Milestones:**
1. Develop reliable procedure for quantifying total $BaCeO_3$ on substrate.
2. Relate $BaCeO_3$ to film properties.

| IDAHO<br>UNIVERSITY RESEARCH PROJECTS | | |
|---|---|---|
| **Priority** | **Project** | |
| 2 | Buffer Layer Growth and the Thickness Dependence of $J_c$ in Coated Conductors | UW-Madison |

**FY -2005 Milestones:**

1. Study relationship between in-plane texture of buffer layer with respect to the ion beam and tape axis directions.
2. Study the thickness dependence of in-and out-of-plane textures of thick YBCO films.
3. Grow on mis-cut IBAD-MgO template (collaboration with Vlad Matthias at LANL).
4. Study development of MOD buffer layer epitaxy.
5. Characterize buffer defects and propagation into YBCO layer.
6. Refine the "physics" model and check by comparison to "uniform-microstructure" films for which milled $J_c$ data will be obtained PLD model films from Chang-Beom Eom
7. Separate GB from pinning effects by knowing when we are in each limit $J_c$ data allows first cut, log V-log I an additional check.
8. Evaluate both BaF2-YBCO bi-crystals grown on CeO2-buffered YSZ and by locating individual grain boundaries within coated conductors
9. Continue strong collaborations with Feenstra, Holesinger, and AMSC.

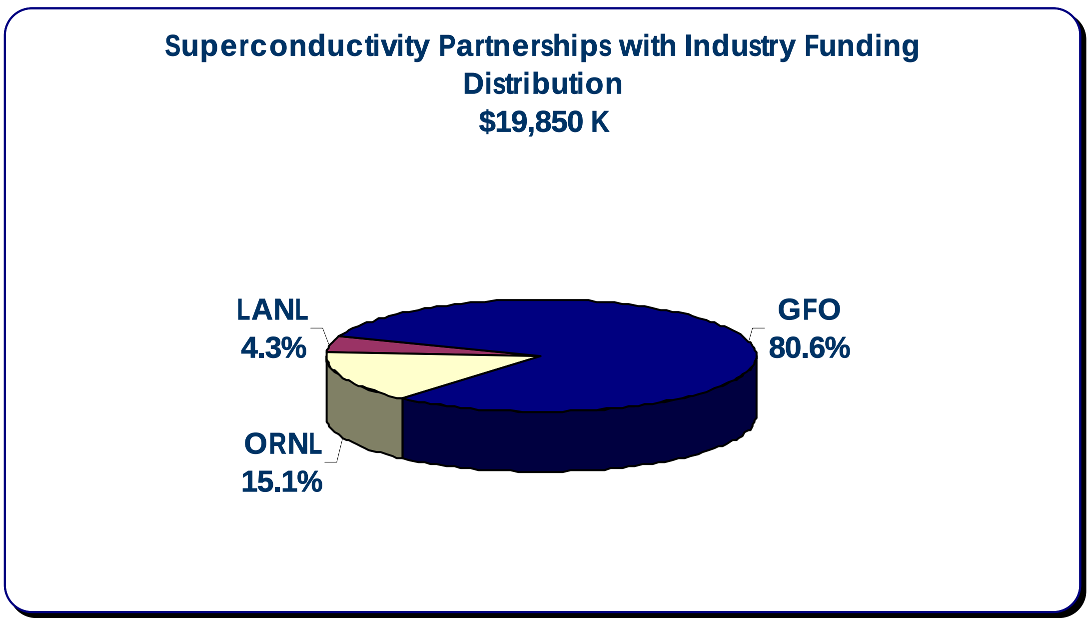
# 4.0 ELECTRIC APPLICATIONS
## *(SUPERCONDUCTIVITY PARTNERSHIPS WITH INDUSTRY)*

### 4.1 SUPERCONDUCTIVITY PARTNERSHIPS WITH INDUSTRY

**FY – 2005 Funding: $19,850,000**

The Superconductivity Partnerships with Industry (SPI) fosters an integrated industry led effort to accelerate the development of HTS application prototypes that can then be commercialized by U.S. industry. The competitive demonstration projects are cost shared by government and industry, and are completed by integrated teams of industry stakeholders, utilities, and national laboratories. Projects are funded through cooperative agreements with the DOE Golden Field Office. The SPI Projects have resulted in successful demonstration of a HTS transmission cable system, power equipment, electric motor, flywheel system, matrix fault current limiter, magnetic resonance imaging, and magnetic separation. As all of the ongoing projects are nearing completion, a solicitation for the next round of new projects is planned to be released in FY – 2007. Exhibit 7 provides a distribution of the Superconductivity Partnerships with Industry breakdown.

**Exhibit 7: Superconductivity Partnerships with Industry Funding Distribution**




| Organization | $ (K) |
|---|---|
| Oak Ridge National Laboratory | $3,000 K |
| Los Alamos National Laboratory | $850 K |
| Golden Field Office | $16,000 K |
| **Total** | **$19,850 K** |

The performance-based, HTS Peer Review to assess the program progress was held in July, 2004. Peer Reviewers provided the following comments about Superconductivity Partnerships with industry:

> *"The SPI readiness Review Program will have a significant impact in reducing risks and eliminate unforeseen problems areas in SPI projects. The implementation of a website for communication critical findings and recommended action across SPI teams is an excellent move. All new projects should be reviewed within six months for plans and processes. Annual reviews should not be needed, as this will unnecessarily burden the SPI team progress. Reviews should be made when the SPI team is ready to go to a significant milestone, such as end of design, start of manufacturing, before major performance tests."* This was the first year reviewers were asked to rate this program. Risk reduction continues to be a major thrust.
>
> *"The team working on the Matrix Fault Current Limiter has shown big progress during FY 2004. The project is moving according to power systems needs that are coming from the recent change in the power system."* In 2005, commercial applications will continue to be broadened; the major goals of the utilities are to reduce costs and maintain/increase reliability.

## 4.2 Golden Field Office of Cooperative Agreements

**FY – 2005 Funding: $16,000,000**

The Golden Field Office (GFO) issued a solicitation in the spring of 2001 for new projects to supplement the suite of seven projects being completed that were awarded in the competitive selections of 1994 and 1996. The selected proposals were announced on September 24, 2001; a new solicitation is planned for the 2007 fiscal year. $16 million is set aside for the funding of these projects in FY - 2005. This foresight will enable an accelerated startup and shorter timetable for the projects.

***FY – 2005 SPI Projects:***

***SPI Readiness Review Program:*** The focus of this project is on collaboration with the SPI teams to identify potential failure modes; issues involving cryogenic temperatures, vacuum and high voltage dielectrics are a major concern. Expertise is obtained as needed from national laboratories, universities, and consultants. The objective for 2005 is to review all active SPI projects.

***Columbus Cable Project***: The purpose of this project is to field test long length HTS cable under real environmental stresses and electric loads. The system will form an important electrical link in a utility substation in Columbus Ohio replacing conventional cables with a limited current-carrying capacity. The project is partnered with Ultera, utility partner: AEP, Bixby substation, using 13.2 kV, load rating 3.0 kV, 69 MVA, triax cable design, cold dielectric, splice, underground, multiple 90 degree bends, length 330 m.

***Albany Cable Project***: This project is partnered with utility Niagara Mohawk, SuperPower, BOC, Sumitomo Electric, and New York State Energy Research and Development Authority. The purpose involves the development and demonstration of a High Temperature Superconducting cable installation between two major substations and splice. This one of a kind demonstration includes the usage of second generation wire cable voltage 34.5 kV, load rating 800 A, 48 MVA, cold dielectric, cable design incorporating YBCO, length 350 m.

***Long Island Cable Project****:* The primary objective of this project involves the demonstration of a High Temperature Superconductor (HTS) power cable in the Long Island Power grid, this project spans nearly half a mile and will serve as a permanent link in the Long Island Power Authority's (LIPA) grid network. The installation will represent the first-ever superconductor cable in a live grid at transmission voltages of 138 kV, 2400 A, 600 MVA, design fault current 69 kA at 250 ms (15 line cycles), coaxial cold dielectric design, 3-phase, to be installed between two major substations, length 610 m.

***HTS Transformer: Waukesha/IGC-SuperPower Superconductivity Partnership Initiative Project*:** The objective in 2005 of the current Phase II Superconductivity Partnership Initiative (SPI) project with Waukesha Electric Systems (WES), SuperPower, Inc. (SP), and Energy East, is to demonstrate the technical and economic feasibility of HTS transformers of medium (30 MVA) to larger ratings. An alpha-prototype 5/10 MVA, 3-phase, HTS transformer, with primary/ secondary voltage ratings of 24.9/4.2 kV and 100-kV BIL has been designed, fabricated, and tested.

***Development of Ultra-Efficient HTS Motor Systems:*** The purpose of the project is to perform research and development related to commercial viability of industrial motors with high temperature superconducting (HTS) windings. The R&D areas identified were based upon the past work that Rockwell Automation had conducted on development and testing of HTS based motors up to and including the laboratory test of a 1600 hp motor.

***Design and Development of a 100 MVA HTS Generator:*** General Electric's Global Research in Niskayuna, N.Y., will design and develop a 100 MVA class high-temperature superconducting (HTS) generator, with designs through 250 MVA. The HTS rotor will be capable of retrofitting into existing generators. ORNL and LANL have entered into CRADAs with GE to provide assistance in several technology areas.

***Development of Flywheel Electricity System:*** The main purpose of this effort is to develop a 10-kWh flywheel energy system based on high-temperature superconducting (HTS) bearings. The first unit developed had a 3-kW motor/generator (M/G). The second unit developed has a 100-kW M/G.

***Waste Water Treatment with Magnetic Separation:*** Los Alamos National Laboratory is leading the SPI development of a 500 mm HTS reciprocating magnetic separator. An HTS magnetic separator offers significant operational energy savings compared to conventional copper coil separators. The DuPont business plan calls for the development of new applications of magnetic separation that can benefit from the energy efficiency.

DuPont and LANL established a CRADA in FY03 that capitalizes on LANL's experience in magnetic separation. After assessing several potential market opportunities, LANL decided to focus on the removal of heavy metals in wastewater using high gradient magnetic separation (HGMS). LANL will work to develop an in-situ ferrite formation process that incorporates the heavy metals in a ferrite crystal lattice. The ferrites, having a high magnetic susceptibility, are then readily removed as they pass near a magnetized matrix material.

***Matrix Fault Current Limiter: SuperPower, Inc., CRADA:*** The purpose of this project is to conduct R&D on specified components and provide technical design support to a SuperPower, Inc. This device incorporates a series-parallel array of bulk HTS elements and inductors in a sub-cooled liquid nitrogen bath. Transition of the HTS elements into the normal state during a fault drives most of the current into the inductors and leads to a sudden increase in impedance that limits the fault current.

## 4.3 National Laboratory Support

**FY – 2005 Funding: $3,850,000**

### 4.3.1 Oak Ridge National Laboratory (ORNL)

**FY – 2005 Funding: $3,000,000**

| Superconductivity Partnerships with Industry Research ORNL | | |
|---|---|---|
| **Priority** | **Project** | **$ (K)** |
| 1 | 100 MVA HTS Generator CRADA | $250 K |
| 1 | HTS Power Cable CRADA | $1,200 K |
| 1 | Matrix Fault Curent Limiter CRADA | $650 K |
| 2 | SPI Readiness Review Program | $200 K |
| 4 | HTS Transformer CRADA | $300 K |
| | **Total** | **$3,000 K** |

In 2005, Oak Ridge National Laboratory will strive to further the development in the Superconductivity Partnerships with Industry projects. Doing so will involve the technologies for producing practical HTS coils for motors, transformers, and other power applications.

Benefits of this research will be:

- √ Transmission cables that are three to five times' current capacity, retrofit in urban applications, and substitute for overhead lines when environmentally prohibited;
- √ Transformers that are smaller, higher efficiency, have decreased fire hazard, and with negligible environmental impact;
- √ Motors and generators that are 50% smaller, 50% more efficient, and quieter that conventional equipment; and
- √ Current limiters that enhance the stability of the United States electricity grid, ORNL will also integrate the activities with other national laboratories, government agencies, universities, and electric utilities.

**FY – 2005 Milestones:**

*Readiness Reviews*

1. At least one review per project is planned in 2005 and 2006 as the SPI projects precede to initial commissioning.
2. We are encouraging all the SPI projects to develop risk identification and mitigation processes such as failure mode and effects analysis (FMEA) to manage risks.
3. Will review each project's risk mitigation plans in 2005
4. In 2005 a web-site will be implemented that will have:
    - Lessons learned from prior SPI projects
    - Some general design guidance on high voltage, vacuum, etc. and a place where SPI participants can post comments or questions and get feedback.
5. Based on continuing issues with the performance of dielectric materials at cryogenic temperatures and at high voltage, more emphasis is needed on R&D and design guidelines in this area for the grid-based SPI projects.
6. A High-Voltage Cryogenic Dielectric Workshop is being considered; it could be held just after the 2005 Wire Development Workshop.
7. Participation by each SPI team facing high voltage component qualification would be expected and the agenda could include some overview talks on liquid nitrogen dielectrics, solid dielectrics, HV design practices, etc.

*Transformer*

1. Cryogenic dielectric studies for 30-MVA+ design ratings
    - PD, aging, ac and impulse breakdown strength
    - Thermal properties–shock, conductivity, heat capacity
    - Partnership with a commercial cast coil manufacturer
    - Tests on full-scale dummy coils
2. Investigate electrical & mechanical compatibility between all insulation systems components.
    - Study YBCO materials for the 30-MVA reference design
    - AC loss
    - $I_c$ and over current capability; operation in liquid nitrogen
3. Fault current limiting
4. New features–pulse tube coolers, tap changers, fault current limiting.

5. Simplify design for best manufacturability, marketability, reliability, cost, and match to utility requirements.

*Matrix Fault Current Limiter*

1. Scale up for non-grid demonstration at high voltage
    - Rating: 138kV, application specific current, single phase
    - Design by June 2005, Prototype by December 2005

### 4.3.2 Los Alamos National Laboratory (LANL)

**FY – 2005 Funding: $850,000**

| SUPERCONDUCTIVITY PARTNERSHIP WITH INDUSTRY RESEARCH LANL | | |
|---|---|---|
| **Priority** | **Project** | **$ (K)** |
| 1 | Matrix Fault Current Limiter CRADA | $100 K |
| 1 | 100 MVA HTS Generator CRADA | $480 K |
| 2 | SPI Readiness Review Program | $70 K |
| 2 | Waste Water Treatment with Magnetic Separation CRADA | $200 K |
| | **Total** | **$850 K** |

In 2005, Los Alamos National Laboratory will work in collaboration with General Electric and Oak Ridge National Laboratory in support of the research and development of 100 MVA HTS Generators. This project is ranked as one of the top priorities for FY-05. LANL will also be working as part of the SPI Readiness Review Team which is vital for risk mitigation and the success of the superconductivity program. LANL will continue to lead a development team with SuperPower and Nexans to demonstrate a HTS Fault Current Limiter (FCL). In addition to the continual research in Waste Water Treatment with Magnetic Separation.

**FY – 2005 Milestones:**

1. Extend CRADA with DuPont or find another industrial partner for magnetic separation project
2. Extend technology to other sites/applications
3. Refine HGMS procedure
    - Establish a larger HTS magnet system at LANL
    - Design, fabricate, assemble, test, verify operational capability of pilot plant

# APPENDIX – ACRONYMS

AA- Atomic Absorption

AAD- Aerosol Assisted Deposition

AC- Alternating Current

AFM- Atomic Force Microscope

C/P Ratio- Cost/Performance Ratio

C4- Coordinated Characterization of Coated Conductors

CC- Coated Conductors

CLMs- Current Limiting Mechanisms

CRADA- Cooperative Research and Development Agreement

CSD- Chemical Solution Deposition

EBKD- Electron Backscatter Kikuchi Diffraction

ED- Electrodeposition

EDS- Energy Dispersion Spectroscopy

EMC- Electron Microscopy Center

FCL- Fault Current Limiter

FIB- Focused Ion Beam

FMEA- Failure Mode and Effects Analysis

FTIR- Fourier Transform Infrared

FW- Flywheel

FWHM- Full Width at Half Maximum

GB- Grain Boundaries

HEP- High Energy Physics

HGMS- High Gradient Magnetic Separation

HTS- High Temperature Superconductivity

IBAD- Ion Beam Assisted Deposition

IP- Intellectual Property

IPP- Independent Power Producer

ISD- Inclined Substrate Deposition

KBS- Key Benchmark Studies

MFCL- Matrix Fault Current Limiter

MOD- Metal Organic Deposition

MOI- Magneto-Optical Imaging

MQMG- “Melt-Quench-Melt-Growth”

MRI- Magnetic Resonance Imaging

MVA- Mega Volt Amp

NRA- Nuclear Reaction Analysis

OP- Over Pressure

PD- Phase Diagram

PDIV- Partial Discharge Initiation Voltage

PED- Pulsed Electron Deposition

PEEK- Polyetheretherketone

PI- Principal Investigator

PLD- Pulsed Laser Deposition

PM- Permanent Magnet

PVD- Physical Vapor Deposition

QA- Quality Assurance

QC- Quality Control

R&D- Research and Development

R2R- Reel to Reel

RHEED- Reflected High Energy Electron Diffraction

RM- Research Management

RRT- Readiness Review Team

SC- Superconducting

SCIM- Superconducting Induction Motor

SEM- Scanning Electron Microscope

SIMS- Second Ions Mass Spectroscopy

SPI- Superconductivity Partnerships with Industry

TEM- Transmission Electron Microscopy

TFA- Triflouracetic acid (used in solution processing)

UPS- Uninterrupted Power Supply

XRD- X-Ray Diffraction

# 2005 Activities

In 2005, three new cable projects will be beginning. Columbus Cable, Albany Cable, and Long Island Power Cable are all very exciting “first of a kind” projects. The SPI teams will be continuing risk mitigation practices and assist project leaders in identifying any unforeseen problems that could arise.  SPI projects will be continuing to receive quarterly reviews at filed locations and there is a greater increase in utility involvement. The following are summaries of the 2005 SPI projects and Fact Sheets describing the goals and performances of each project.

***SPI Readiness Review Program:*** The focus of this project is on collaboration with the SPI teams to identify potential failure modes; issues involving cryogenic temperatures, vacuum and high voltage dielectrics are a major concern. Expertise is obtained as needed from national laboratories, universities, and consultants. The objective for 2005 is to review all active SPI projects.

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**Future NY site**

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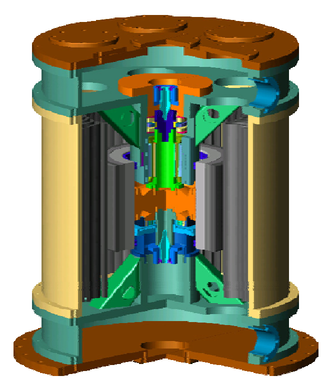

**Pictorial Representation of MFCL**

# Conclusions

The DOE Superconductivity for Electric Systems Program continues its long-running commitment to high quality, technically credible peer review. Over the past decade, the peer review process and criteria has been refined and validated to result in an efficient and effective management tool. The peer review successfully merges two elements operationally into a single review process:

1. "Review of a program of research," which examines the nature of the component projects as an in-depth technical review; and

2. "Review of a research program," which examines the nature of the structural relationships among the projects and between the projects and their external environment as a management review.

The peer review supports many diverse purposes. Peer reviews can provide legitimacy and competency to increase a program's visibility and support. The objectives of the peer review range from being an efficient resource allocation mechanism, to a credible predictor of research impact. A properly conducted program peer review can provide credible indications to the funding organization of program quality, program relevance, management quality, and appropriateness of direction.

Peer Reviews provide value at critical times of technological advancements. The period between the reviews is the performance phase when researchers will maintain a higher level of performance quality because of the knowledge of the forthcoming expert review. During the period of review preparation, researchers reflect on their results during the rehearsing of their presentations. This valuable experience provides a focal point for internal discussions of unresolved issues and priorities, and fuels substantive discussions in order to arrive at a quality presentation. Then at the actual review, independent viewpoints are injected in a public forum, high quality research is re-affirmed, and strong recommendation are provided to remediate any weak research.

The superconductivity Peer Review continues to provide many benefits as a management tool. Primarily, constructive feedback to the program and projects usually results in improvements to the focus and conduct of research. Finally, it should be noted that the peer review process adds value to the program's investment strategy. While investment is the allocation of resources among the program components, the strategy is the rationale for the prioritization of those resources. The determination of what research will produce the most relevant and highest quality results will obviously have the greatest impact on the program's mission.

# Appendix A:
# Superconductivity Partnerships with Industry Fact Sheets

# Appendix B:

# Probability of Risk Report

# FMEA FOR CRYOGENIC SYSTEM

## Accident Frequency Categories

| Description | Designation | Specific Individual Operation (Frequency, $year^{-1}$) | Overall Facility Operation |
|---|---|---|---|
| | | | |
| **Anticipated** | A | Likely to occur frequently ($F > 10^{-2}$) | Will occur periodically |
| **Unlikely** | B | Likely to occur sometime in the life of the operation ($10^{-4} \leq F \leq 10^{-2}$) | Will occur |
| **Extremely Unlikely** | C | Probability of occurrence is so small it can be assumed it will not be experienced ($F < 10^{-4}$) | Can be assumed that although possible, it will not be experienced |

## Chemical Accident Consequence Categories

| Description | Designation | Public Effects | Worker Effects |
|---|---|---|---|
| | | | |
| **High consequence** | a | >EPRG-2 at site boundary | >EPRG-3 at 100 m or prompt death in facility |
| **Moderate consequence** | b | Not applicable | Serious injury in facility |
| **Low consequence** | c | <EPRG-2 at site boundary | No serious injuries in facility |

## Risk Matrix

| Consequence/Frequency | $F > 10^{-2}$ (A) | $10^{-4} \leq F \leq 10^{-2}$ (B) | $F < 10^{-4}$ (C) |
|---|---|---|---|
| | | | |
| **High consequence, (a)** | I | I | II |
| | | | |
| **Moderate consequence, (b)** | I | II | III |
| | | | |
| **Low consequence, (c)** | III | III | IV |

| Symbol | Number | Description | Function | Failure Mode | Effect | Detection | Mitigation or Prevention | Freq. | Cons | Risk |
|---|---|---|---|---|---|---|---|---|---|---|
| BC | 1 | Bayonet Connection | Return from Load | Clogged | Increased pressure drop reduces flow from load | System pressure drop increases; coolant flow decreases | Coolant filtered; connections capped when disconnected | A | c | III |
| | | | | Coolant leak | Increased heat load; potential frostbite and asphyxiation hazard | Increased coolant loss; leak visually observed | Connections and seals inspected prior to use; workers use personal protective equipment; connections located outside | A | b | I |
| BC | 2 | Bayonet Connection | Supply to Load | Clogged | Increased pressure drop reduces flow from load | System pressure drop increases; coolant flow decreases | Coolant filtered; connections capped when disconnected | A | c | III |
| | | | | Coolant leak | Increased heat load; potential frostbite and asphyxiation hazard | Increased coolant loss; leak visually observed | Connections and seals inspected prior to use; workers use personal protective equipment; connections located outside | A | b | I |
| BC | 3 | Bayonet Connection | Cooldown to Load | Clogged | Decreased flow to system | System cools slowly | Connections capped when disconnected | A | c | III |
| | | | | Coolant leak | Increased heat load; potential frostbite and asphyxiation hazard | Increased coolant usage; leak visually observed | Connections and seals inspected prior to use; workers use personal protective equipment; connections located outside | A | b | I |
| BC | 4 | Bayonet Connection | LN2 Dewar Fill | Clogged | Decreased flow to tank | Tank fills slowly | Connections capped when disconnected | A | c | III |
| | | | | Coolant leak | Increased heat load; potential frostbite and asphyxiation hazard | Leak visually observed | Connections and seals inspected prior to use; workers use personal protective equipment; connections located outside | A | b | I |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| V | 1 | Valve | Utility Gas Supply | Fails to open; opens only partially or is partially blocked | No impact on normal operation; utility gas supply unavailable or inadequate | Nonexistent or insufficient utility gas supply | Tested prior to use; capped when not in use | A | c | III |
| | | | | Leaks or not properly closed | Excessive loss of nitrogen supply | Inability to maintain tank pressure; visually observed | Tested prior to use; capped when not in use | A | c | III |
| PC | 2 | Pressure Control | LN2 Tank Pressure Control (Vent) | Fails to open; opens only partially or is partially blocked | Tank, utility gas and system gas pressure increase may be uncontrolled | Tank pressure increases | Tested prior to use and periodically tested | C | b | III |
| | | | | Leaks or does not properly close | Tank, utility gas and system gas pressure increase may be uncontrolled | Inability to maintain tank pressure; visually observe venting | Tested prior to use and periodically tested | A | c | III |
| V | 3 | Valve | Gas Supply to System | Fails to open; opens only partially or is partially blocked | System gas supply unavailable or inadequate | Nonexistent or insufficient gas supply | Tested prior to use; capped when not in use | A | c | III |
| | | | | Leaks or not properly closed | Excessive loss of nitrogen supply | Inability to maintain tank pressure; visually observed | Tested prior to use; capped when not in use | A | c | III |
| V | 4 | Valve | LN2 Fill | Fails to open; opens only partially or is partially blocked | Tank cannot be filled or fills slowly | Liquid nitrogen level in tank fails to increase | Tested prior to use; capped when not in use | A | c | III |
| | | | | Leaks or not properly closed | Excessive loss of nitrogen supply | Inability to maintain tank level; visually observed | Tested prior to use; capped when not in use | A | c | III |
| V | 5 | Valve | LN2 Precool | Fails to open; opens only partially or is partially blocked | Transfer line cannot be cooled or cools slowly | Operator observes inadequate flow | Tested prior to use; capped when not in use | A | c | III |
| | | | | Leaks or not properly closed | Excessive loss of nitrogen supply | Inability to maintain tank level; visually observed | Tested prior to use; capped when not in use | A | c | III |
| R | 6 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Pressure buildup circuit and feed line may overpressure | If buildup line open to tank, tank pressure increases | Tested prior to use and periodically tested; tank protected by dedicated relief system | C | b | III |
| | | | | Leaks or does not properly close | Tank pressure decrease uncontrolled | Inability to maintain tank pressure; visually observe venting | Tested prior to use and periodically tested | A | c | III |
| V | 7 | Valve | LN2 Tank Liquid Isolation | Fails to open; opens only partially or is partially blocked | Tank cannot be filled or fills slowly | Liquid nitrogen level in tank fails to increase | Tested prior to use | A | c | III |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Leaks or not properly closed | No effect if pressure buildup system operational | Inability to maintain tank level | Tested prior to use | A | c | III |
| F | 8 | Filter | | Clogged | Increased pressure drop reduces flow to pressure buildup unit | Tank, utility gas or system gas pressure low | Tested prior to use; periodically inspected and cleaned | A | c | III |
| | | | | Open | Contaminants enter pressure buildup system; components plug and/or loose efficiency | Tank, utility gas and system gas pressure low if input blocked; tank, utility gas and system gas pressure high if exhaust blocked | Tested prior to use; periodically inspected and cleaned | A | c | III |
| PC | 9 | Pressure Control | LN2 Tank Pressure Control (Pressurize) | Fails to open; opens only partially or is partially blocked | Tank, utility gas and system gas pressure may decrease | If not isolated from tank, tank pressure low | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Tank, utility gas and system gas pressure may increase | If not isolated from tank, tank pressure high | Tested prior to use and periodically tested | C | b | III |
| R | 10 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Pressure buildup circuit may overpressure | If buildup line open to tank, tank pressure increases | Tested prior to use and periodically tested; tank protected by dedicated relief system | C | b | III |
| | | | | Leaks or does not properly close | Tank, utility gas and system gas pressure may decrease | Inability to maintain tank utility gas and system gas pressure; visually observe venting | Tested prior to use and periodically tested | A | c | III |
| V | 11 | Valve | LN2 Tank Gas Isolation | Fails to open; opens only partially, is partially blocked or is closed | Tank fills slowly; tank pressure cannot be maintained | Liquid nitrogen level in tank fails to increase; tank pressure decreases or increases | Tested prior to use; locked open in operation | B | b | II |
| | | | | Leaks or not properly closed | No effect if pressure buildup system operational | Should be open in normal operation | Tested prior to use | A | c | III |
| V | 12 | Valve | Relief/Burst Disc Isolation/Selection | Fails to open; opens only partially or is partially blocked | Tank not properly connected to relief system | Tank pressure may increase | Tested prior to use | C | b | III |
| | | | | Leaks or not properly closed | No effect if alternate relief system in place | Visual if alternate relief system removed | Tested prior to use | A | c | III |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| BD | 13 | Burst Disc | LN2 Dewar Safety | Fails to open; opens only partially or is partially blocked | Tank may overpressure | Tank pressure increases | Tank protected by parallel relief valve; inspect on installation | B | b | II |
| | | | | Leaks | Tank pressure may decrease | Tank pressure decreases | Leak check on installation | A | c | III |
| R | 14 | Relief Valve | LN2 Dewar Safety | Fails to open; opens only partially or is partially blocked | Tank may overpressure | Tank pressure increases | Tank protected by parallel burst disc; periodically tested | B | b | II |
| | | | | Leaks | Tank pressure may decrease | Tank pressure decreases | Periodically tested | A | c | III |
| R | 15 | Relief Valve | LN2 Dewar Safety | Fails to open; opens only partially or is partially blocked | Tank may overpressure | Tank pressure increases | Tank protected by parallel burst disc; periodically tested | B | b | II |
| | | | | Leaks | Tank pressure may decrease | Tank pressure decreases | Periodically tested | A | c | III |
| BD | 16 | Burst Disc | LN2 Dewar Safety | Fails to open; opens only partially or is partially blocked | Tank may overpressure | Tank pressure increases | Tank protected by parallel relief valve; inspect on installation | B | b | II |
| | | | | Leaks | Tank pressure may decrease | Tank pressure decreases | Leak check on installation | A | c | III |
| V | 17 | Valve | LN2 Isolation | Fails to open; opens only partially or is partially blocked | System cannot be filled or fills slowly | System fails to properly cool; subcoolers fail to fill | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Minor loss of nitrogen supply | Slightly increase in LN2 usage | Test prior to installation | A | c | III |
| R | 18 | Relief Valve | Return Phase Separator Tank Relief | Fails to open; opens only partially or is partially blocked | Phase separator may overpressure | System pressure may increase | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Phase separator pressure decrease uncontrolled | Inability to maintain system pressure; visually observe venting | Tested prior to use and periodically tested | A | c | III |
| AV | 19 | Automatic Valve | Loop pressure control (Vent) | Fails to open; opens only partially or is partially blocked | System cannot be vented or vents slowly | Pump may cavitate causing flow to decrease | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | System may loose excessive nitrogen | Slightly increase in LN2 usage | Test prior to installation | A | c | III |
| CV | 20 | Check Valve | | Fails to open; opens only partially or is partially blocked | Phase separator may overpressure | System pressure may increase | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Phase separator could receive air | Visually observe venting | Tested prior to use and periodically tested | A | c | III |

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| CV | 21 | Check Valve | Subcooler passive vent | Fails to open; opens only partially or is partially blocked | Subcooler may overpressure | Subcooler vent line pressure high | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Subcoller could receive air | Subcooler vent line pressure low | Tested prior to use and periodically tested | A | c | III |
| AV | 22 | Automatic Valve | Subcooler Vent Isolation | Fails to open; opens only partially or is partially blocked | Subcooler cannot be vented or vents slowly | Subcooler vent line pressure low; system temperature high | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | If offline, subcooler cannot be isolated from vacuum | Slightly increase in LN2 usage | Test prior to installation | A | c | III |
| R | 23 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Isolated volume may overpressure | None | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | System pressure decrease; LN2 consumption increase | Inability to maintain system pressure; visually observe venting | Tested prior to use and periodically tested | A | c | III |
| R | 24 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Isolated volume may overpressure | None | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | System pressure decrease; LN2 consumption increase | Inability to maintain system pressure; visually observe venting | Tested prior to use and periodically tested | A | c | III |
| R | 25 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Isolated volume may overpressure | None | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | System pressure decrease; LN2 consumption increase | Inability to maintain system pressure; visually observe venting | Tested prior to use and periodically tested | A | c | III |
| P | 26 | Pressure Transducer | Subcooler Vacuum Manifold Pressure | Fails low | Subcooler pressure may be high and may overpressure | System temperature increase | Test periodically; vacuum manifold protected by relief valve | A | c | III |
| | | | | Fails high | Subcooler pressure may be low | System temperature decrease | Test periodically | A | c | III |
| AV | 27 | Automatic Valve | Subcooler Pressure Control | Fails to open; opens only partially or is partially blocked | Subcooler cannot be evacuated or evacuates slowly | Subcooler vacuum manifold pressure high; system temperature high | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Subcooler vacuum cannot be controlled | Subcooler vacuum manifold pressure low; system temperature low | Test prior to installation | A | c | III |

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| AV | 28 | Automatic Valve | Subcooler Vent Isolation | Fails to open; opens only partially or is partially blocked | Subcooler cannot be vented or vents slowly | Subcooler vent line pressure low; system temperature high | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | If offline, subcooler cannot be isolated from vacuum | Slightly increase in LN2 usage | Test prior to installation | A | c | III |
| AV | 29 | Automatic Valve | Vacuum Pump Isolation | Fails to open; opens only partially or is partially blocked | Subcooler cannot be vented or vents slowly | Subcooler vent line pressure high; system temperature high | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Pump oil and/or air may enter vacuum line | High vacuum manifold pressure | Test prior to installation; pump has anti-suckback valve; pump exhaust has check valve | A | c | III |
| AV | 30 | Automatic Valve | Vacuum Pump Isolation | Fails to open; opens only partially or is partially blocked | Subcooler cannot be vented or vents slowly | Subcooler vent line pressure high; system temperature high | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Pump oil and/or air may enter vacuum line | High vacuum manifold pressure | Test prior to installation; pump has anti-suckback valve; pump exhaust has check valve | A | c | III |
| AV | 31 | Automatic Valve | Vacuum Pump Isolation | Fails to open; opens only partially or is partially blocked | Subcooler cannot be vented or vents slowly | Subcooler vent line pressure high; system temperature high | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Pump oil and/or air may enter vacuum line | High vacuum manifold pressure | Test prior to installation; pump has anti-suckback valve; pump exhaust has check valve | A | c | III |
| F | 32 | Filter | Vacuum Pump Oil Return | Clogged | Increased back-pressure reduces flow through pump | Vacuum manifold pressure increases; system temperature increases | Tested prior to use; periodically inspected and cleaned | A | c | III |
| | | | | Open | Excessive loss of vacuum pump oil | Visually observe oil effluent from exhaust line | Tested prior to use; periodically inspected | A | c | III |
| F | 33 | Filter | Vacuum Pump Oil Return | Clogged | Increased back-pressure reduces flow through pump | Vacuum manifold pressure increases; system temperature increases | Tested prior to use; periodically inspected and cleaned | A | c | III |

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| | | | | Open | Excessive loss of vacuum pump oil | Visually observe oil effluent from exhaust line | Tested prior to use; periodically inspected | A | c | III |
| F | 34 | Filter | Vacuum Pump Oil Return | Clogged | Increased back-pressure reduces flow through pump | Vacuum manifold pressure increases; system temperature increases | Tested prior to use; periodically inspected and cleaned | A | c | III |
| | | | | Open | Excessive loss of vacuum pump oil | Visually observe oil effluent from exhaust line | Tested prior to use; periodically inspected | A | c | III |
| CV | 35 | Check Valve | Back Flow Elimination | Fails to open; opens only partially or is partially blocked | Increased back-pressure reduces flow through pump | Vacuum manifold pressure increases; system temperature increases | Tested prior to use; periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Subcoller could receive air | None | Tested prior to use and periodically tested | A | c | III |
| CV | 36 | Check Valve | Back Flow Elimination | Fails to open; opens only partially or is partially blocked | Increased back-pressure reduces flow through pump | Vacuum manifold pressure increases; system temperature increases | Tested prior to use; periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Subcoller could receive air | None | Tested prior to use and periodically tested | A | c | III |
| CV | 37 | Check Valve | Back Flow Elimination | Fails to open; opens only partially or is partially blocked | Increased back-pressure reduces flow through pump | Vacuum manifold pressure increases; system temperature increases | Tested prior to use; periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Subcoller could receive air | None | Tested prior to use and periodically tested | A | c | III |
| V | 38 | Valve | Load Return Isolation | Fails to open; opens only partially or is partially blocked | System flow low | Low flowrate; high pressure drop | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Return line cannot be isolated | None | Test prior to installation | A | c | III |
| V | 39 | Valve | Load Supply Isolation | Fails to open; opens only partially or is partially blocked | System flow low | Low flowrate; high pressure drop | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Supply line cannot be isolated | None | Test prior to installation | A | c | III |
| AV | 40 | Automatic Valve | Off Cycle Cooldown | Fails to open; opens only partially or is partially blocked | System does not cool or is slow to cool | Visually observe low vent rate and slow temperature drop | Test prior to installation | A | c | III |

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| | | | | Leaks or not properly closed | System looses high pressure LN2 to LN2 supply line | Inability to maintain system LN2 inventory and pressure | Test prior to installation | A | c | III |
| T | 41 | Temperature Sensor | Return Temperature | Fails low | Return stream of lower quality than indicated; insufficient phase separation and circulation pump cavitation | Circulation pump exit temperature and flowrate | Test prior to installation | A | c | III |
| | | | | Fails high | Return stream of higher quality than indicated; excessive phase separation could increase LN2 consumption | Circulation pump exit temperature | Test prior to installation | A | c | III |
| AV | 41 | Automatic Valve | Subcooler Fill | Fails to open; opens only partially or is partially blocked | Subcooler does not fill or is slow to fill | Subcooler level sensor | Test prior to installation; redundant subcooler | A | c | III |
| | | | | Leaks or not properly closed | Subcooler level may be high; LN2 enters vacuum manifold; vacuum manifold overpressures and/or vacuum pumps freeze | Subcooler level sensor high; vacuum manifold pressure increases | Test prior to installation; redundant subcooler | A | c | III |
| T | 42 | Temperature Sensor | Supply Temperature | Fails low | Supply stream of lower quality than indicated; insufficient cooling capacity | Return temperature high | Test prior to installation | A | c | III |
| | | | | Fails high | Supply stream of higher quality than indicated | Return temperature low | Test prior to installation | A | c | III |
| AV | 42 | Automatic Valve | Subcooler Fill | Fails to open; opens only partially or is partially blocked | Subcooler does not fill or is slow to fill | Subcooler level sensor | Test prior to installation; redundant subcooler | A | c | III |
| | | | | Leaks or not properly closed | Subcooler level may be high; LN2 enters vacuum manifold; vacuum manifold overpressures and/or vacuum pumps freeze | Subcooler level sensor high; vacuum manifold pressure increases | Test prior to installation; redundant subcooler | A | c | III |

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| T | 43 | Temperature Sensor | LN2 Supply/Cooldown Temperature | Fails low | LN2 supply stream of lower quality than indicated; insufficient cooling capacity; vapor lock loop pressure pump | Slower than expected system cooldown rate; inability to maintain system pressure | Test prior to installation | A | c | III |
| | | | | Fails high | Supply stream of higher quality than indicated | System behaves better than anticipated | Test prior to installation | A | c | III |
| AV | 43 | Automatic Valve | Isolation Valve Loop Pressure Pump | Fails to open; opens only partially or is partially blocked | System pressure cannot be maintained | Pump exit pressure low | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | System receives excessive LN2 and overpressures | Pump exit pressure high | Test prior to installation; redundant series valve; system pressure controlled by venting; system protected by relief valves | A | c | III |
| V | 44 | Valve | Heat Exchanger Isolation | Fails to open; opens only partially or is partially blocked | System flow low | Low flowrate; high pressure drop | Test prior to installation; redundant system; circuit has filter | A | c | III |
| | | | | Leaks or not properly closed | Heat exchancge circuit cannot be isolated | None | Test prior to installation; redundant valve | A | c | III |
| V | 45 | Valve | Heat Exchanger Isolation | Fails to open; opens only partially or is partially blocked | System flow low | Low flowrate; high pressure drop | Test prior to installation; redundant system; circuit has filter | A | c | III |
| | | | | Leaks or not properly closed | Heat exchancge circuit cannot be isolated | None | Test prior to installation; redundant valve | A | c | III |
| V | 46 | Valve | Heat Exchanger Isolation | Fails to open; opens only partially or is partially blocked | System flow low | Low flowrate; high pressure drop | Test prior to installation; redundant system; circuit has filter | A | c | III |
| | | | | Leaks or not properly closed | Heat exchancge circuit cannot be isolated | None | Test prior to installation; redundant valve | A | c | III |
| V | 47 | Valve | Heat Exchanger Isolation | Fails to open; opens only partially or is partially blocked | System flow low | Low flowrate; high pressure drop | Test prior to installation; redundant system; circuit has filter | A | c | III |

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| | | | | Leaks or not properly closed | Heat exchancge circuit cannot be isolated | None | Test prior to installation; redundant valve | A | c | III |
| V | 48 | Valve | Heat Exchanger Bypass | Fails to open; opens only partially or is partially blocked | Bypass flow low | Low flowrate; high pressure drop | Test prior to installation; circuit has filter | A | c | III |
| | | | | Leaks or not properly closed | Heat exchange circuit bypassed | Supply temperature high | Test prior to installation | A | c | III |
| D | 49 | Differential Press Trans | Subcooler Level | Fails low | Subcooler level may be high; LN2 enters vacuum manifold; vacuum manifold overpressures and/or vacuum pumps freeze | Vacuum manifold pressure increases | Test periodically; vacuum manifold protected by relief valve; redundant system | A | c | III |
| | | | | Fails high | Subcooler level may be low; system receives insufficient cooling | Supply temperature increases | Test periodically; redundant system | A | c | III |
| D | 50 | Differential Press Trans | Subcooler Level | Fails low | Subcooler level may be high; LN2 enters vacuum manifold; vacuum manifold overpressures and/or vacuum pumps freeze | Vacuum manifold pressure increases | Test periodically; vacuum manifold protected by relief valve; redundant system | A | c | III |
| | | | | Fails high | Subcooler level may be low; system receives insufficient cooling | Supply temperature increases | Test periodically; redundant system | A | c | III |
| V | 51 | Valve | Calorimeter Inlet | Fails to open; opens only partially or is partially blocked | Calorimeter flow low | Low flowrate; high pressure drop | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | System flow bypassed; system receives insufficient cooling | System temperatures high | Test prior to installation; redundant series valve | A | c | III |
| V | 52 | Valve | Calorimeter Outlet | Fails to open; opens only partially or is partially blocked | Calorimeter flow low | Low flowrate; high pressure drop | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | System flow bypassed; system receives insufficient cooling | System temperatures high | Test prior to installation; redundant series valve | A | c | III |
| V | 53 | Valve | Isolation Valve Loop Pressure Pump | Fails to open; opens only partially or is partially blocked | System pressure cannot be maintained | Pump exit pressure low | Test prior to installation; circuit has filter | A | c | III |

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| | | | | Leaks or not properly closed | System receives excessive LN2 and overpressures | Pump exit pressure high | Test prior to installation; redundant series valve; system pressure controlled by venting; system protected by relief valves | A | c | III |
| AV | 54 | Automatic Valve | Subcooler/Loop Cooldown | Fails to open; opens only partially or is partially blocked | Subcooler/Loop does not cool or is slow to cool | Slow temperature drop | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Subcooler/Loop looses high pressure LN2 to LN2 supply line | Inability to maintain system LN2 inventory and pressure | Test prior to installation | A | c | III |
| T | 55 | Temperature Sensor | Subcooler Loop Inlet Temperature | Fails low | Subcooler inlet stream of lower quality than indicated; insufficient stream subcooling | Supply temperature high | Test prior to installation | A | c | III |
| | | | | Fails high | Subcooler inlet stream of higher quality than indicated | Supply temperature low | Test prior to installation | A | c | III |
| P | 56 | Pressure Transducer | Loop pressure | Fails low | Loop pressure may be high; Loop overpressures | None | Test periodically; system pressure controlled by venting; system protected by relief valves; maximum pressure limited by pump characteristics | A | c | III |
| | | | | Fails high | Loop pressure may be low; coolant looses dielectric strength; decreased coolant quality leads to system temperature rise | Return temperature increases | Test periodically | A | c | III |
| FS | 57 | Flow Sensor | Loop Mass Flow | Fails low | Loop flow may be high; high flowrate may damage conductor | Loop temperature drop low | Test periodically; maximum flow limited by pump characteristics | A | c | III |

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| | | | | Fails high | Loop flow may be low; system receives insufficient cooling; system temperature rise | Return temperature increases | Test periodically | A | c | III |
| V | 58 | Valve | LN2 to Load Return | Fails to open; opens only partially or is partially blocked | Circulation pump cannot be recirculated; phase separator and pressurization pump circuits cannot be precooled | None | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Circulation pump is bypassed; insufficient loop flow | Loop flowrate low | Test prior to installation | A | c | III |
| V | 59 | Valve | Circulation Pump Isolation | Fails to open; opens only partially or is partially blocked | Insufficient loop circulation | Loop flowrate low | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Circulation pump cannot be fully isolated from loop | None | Test prior to installation | A | c | III |
| V | 60 | Valve | Circulation Pump Isolation | Fails to open; opens only partially or is partially blocked | Insufficient loop circulation | Loop flowrate low | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | Circulation pump cannot be fully isolated from loop | None | Test prior to installation | A | c | III |
| F | 61 | Filter | Circulation Pump Inlet Filter | Clogged | Increased pressure drop reduces flow through pump | Loop flowrate low | Tested prior to use; periodically inspected and cleaned | A | c | III |
| | | | | Open | Potential for particulates to block loop | Loop flowrate low | Tested prior to use; periodically inspected | A | c | III |
| V | 62 | Valve | Circulation Pump Evacuation/Purge | Fails to open; opens only partially or is partially blocked | Circulation Pump cannot be purged | Visual | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | System looses LN2 | Visual | Test prior to installation; may be capped | A | c | III |
| V | 63 | Valve | Purge/Evacuation | Fails to open; opens only partially or is partially blocked | LN2 feed line cannot be vented | Visual | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | System looses LN2 | Visual | Test prior to installation; may be capped | A | c | III |

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| R | 64 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Isolated volume may overpressure | None | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | LN2 feed pressure decrease; LN2 consumption increase | Visually observe venting | Tested prior to use and periodically tested | A | c | III |
| V | 65 | Valve | Purge/Evacuation | Fails to open; opens only partially or is partially blocked | Phase separator cannot be vented | Visual | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | System looses LN2 | Visual | Test prior to installation; may be capped | A | c | III |
| V | 66 | Valve | Purge/Evacuation | Fails to open; opens only partially or is partially blocked | Circulation pump cannot be vented | Visual | Test prior to installation; redundant valve | A | c | III |
| | | | | Leaks or not properly closed | System looses LN2 | Visual | Test prior to installation; may be capped | A | c | III |
| V | 67 | Valve | Purge/Evacuation | Fails to open; opens only partially or is partially blocked | Circulation pump cannot be vented | Visual | Test prior to installation; redundant valve | A | c | III |
| | | | | Leaks or not properly closed | System looses LN2 | Visual | Test prior to installation; may be capped | A | c | III |
| V | 68 | Valve | Purge/Evacuation | Fails to open; opens only partially or is partially blocked | Subcooler heat transfer loop cannot be vented | Visual | Test prior to installation; circuit protected by relief valve | A | c | III |
| | | | | Leaks or not properly closed | System looses LN2 | Visual | Test prior to installation; may be capped | A | c | III |
| R | 69 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Isolated volume may overpressure | None | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Loop flow and pressure decrease; insufficient cooling; reduced dielectric strength; LN2 consumption increase | Loop flow and pressure decreases; visually observe venting | Tested prior to use and periodically tested | A | c | III |
| R | 70 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Isolated volume may overpressure | System pressure high | Tested prior to use and periodically tested | A | c | III |

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| | | | | Leaks or does not properly close | Loop flow and pressure decrease; insufficient cooling; reduced dielectric strength; LN2 consumption increase | Loop flow and pressure decreases; visually observe venting | Tested prior to use and periodically tested | A | c | III |
| V | 71 | Valve | Purge/Evacuation | Fails to open; opens only partially or is partially blocked | Subcooler heat transfer loop cannot be vented | Visual | Test prior to installation; circuit protected by relief valve | A | c | III |
| | | | | Leaks or not properly closed | System looses LN2 | Visual | Test prior to installation; may be capped | A | c | III |
| V | 72 | Valve | Purge/Evacuation | Fails to open; opens only partially or is partially blocked | Pressurization Pump cannot be purged | Visual | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | System looses LN2; system pressure low; insufficient dielectric strength | System pressure low; visually observe venting | Test prior to installation; may be capped | A | c | III |
| V | 73 | Valve | Purge/Evacuation | Fails to open; opens only partially or is partially blocked | Pressurization Pump inlet cannot be purged | Visual | Test prior to installation | A | c | III |
| | | | | Leaks or not properly closed | System looses LN2; system pressure low; insufficient dielectric strength; pressurization pump may introduce air into system | System pressure low; visually observe venting; no detection for negative pressure | Test prior to installation; may be capped | A | c | III |
| R | 74 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Isolated volume may overpressure | None | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | System looses LN2; system pressure low; insufficient dielectric strength; pressurization pump may introduce air into system | System pressure low; visually observe venting; no detection for negative pressure | Tested prior to use and periodically tested | A | c | III |
| V | 75 | Valve | Purge/Evacuation | Fails to open; opens only partially or is partially blocked | Calorimeter cannot be vented | Visual | Test prior to installation | A | c | III |

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| | | | | Leaks or not properly closed | Calorimeter looses LN2; loop cooling capabilities underestimated | Visual | Test prior to installation; may be capped | A | c | III |
| R | 76 | Relief Valve | Isolated Volume Relief | Fails to open; opens only partially or is partially blocked | Calorimeter may overpressure | None | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Calorimeter looses LN2; loop cooling capabilities underestimated | Visual | Tested prior to use and periodically tested | A | c | III |
| P | 77 | Pressure Transducer | LN2 Tank Pressure | Fails low | Tank pressure may be high; Tank overpressures | None | Test periodically; pressure controlled by regulator; system protected by relief system | A | c | III |
| | | | | Fails high | Tank pressure may be low | None | Test periodically; pressure controlled by regulator | A | c | III |
| F | 77 | Filter | Pressurization Pump Inlet Filter | Clogged | Increased pressure drop reduces flow through pump | Loop pressure low | Tested prior to use; periodically inspected and cleaned | A | c | III |
| | | | | Open | Potential for particulates to block loop | Loop flowrate low | Tested prior to use; periodically inspected | A | c | III |
| D | 78 | Differential Press Trans | LN2 Dewar Level | Fails low | Tank level may be high; tank could be overfilled freeze and damage regulators and relief valves | Visually observe liquid venting during fill | Test periodically; delivery pressure limited; track tank inventory | A | c | III |
| | | | | Fails high | Tank level may be low; system may have insufficient LN2 supply | System pressure decreases; subcoolers cannot be filled | Test periodically; track tank inventory | A | c | III |
| D | 79 | Differential Press Trans | Flow Sensor Differential | Not shown | | | | | | |
| | | | | | | | | | | |
| CV | 79 | Check Valve | Prevents backflow to pressurization pump | Fails to open; opens only partially or is partially blocked | Loop pressure may fail to build or build slowly | Loop pressure | Tested prior to use and periodically tested | A | c | III |
| | | | | Leaks or does not properly close | Loop may depressurize when pump turned off | Loop pressure | Tested prior to use and periodically tested | A | c | III |
| H | 80 | Heater | Subcooler Regeneration/Calorimeter Heater | Not shown | | | | | | |

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| H | 81 | Heater | Subcooler Regeneration/Calorimeter Heater | Not shown | | | | | | |
| | | | | | | | | | | |
| H | 82 | Heater | Load Simulation Calorimeter Heater | Not shown | | | | | | |
| | | | | | | | | | | |
| H | 83 | Heater | Heater-Purge Gas Supply | Not shown | | | | | | |
| | | | | | | | | | | |
| T | 84 | Temperature Sensor | Cooldown Supply Temperature | Not shown | | | | | | |
| | | | | | | | | | | |
| V | 85 | Valve | Cooldown Temperature Moderation | Not shown | | | | | | |
| | | | | | | | | | | |
| R | 86 | Relief Valve | Subcooler Vessel Relief | Not shown | | | | | | |
| | | | | | | | | | | |
| R | 87 | Relief Valve | Subcooler Vessel Relief | Not shown | | | | | | |
| | | | | | | | | | | |
| R | 88 | Relief Valve | Vacuum Jacket Relief | Not shown | | | | | | |
| | | | | | | | | | | |
| VP | 1 | Vacuum Pump | Evacuate Subcoolers | Fails to run or provide adequate vacuum | Subcooler pressure high; insufficient cooling for system | Supply temperature high | Test pump prior to installation; redundant pumps | A | c | III |
| | | | | Anti-suckback valve fails | Vacuum pump oil enters vacuum manifold | None | Test pump prior to installation; close inlet valve prior to shutting pump off | A | c | III |
| VP | 2 | Vacuum Pump | Evacuate Subcoolers | Fails to run or provide adequate vacuum | Subcooler pressure high; insufficient cooling for system | Supply temperature high | Test pump prior to installation; redundant pumps | A | c | III |
| | | | | Anti-suckback valve fails | Vacuum pump oil enters vacuum manifold | None | Test pump prior to installation; close inlet valve prior to shutting pump off | A | c | III |
| VP | 3 | Vacuum Pump | Evacuate Subcoolers | Fails to run or provide adequate vacuum | Subcooler pressure high; insufficient cooling for system | Supply temperature high | Test pump prior to installation; redundant pumps | A | c | III |

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| | | | | Anti-suckback valve fails | Vacuum pump oil enters vacuum manifold | None | Test pump prior to installation; close inlet valve prior to shutting pump off | A | c | III |
| CP | 1 | Circulation Pump | Circulate LN2 in Loop | Fails to run or provide adequate flow | Loop flow low; insufficient cooling | Loop flow sensor | Test pump prior to installation | A | c | III |
| | | | | Excessive flow | Loop flow high; potential damage to conductor | Loop flow sensor | Test pump prior to installation | A | c | III |
| CP | 2 | Pressurization Pump | Pressurizes LN2 in Loop | Fails to run or provide adequate pressure | Loop pressure low; loss of dielectric strength | Loop pressure sensor | Test pump prior to installation | A | c | III |
| | | | | Pump develops excessive pressure | Loop overpressured | Loop pressure sensor | Test prior to installation; control pressure with valve; system pressure also controlled by venting; system protected by relief valves | A | c | III |
| | | Storage Tank | 10,000 LN2 Storage Tank | Ruptures | Large spill of LN2 to the environment | Tank pressure and level drop; visual | Tank constructed to ASME pressure vessel code; sited away form site boundary, heavily traveled areas and building air intakes; dikes around tank | C | b | III |
| | | | | Insulation fails | Excessive LN2 consumption; overpressure | Level trend; tank pressure; tank sweating | Initially vacuum leak checked; re-evacuated when necessary | A | c | III |
| | | | | Natural event | Large spill of LN2 to the environment | Tank pressure and level drop; visual | Tank constructed to ASME pressure vessel code; sited away form site boundary, heavily traveled areas and building air intakes; dikes around tank; tank anchored to ground and protected by barricades | C | b | III |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Heat Exchanger | Pressure Buildup | Ruptures | Loss of LN2 and tank pressure | Tank pressure and level drop; visual | Tested prior to installation; protected from damage | A | c | III |
| | | | | Plugs | Loss of tank pressure | Tank pressure and level drop; visual | Protected by filter | A | c | III |
| | | | | Freezes | Reduced heat transfer coefficient; loss of tank pressure | Tank pressure drops; visual | Designed for maximum LN2 consumption rate | A | c | III |
| | | Pressure Vessel | Phase Separator | Ruptures | Release of LN2 to guard vacuum | System pressure drops; guard vacuum spoiled | Tank constructed to ASME pressure vessel code; guard vacuum provides secondary containment | B | c | III |
| | | | | Plugs | Loop flowrate reduced | LN2 flowrate | Loop has filters | A | c | III |
| | | Pressure Vessel | Subcooler | Ruptures | Release of LN2 to guard vacuum | System pressure drops; guard vacuum spoiled | Tank constructed to ASME pressure vessel code; guard vacuum provides secondary containment | B | c | III |
| | | | | Plugs | Loop flowrate reduced | LN2 flowrate | Loop has filters | A | c | III |
| | | Pressure Vessel | Subcooler | Ruptures | Release of LN2 to guard vacuum | System pressure drops; guard vacuum spoiled | Tank constructed to ASME pressure vessel code; guard vacuum provides secondary containment | B | c | III |
| | | | | Plugs | Loop flowrate reduced | LN2 flowrate | Loop has filters | A | c | III |
| | | Pressure Vessel | LN2 Accumulator | Ruptures | Release of LN2 to guard vacuum | System pressure drops; guard vacuum spoiled | Tank constructed to ASME pressure vessel code; guard vacuum provides secondary containment | B | c | III |
| | | | | Plugs | Loop flowrate reduced | LN2 flowrate | Loop has filters | A | c | III |
| | | Pressure Vessel | Calorimeter | Ruptures | Release of LN2 to guard vacuum | System pressure drops; guard vacuum spoiled | Tank constructed to ASME pressure vessel code; guard vacuum provides secondary containment | B | c | III |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Plugs | Loop flowrate reduced | LN2 flowrate | Loop has filters | A | c | III |
| | | Pressure Vessel | Guard Vacuum | Ruptures | Guard vacuum spoiled; system warms | System temperature and pressure; potential for overpressure | Tank constructed to ASME pressure vessel code; protected from damage by barricades | B | c | III |
| | | Process control | Automatic Process Control | Fails | System uncontrolled | Visual | System protected by relief valves | A | c | III |
| | | Electrical Power | Operates Entire System | Fails | System stops | Visual | System protected by relief valves | A | c | III |
| | | | | | | | | | | |

# Appendix C: Superconductivity for Electric Systems 2004 Peer Review Agenda

# 2004 Annual Superconductivity Peer Review Agenda

***July 27-29, 2004***
***Loews L'Enfant Plaza Hotel, Washington, DC***

# Agenda

### TUESDAY, JULY 27th – DAY ONE

8:00 - 9:00 am **Registration/Continental Breakfast**

8:15 – 9:00 am **Reviewers' Breakfast (Caucus Room)**

9:00 - 9:10 am **Welcome - Program Overview and Purpose of Peer Review**
*James Daley, U.S. DOE Superconductivity for Electric Systems*

9:10 - 9:20 am **Opening Remarks**
*Jimmy Glotfelty, Director, U.S. DOE Office of Electric Transmission and Distribution*

9:20 – 10:10 am **Superconductivity Partnership with Industry Project Updates -** (approx. 10 minutes each)
*Chair: Paul Bakke, U.S. DOE Golden Field Office*

Design and Development of a 100 MVA HTS Generator for Commercial Entry (GE) ..................... *J. Fogarty*
Waukesha 5/10 MVA Transformer.................................................................................................. *E. Pleva*
Columbus Cable (AEP)................................................................................................................... *D. Lindsay*
Albany Cable (Niagara Mohawk) .................................................................................................... *C. Weber*
Long Island Cable (LIPA)................................................................................................................ *J. Maguire*

10:15 am **Break**

10:45 – 11:45 am **International R&D Activities Panel**
*Chair: Guy Deutscher, IEA Executive Committee*
*Panelists: Japan, Korea, Germany (Europe), China*

11:45 am – 1:00 pm Luncheon

1:00 pm **Commence Annual Peer Review**
*(Note: Numbers in parentheses indicate presentation + question/answer time)*

## TUESDAY, JULY 27th – DAY ONE *(continued)*

| 2nd GENERATION WIRE SESSION | UNIVERSITY RESEARCH SESSION | SUPERCONDUCTIVITY PARTNERSHIP WITH INDUSTRY (SPI) SESSION |
|---|---|---|
| 1:00 – 2:20 pm<br>**Scale-Up of Coated Conductor Technology at SuperPower** (60+20)<br>*V. Selvamanickam, J. Reeves (SuperPower), and D.E. Peterson (LANL)* | 1:00 – 1:45 pm<br>**Microstructure and Mechanics of Superconductor Epitaxy via the Chemical Solution Deposition Method** (30+15)<br>*F.F. Lange (University of California, Santa Barbara)* | 1:00 – 2:00 pm<br>**SPI Readiness Reviews** (40+20)<br>*M.J. Gouge (ORNL), S. Ashworth (LANL), P. Bakke (DOE-GO)* |
| 2:20 – 3:20 pm<br>**Electromechanical Studies for Superconductor Development** (45+15)<br>*Jack Ekin and Najib Cheggour (NIST-CO)* | 1:45 – 2:30 pm<br>**Enhancing YBCO Performance Through Fundamental Process Evaluation and Characterization** (30+15)<br>*Manisha Rane and Kathleen Dunn (SUNY-Albany)* | 2:00 – 3:10<br>**Waukesha 5/10 MVA HTS Transformer Cooperative Research** (50+20)<br>*S.W. Schwenterly (ORNL), E.F. Pleva (WES), D.W. Hazelton (SP)* |
| | 2:30 – 3:15 pm<br>**Epitaxial Electrodeposition of Metal and Metal Oxide Capping Layers for RABiTS-Based Second Generation Coated Conductors** (30+15)<br>*Jay A. Switzer (University of Missouri-Rolla)* | |
| 3:20 pm **Break** | 3:15 pm **Break** | 3:10 pm<br>**Break** |
| 3:40 – 5:00 pm<br>**Scale-Up of Coated Conductor (2G) Technology at American Superconductor** (60+20)<br>*A. Malozemoff, M. Rupich, and U. Schoop (AMSC)* | 3:40 – 4:25 pm<br>**Systematic Decrease of $J_c$ Decrease in Thick Film Coated Conductors Based on Microelectrical and Micromechanical Properties**<br>*A. Ignatiev (University of Houston)* | 3:30 – 4:00 pm<br>**Development of Ultra-Efficient HTS Motor Systems** (20+10)<br>*Rich Schiferl* **(***Rockwell)* |
| | 4:25 – 5:10 pm<br>**Conversion of Oxy-Fluoride Based Coated Conductors** (30+15)<br>*M.J. Cima, Masaki Suenaga (MIT, BNL)* | 4:00 – 5:00 pm<br>**Open Geometry HTS MRI System** (45+15)<br>*K. Marken, G. Gilgrass (OMT) and T. Holesinger (LANL)* |
| 5:00 pm **2nd Generation Wire Session Adjourn for Day** | 5:10 pm<br>**University Research Session Adjourn for the Day** | 5:00 pm<br>**SPI Session**<br>**Adjourn for the Day** |
| 5:40 pm<br>**Reception – Poster Session** | | |
| 7:00 pm **Optional Group Activity (Pre-paid Dinner Cruise - Meet in Hotel Lobby by 6:45 pm)**<br>**Or, if not participating in Group Activity, Dinner is on your own** | | |

## WEDNESDAY, JULY 28th – DAY TWO

7:30 – 8:30am **Continental Breakfast**

**8:30 am** **Reconvene Annual Peer Review**

*(Note: Numbers in parentheses indicate presentation + question/answer time)*

| 2nd GENERATION WIRE SESSION | UNIVERSITY RESEARCH SESSION | SUPERCONDUCTIVITY PARTNERSHIP WITH INDUSTRY (SPI) SESSION |
|---|---|---|
| 8:30 – 9:50 am<br>**Development of Coated Conductors by Inclined Substrate Deposition** (60+20)<br>*Balu Balachandran, Beihai Ma, and Dean J. Miller (ANL)* | 8:30 9:15 am<br>**Buffer Layer Growth and the Thickness Dependence of $J_c$ in Coated Conductors** (30+15)<br>*Chang-Beom Eom, Alex Gurevich, David Larbalestier (UW)* | 8:30 – 9:45 am<br>**GE 100 MVA HTS Generator Cooperative Research** (55+20)<br>*J. Fogarty (GE), R. Duckworth (ORNL), J. Waynert (LANL)* |
| 9:50 – 10:30 am<br>**Applied R&D of 1st and 2nd Generation HTS Conductors** (30+10)<br>*M.J. Gouge (ORNL)* | 9:15 – 10:00 am<br>**Stanford In-Situ High Rate YBCO Process: Transfer to Metal Tapes and Process Scale Up** (30+15)<br>*H.-Y. Zhai, J.-U. Huh (Stanford), J. Storer (LANL)* | 9:45 – 10:30 am<br>**Development Status of Flywheel Electricity System** (35+10)<br>*Mike Strasik (Boeing)* |
| 10:30 am **Break** | 10:00 am<br>**University Research Session**<br><br>**Adjourned** | 10:30 am **Break** |
| 10:45 – 12:00 pm<br>**RABiTS Template Research and Development** (60+15)<br>*A. Goyal, F.A. List, and M. Paranthaman (ORNL)* | **STRATEGIC RESEARCH SESSION** | 10:50 – 12:00 pm<br>**Southwire – ORNL HTS Power Cable Cooperative Research** (50+20)<br>*David Lindsay (Southwire Co.), Jonathan Demko (ORNL)* |
| | 10:40 – 12:00 pm<br>**Strategic Research on IBAD-MgO Based Coated Conductors** (60+20)<br>*Paul Arendt, Steve Foltyn* (LANL) | |
| 12:00 pm **Luncheon** | 12:00 pm **Luncheon** | 12:00 pm **Luncheon** |

## WEDNESDAY, JULY 28th – DAY TWO *(continued)*

| 2nd GENERATION WIRE SESSION | STRATEGIC RESEARCH SESSION | SUPERCONDUCTIVITY PARTNERSHIP WITH INDUSTRY (SPI) SESSION |
|---|---|---|
| 1:00 – 2:00 pm<br>**Non-Vacuum Techniques for HTS Coated Conductors** (45+15)<br>*Raghu Bhattacharya (NREL)* | 1:00 – 2:20 pm<br>**Wire Development Group** (60+20)<br>*Alex Malozemoff (AMSC), Eric Hellstrom (UW) Leonardo Civale (LANL) and David Larbalestier (UW)* | 1:00 – 1:45 pm<br>**Magnetic Separator SPI Project** (30+15)<br>*Joe Waynert (LANL), Jon Bernard (DuPont/LANL)* |
| 2:00 – 3:15 pm<br>**Ex-Situ Processing of YBCO for Coated Conductors** (60+15)<br>*H.M. Christen, D.F. Lee, and F.A. List (ORNL)* | 2:20 – 3:00 pm<br>**AC Loss Studies in Coated Conductors** (30+10)<br>*Steve Ashworth (LANL)* | 1:45 – 2:45 pm<br>**SuperPower HTS Matrix Fault Current Limiter** (45+15)<br>*L. Kovalsky (SuperPower), J. Bock (Nexans), S.W. Schwenterly (ORNL)* |
| 3:15 pm<br>**Break** | 3:00 pm **Break** | 2:45 pm<br>**SPI Session Adjourn for Day**<br><br>*Reviewer Work Room is Available* |
| 3:45 – 5:05 pm<br>**Coordinated Characterization of Coated Conductors** (60+20)<br>*Kenneth E. Gray, Dean J. Miller, and Victor A. Maroni (ANL)* | 3:30 – 5:00 pm<br>**ORNL-American Superconductor Strategic Research** (60+30)<br>*A. Goyal, M. Paranthaman (ORNL), and U. Schoop (AMSC)* | |
| | 5:00 – 6:00 pm<br>**Phase Relations of High $T_c$ Superconductors** (45+15)<br>*W. Wong-Ng and L.P. Cook (NIST-MD)* | |
| 5:05 pm<br>**2nd Generation Wire Session Adjourn for Day** | 6:00 pm<br>**Strategic Research Session Adjourn for Day** | |
| 5:45 pm **Posters are Available for Viewing** | | |

## THURSDAY, JULY 29th – DAY THREE

7:30 – 8:30 am **Continental Breakfast**

**8:30 am** **Reconvene Annual Peer Review**
*(Note: Numbers in parentheses indicate presentation + question/answer time)*

| 2nd GENERATION WIRE SESSION | STRATEGIC RESEARCH SESSION |
|---|---|
| 8:30 – 10:00 am<br>**Los Alamos Coated Conductor Development** (60+30)<br>*Vladimir Matias, Brady Gibbons, Leonardo Civale (LANL)* | 8:30 – 10:00 am<br>**RABiTS-Based Strategic Research** (60+30)<br>*A. Goyal, S. Sathyamurthy, and T. Aytug (ORNL)* |
| 10:00 am **Break** | 10:00 am **Break** |
| 10:20 – 11:20 am<br>**Solution-Based Deposition of YBCO Coated Conductors** (40+20)<br>*P. Clem, J. Voigt (SNL)* | 10:20 – 11:40 am<br>**Understanding and Improving Pinning in Coated Conductors** (60+20)<br>*Leonardo Civale, Judith Driscoll (LANL)* |
| 11:20 am<br>**2nd Generation Wire Session Adjourned** | |
| 11:40 am **Luncheon** | 11:40 am **Luncheon** |
| | 12:45 – 2:00 pm<br>**Development of Ex Situ Processed, High $I_c$ Coated Conductors** (60+15)<br>*T. Holesinger (LANL), M. Feldmann (UW), and R. Feenstra (ORNL)* |
| | 2:00 – 3:00 pm<br>**Nucleation and Growth of YBCO by the $BaF_2$ Process and AC Losses of YBCO Films** (45+15)<br>*M. Suenaga and D.O. Welch (BNL)* |
| | 3:00 pm **Strategic Research Session Adjourned** |

# Appendix D:
# Summaries of Research Projects
# High Temperature Superconductivity
# for Electric Systems

# $2^{nd}$ GENERATION WIRE SESSION

Reviewers for Second Generation Wire Panel:

Guy Deutscher, Tel Aviv University
Herb Freyhardt, University of Gottingen
Les Fritzemeier, Consultant
Timothy Haugan, Air Force Research Laboratory
Alan Lauder, Consultant
Heinz-Werner Neumueller, Siemens
Chan Park, KERI
Kamel Salama, University of Houston
Harold Weinstock, AFOSR

Review Projects for Second Generation Wire Panel:

Scale Up of Coated Conductor Technology at SuperPower
Electromechanical Studies for Superconductor Development
Scale-Up of Coated Conductor (2G) Technology at AMSC
Development of Coated Conductors by Inclined Substrate Deposition
Applied R&D of 1st and 2nd Generation HTS Conductors
RABiTS Substrates Research and Development
Non-Vacuum Techniques for HTS Coated Conductors
Ex-Situ Processing of YBCO Precursors
Coordinated Characterization of Coated Conductors
Los Alamos Coated Conductor Development
All Solution Deposited YBCO Coated Conductors

| | |
|---|---|
| **Project Title:** | **Scale Up of Coated Conductor Technology at SuperPower** |
| **Organization(s):** | **SuperPower** |
| **Presenters:** | V. Selvamanickam, J. Reeves (SuperPower), and D.E. Peterson (LANL) |
| **FY 2004 Funding:** | FY 2004 Funding: $0 to date; FY 2003 Carryover: $434 K |

**Project Purpose and FY 2004 Objectives:** The main purpose of this program is to scale up coated conductor technology to pilot-scale manufacturing. The emphasis of this program is to develop R&D solutions for scale up issues in pilot-scale operations to lay the foundation for a framework for large-scale manufacturing of coated conductors. As outlined in our FY'03 Peer Review presentation, the objectives for FY'04 were :

1) Modify existing Pilot facilities and add new Pilot facilities for IBAD, Buffer, HTS deposition, and Stabilizer to produce 100 m lengths.
2) Demonstrate at least 50 A over 100 m.
3) Demonstrate linear speed greater than 10 m/h in every processing step to produce 100 A conductor.
4) Modify and add QC tools for rapid reel-to-reel measurements over 100 m lengths.
5) Transition IBAD MgO technology from LANL.
6) Scale up a high rate IBAD process to produce 100 A conductor in at least meter lengths in Pilot facilities.
7) Continue to build on progress with performance of conductor in high magnetic fields, mechanical strain, and electrical stabilization.
8) Develop slitting technology to produce 1 - 10 m long conductors in 4 mm width with at least 100 A/cm performance.
9) Provide several 10 m single piece lengths of 4 mm wide conductor to our SPI partner, Sumitomo Electric Industries (SEI) for construction of prototype second-gen cable.

**FY 2004 Performance and FY 2005 Plans:** Significant progress was made in all of the FY 2003 objectives. (1) Substantial modifications were made to existing pilot-scale facilities as well as new pilot-scale facilities were installed with capabilities to produce 100+ m lengths 2) We focused on achieving 100 A performance in 50 m lengths. In March 2004, we reported world-record performance of 6000 A-m in 57 m long tape. 3) We demonstrated 100 A performance at a linear tape speed of 10 m/h in the MOCVD process. Existing equipment and new equipment have been added to achieve linear tape speeds of 10 m/h in other steps. 4) We have established automated reel-to-reel Ic measurements in two systems, one with 0.1 m – 1 m measurement intervals and another with 0.01 m measurement intervals. A Normarski microscope system with reel-to-reel tape handling capability has been established for qualification of substrates for IBAD MgO. An on-line thickness measurement system has been added to our Pilot IBAD facility. 5) A dedicated prototype IBAD facility has been established for transitioning IBAD MgO technology from LANL. IBAD MgO deposited tapes are being produced in this facility with a good degree of in-plane texture, enabled by strong support from LANL. 6) The IBAD MgO process is being scaled up to long lengths in the prototype IBAD facility and prototype buffer facility. 7) The performance of our tapes in a magnetic field has been improved over a wide range of field orientations using rare-earth substitution. A new conductor structure has been developed to achieve better electrical stabilization. Mechanical properties of this new structure have been examined. 8) Slitting processes have been developed to produce 1 – 10 m long conductors in 4 mm width with performance exceeding 100 A/cm-width 9) A total of 60 m of 4 mm wide, copper-stabilized conductor is being provided to SEI for the Albany Cable project.

In FY 2005, SuperPower will continue the scale up program to produce 100 m lengths of coated conductor with high tape throughput in all steps. High rate processes in IBAD and buffer deposition will be scaled up to 100 m lengths. All post-HTS processing steps such as silver sputtering, copper electroplating, and slitting will be scaled up to 100 m lengths. Fully-processed conductors in long lengths would be provided to our SPI partner SEI for the Albany Cable Project and other customers. Mechanical, in-field, and ac loss performance of our tapes will be further improved. Additional QA/QC tools will be added, particularly for on-line tape inspection during processing.

**FY 2004 Results:** Key results from the FY 2004 program are summarized below.

1) Coated conductor tapes have been produced in lengths of up to 57 m. Critical currents exceeding 100 A have been achieved over 57 m length, corresponding to a world record of 6000 A-m. A second reel-to-reel critical current measurement system has been added for critical current profiling in 0.01 m steps over 50+ m long tapes. The critical current profiles of long tapes have been studied in detail and have been correlated to texture, room-temperature resistivity, composition, secondary phases, and microstructure. This detailed study has enabled us to determine the problems causing local degradation in Ic. Once these problems were identified, appropriate in-situ process monitors have been added to the process equipment to monitor and improve the stability of the process in fabrication of 50+ m tapes.

   A production-scale electropolishing system is routinely used to produce 200+ m long tapes with a high-degree of surface finish. Our Pilot IBAD facility has been retrofitted with longer ion sources and a new helix tape handling system which has enabled a 3x increase in tape throughput. A large deposition area that is 0.6 m in length and 7 cm in width has been achieved with this helix tape handling system. The IBAD process was optimized to achieve uniform texture over this entire large deposition area. This has enabled us to produce 100 m long IBAD tapes with uniformly good texture over the entire length. Rapid in-plane texture measurements have been obtained on all 100 m long IBAD tapes using a unique texture measurement tool. A new Pilot MOCVD facility was recently brought into operation. New QC tools have been added for on-line thickness measurements in Pilot IBAD facility, for on-line 100% tape inspection in the substrate electropolishing facility, and for reel-to-reel Normaski microscopy.

2) We demonstrated high deposition rates with MOCVD, up to 120 Angstroms/s and still achieved critical currents of 230 A/cm. Using such high deposition rates, we demonstrated a linear tape speed of 10 m/h and still demonstrated 100 A/cm performance. A new prototype IBAD facility equipped with a helix tape handling system and RHEED has been brought on line for scale up of IBAD MgO. This facility contains a helix tape handling system with a deposition zone of 20 cm in length and 7 cm in width. The RHEED system has been equipped for texture measurements on all the 6 tape tracks in the deposition zone. Tape speeds in excess of 10 m/h are possible with the helix tape handling system. Good in-plane textures have been achieved in IBAD MgO processed in the prototype facility. Buffer layers and HTS layers have been deposited on the IBAD MgO tapes. We have scaled up the electroplating process for copper stabilizer application to 50+ m lengths. Long tapes have been plated with copper stabilizer with no degradation in critical current. A slitter has been installed for slitting tapes to narrow widths. Long tapes have been slit to 4 mm widths with performance exceeding 100 A/cm. Tape speeds exceeding 10 m/h have been demonstrated in all post-HTS processing steps while maintaining Ic > 100 A/cm.

3) The magnetic field dependence of Ic has been further improved in our tapes in a wide range of field orientations using rare-earth substitution. The drop in Ic from zero field to 1 T is less than a factor of 5 both in the orientation of field perpendicular to tape as well as at 45 degrees to the tape. AC loss characteristics of our tapes have been improved by modification of the conductor structure. Sixty meters of 4 mm wide, copper stabilized tapes are being provided to SEI, our partner in the Albany Cable Project. The mechanical, physical, and electrical properties of these tapes have been inspected in detail.

**Research Integration:** SuperPower worked very closely with LANL and ANL during the course of this program. We are in the midst of a 2-year CRADA with LANL and research integration has occurred in numerous areas. Progress with IBAD MgO has been accelerated by buffer deposition of SuperPower's IBAD tapes at LANL followed by texture measurements. Problems with electropolishing stability over long time periods were solved by collaborative work with LANL. Substantial collaboration with LANL occurred in tape characterization including ac loss measurements, critical current measurements in magnetic field, reel-to-reel critical current measurements, and magnetic imaging to examine non uniformity in critical current across tape width. We worked closely with ANL on Raman Spectroscopy and Transmission Electron Microscopy studies on our MOCVD tapes, which have proved valuable in our process optimization for long lengths. Several visits have been made by SuperPower employees to LANL and ANL and vice versa. SuperPower employees closely interacted with the lab scientists by frequent e-mail and phone communication. In addition to LANL and ANL, we worked with BNL for ac loss measurements as well as film composition measurements and with ORNL on buffer development. We also collaborated with the Air Force Research Laboratory and Air Force Institute of Technology for on-line plume monitoring in our PLD facility as well as on-line vapor composition monitoring in our MOCVD facility. We also enjoyed a close collaboration on advanced characterization of our coated conductors with NIST, U. Albany, U. Kansas, MIT, and U. Wisconsin.

The program has been reviewed in this FY on site at SuperPower by DOE and DOD lab representatives.

| | |
|---|---|
| **Project Title:** | **Electromechanical Studies for Superconductor Development** |
| **Organization(s):** | **National Institute of Standards and Technology, Boulder, CO** |
| **Presenters:** | Jack Ekin and Najib Cheggour |
| **FY 2004 Funding:** | $195 K |

**Project Purpose and FY 2004 Objectives:** This project provides the electromechanical research needed to develop YBCO and BSCCO superconductors for high-field magnet and electric power applications. Stress and strain management is one of the key feedback parameters needed to move the second generation conductors to the market place. The project utilizes the expertise and unique electromechanical measurement facilities at NIST to provide performance feedback to companies and organizations developing the conductors (AMSC, SuperPower, ORNL, LANL, ANL), as well as to provide engineering design data to the SPI partners. We have achieved significant progress in our primary objectives for FY 2004:

1) **Cu stabilization:** Measure the effect of axial strain ($\varepsilon$) on critical-current density ($J_c$), at 76 K and self field, in YBCO (both RABiTS and IBAD) coated-conductors that incorporate a stabilizing Cu layer either by lamination or Cu-plating, and compare to samples without Cu stabilizer.
2) **Magnetic-field effect:** Measure the magnetic field dependence of the reversible strain effect (which we discovered last year) at 76 K and fields up to 16.5 T, to investigate any correlation of this effect to strain-induced variations of the fundamental superconducting parameters $T_c$ and $B_{c2}$.
3) **Liquid-helium measurements:** Investigate the effect of axial strain on $J_c$ in YBCO RABiTS at 4K as a function of magnetic field up to 16.5 T.
4) **Substrates:** Measure stress-strain characteristics of bare and fully coated substrates, as well as new conductor geometries.
5) **YBCO thickness:** Start preliminary tests of the effect of film thickness on the axial strain effect.

**FY 2004 Performance:** Key results from the FY 2004 program are summarized below.

1,5) Measurements of $J_c(\varepsilon)$ were made at 76 K and self-field in a series of YBCO on Ni-W RABiTS and IBAD Hastalloy conductors with and without Cu stabilizer. These data were obtained with our stress-free-cooling strain apparatus. In both IBAD and RABiTS samples that incorporate a stabilizing Cu layer (either by Cu-plating or lamination), the results show that the Cu stabilizer significantly increases the irreversible strain ($\varepsilon_{irr}$) from ~ 0.38-0.4 % to 0.52-0.6 %, probably by providing an additional pre-compression of the YBCO layer during sample cooling from room temperature to 76 K. Therefore, the impact of Cu, besides providing a good electric and thermal stability to the conductor, is also to markedly widen the strain window for applications of these composites. Furthermore, some Cu-laminated YBCO/Ni-W samples also showed a small (2%) increase of $J_c$ as a function of strain, which peaks at $\varepsilon \approx 0.3$ %. Compared to last-year's results, $\varepsilon_{irr}$ also maintained high values in the new higher-$J_c$ YBCO coated conductors. Preliminary tests of $J_c(\varepsilon)$ at 76 K and self-field on thick ($\geq 2$ μm) YBCO coated conductor RABiTS are underway.

2) The first detailed $J_c$ measurements in YBCO coated conductors as a function of strain and magnetic field were made at 76 K. Data, obtained for YBCO on Ni-5at.%W RABiTS, show the dependence of the newly discovered reversible strain effect on magnetic field, both at low (50 mT) and high (up to 16.5 T) field intensities. Among preliminary conclusions is that the $J_c$ sensitivity to strain is increased with magnetic field above 3 T, and that, unexpectedly, this strain sensitivity is reduced in low magnetic field up to ~ 3T. These results will impact high-field applications such as industrial magnets, motors, and magnetic separators, as well as low-field applications such as power transmission lines, MRIs and transformers. The degradation of $J_c$ at the irreversible strain ($\varepsilon_{irr}$) dramatically increases from ~ 2 % at self-field to ~ 30 % at 16.5 T. The pinning force density $F_p = J_c \times B$ is studied as a function of magnetic field and applied strain.

This opens a whole new area of study of strain effects in high-$T_c$ superconductors in general and YBCO in particular. These materials were, for nearly two decades, thought to have no intrinsic strain effect on their transport properties at practical fields and temperatures (unlike their low-$T_c$ superconductor counterparts). These findings provide insight into the origin of the reversible-strain effect in YBCO coated conductors and into the influence of strain both on the weak- and strong-link conduction regimes. A weak-link strain model is being developed to interpret these $J_c(B,\varepsilon)$ results that should also be useful in application design.

3) Measurements of $J_c(\varepsilon)$ were carried out in Cu-laminated YBCO/Ni-W RABiTS coated conductors at 4 K and magnetic field up to 16.5 T. In comparison to the samples of last year, $J_c$ at 4 K and 16.5 T improved by 60 %. Furthermore, the irreversible strain effect was also found at 4 K, both in earlier RABiTS samples (~ 3.5 MA/cm$^2$ at 16.5 T) and new RABiTS samples (~ 6 MA/cm$^2$ at 16.5 T). The irreversible strain $\varepsilon_{irr}$ at 4 K and 16.5 T has similar values compared with those measured at 76 K and self-field. These results will impact high-field magnet applications.

4) Measurements of stress-strain characteristics on bare and YBCO coated Hastalloy C-276 substrates as well as on copper-plated conductors were obtained at 76 K. These sample were supplied by SuperPower. The modulus of elasticity, yield strength, and proportional limit of elasticity were determined for these conductors and added to our database on substrate mechanical properties for feedback to the wire manufacturers. The results confirm that the mechanical properties of fully coated conductors are dominated by those of the substrate.

**FY 2005 Plans:** Determined in consultation with the manufacturers and a number of research collaborators within the DoE/OETD community. Direct feedback is given to the wire manufacturer within each project and then disseminated to the general wire-development and SPI community:

- Continue the extensive study of the effects of *magnetic field* strength on $J_c(B,\varepsilon)$ at 76 K in YBCO coated conductors. Provide data feedback and engineering design equations to AMSC, SuperPower, ORNL, and LANL on the performance of their conductors for use in applications at low and moderate magnetic-field intensities: power-transmission lines, rotating machinery, industrial magnets, and transformer applications.
- Acquire the first data on the effect of axial strain on the $J_c$ of YBCO coated conductors as a *function of temperature* for applications in pumped liquid nitrogen. This will be conducted on new coated conductor geometries in collaboration with AMSC, SuperPower, ORNL, and LANL.
- Study the effect of YBCO *film thickness* on the strain response of YBCO coatings, as samples become available. This will be carried out in collaboration with ORNL, AMSC, and SuperPower.
- Add to the growing stress-strain *database* of new substrate-materials/conductor-geometries being developed by the manufacturers and DoE research laboratories.
- Design and construct a new apparatus for measuring the effects of strain on $J_c$ as a function of magnetic-field/sample *angle*. Out-of-plane field orientations will probably play the limiting role for strain effects in most rotating machinery and magnet applications. The apparatus will be commissioned next year to enable measurements to commence as soon as possible in the following year.

**Research Integration:** NIST collaborates closely with researchers and managers at AMSC and SuperPower, ORNL, LANL, and ANL to implement a research program that utilizes NIST's specialized electromechanical test facilities and expertise. The resulting data provide feedback to the wire manufacturers, national labs, and SPI application developers, where they are integrated into conductor development and system design processes. Several collaborative papers with these organizations have been published or are being written.

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| **Project Title:** | **Scale-Up of Coated Conductor (2G) Technology at AMSC** |
| **Organization(s):** | **American Superconductor Corporation** |
| **Presenters:** | A. Malozemoff, M. Rupich, and U. Schoop |
| **FY 2004 Funding:** | $1,000,000 |

**Project Purpose and FY 2004 Objectives:** The purpose of this project is to develop a low-cost and robust manufacturing process for Coated Conductor (2G) composite wire. Key elements of this project include: (a) establish a fundamental understanding for the substrate, buffer and HTS layer properties and processing, (b) improve $I_c$, (c) achieve uniform performance over 10 meter lengths (determine process windows for each process step and eliminate process defects), and (d) confirm low-cost processes to justify Pilot scale-up.

The FY 2004 Objectives were focused toward three critical areas:

1) Demonstrate $I_c$ progress (>250A/cm-w)
2) Confirm process uniformity over length (10 meter process lengths)
3) Demonstrate process capability for high risk Pilot-scale equipment concepts.

Comments from the 2003 Peer Reviewer team suggested that AMSC should consider revising the demonstration objectives to include increasing performance and wire length, and to address potential long length-related problems early.

**FY 2004 Performance and Results, and FY 2005 Plans:** Significant progress has been made against all key elements of the project and the FY 2004 Objectives. The AMSC 2G efforts over the past year have been directed toward four major areas of research and development:

1) **Baseline Manufacture** – AMSC maintains a documented baseline 2G wire manufacturing process; this is the standard to which we compare all new process improvements. Over time, new processes are inserted into the baseline process, improving the overall $I_c$, uniformity, reliability and cost-performance of the 2G wire. Process changes are only incorporated when they equals or exceeds the performance of the baseline practice. During February 2004, AMSC conducted a process capability study, manufacturing four consecutive baseline wires (1 cm wide, 10 meters long, neutral axis wire configuration). All four of these wires exceeded 250 A/cm-w and 3.4 $MA/cm^2$ in the HTS (77K, sf) and showed excellent uniformity (1 standard deviation <4% for all wires) and reproducibility. This compares to a previous capability study performed in May 2003, averaging 168 A/cm-w for 45 meters of wire (1.5 m x 30 wires), this demonstration was presented at the 2003 Peer Review. **High $I_c$ and uniformity achieved**
2) **New Technology Process Insertions –** Innovation, detailed understanding of fundamental and applied aspects of each 2G layer, and thorough failure analysis have all contributed to improvement in wire performance, establishing broad processing windows and reducing the cost AMSC's 2G process. The significant increase in $I_c$ observed in the February 2004 baseline capability study was directly related to improvements in substrate (0.5° FWHM reduction), buffer (improved diffusion characteristics), and HTS (optimized HTS nucleation and growth). Additional process insertions include buffer thickness reduction (barrier layer reduced >50%), reactive sputtering buffer deposition (up to 10x increase in deposition rate), and HTS nano-dots (increasing the in-field Ic performance). **Continuous process improvement is on-going.**
3) **R&D Equipment Conversion to 4 cm wide and 100 meters long** – AMSC intended to upgrade the existing (slow) R&D equipment for 4 cm wide x 10-20 meter long operation. Based on the comments from the 2003 Peer Reviewers, AMSC modified this plan to increase the capability of this R&D equipment to 4 cm wide x 100 meter long operation. The increase in length did not

materially change the 4 cm wide deposition or reaction processes, however significant additional work has been required to accommodate the physical size of spools, weight of 100 meter tapes, and adjustments to the build-up of tape on the take-up spools . Conversion of all R&D equipment to the 4 cm x 100 meter standard is still underway. Uniform (across width and length) 4 cm processing has been confirmed for substrate, buffer seed, buffer barrier, and lamination steps. **Pre-Pilot R&D equipment is being modified for 4 cm wide x 100 meter long 2G wire manufacture.**

4) **High Risk Pilot-scale Equipment Demonstration** – The basic AMSC RABiTS/MOD HTS process can be divided into five generic types of Pilot equipment: rolling mill, PVD deposition tools, linear heat treatment ovens, lamination, and slitting. Of these, the PVD tools and linear heat treatment ovens are significantly unique to 2G processing. AMSC's plan is to demonstrate the Pilot-scale tooling concepts for these unique pieces of equipment prior to purchasing the additional PVD tools and heat treatment ovens needed to construct the 2G Pilot manufacturing facility. AMSC is now commissioning the Pilot-scale PVD tool at our Devens, MA facility. Tape handling, deposition rates, and uniformity have been confirmed. The Pilot reaction heat treatment concept has been confirmed and was utilized to fabricate the baseline 250+A/cm-width wires discussed above. A larger and more capable linear reaction oven is now in the final stages of fabrication and will be used to test material handling and atmospheric control for all Pilot-scale oven types. **Risk mitigation strategy is confirming AMSC Pilot scale-up planning and cost models.**

FY 2005 plans focus on establishing a reliable pre-pilot production capacity of over 10,000 m/yr., based on the 4 cm wide wire process with subsequent slitting to 4 mm wire width, and with 100m length capability. Continuing efforts include demonstrating commercially practical wire configurations (mechanical and electrical stabilization and hermeticity), increasing performance, improving process reliability, reducing wire cost for both industrial and military 2G applications, and confirming readiness for Pilot scale manufacture.

**Research Integration:** AMSC has leveraged the DoE 2G funding by developing partnerships with a broad array of government, laboratory, university, and commercial entities and has been a leader in supplying robust lengths of 2G HTS wire for characterization by DOE labs and other parties. Many of these groups also contribute to the innovations that will result in future process improvement insertions. Our partners include:

**Substrate**: ORNL, WPAFB, IFW, DARPA, MDA

**Buffer:** ORNL, SNL, LANL, WPAFB, IFW, ATFI, NRL

**HTS:** SNL, ANL, University of Wisconsin, BNL, NIH, NIST, NRL, LANL, IRL, NHMFL, University of Albany, ARACOR, MIT

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| **Project Title:** | **Development of Coated Conductors by Inclined Substrate Deposition** |
| **Organization(s):** | **Argonne National Laboratory** |
| **Presenters:** | Balu Balachandran, Beihai Ma, and Dean J. Miller |
| **FY 2004 Funding:** | $470 K |

**Project Purpose and FY 2004 Objectives:** The purpose of this project is to develop high-performance YBCO-coated conductors for electric power applications by the inclined substrate deposition (ISD) technique. To achieve this goal, we are applying advanced characterization tools to understand texture formation and current-transport issues for ISD-based coated conductors and relate them to fabrication parameters. ISD, characterized by its fast deposition rate and good tolerance to substrate surface roughness, is an excellent candidate for cost-effective fabrication of high-performance coated conductors. In order to realize the great potential of the ISD process, our objectives in FY2004 were to: (1) understand and control fabrication parameters (including layer thickness and inclination angle) for reduced film surface roughness and enhanced biaxial texture formation in the ISD-MgO template films; (2) develop simplified buffer layer structure for the fabrication of coated conductors using ISD-MgO architecture; (3) measure and model residual strain/stresses in coated conductors and evaluate their strain tolerance to characterize the effects of various processing parameters on their mechanical reliability; and (4) assist our industrial partners in their efforts to develop practical methods for fabricating long-length coated conductors. These objectives all focus on the primary goal of DOE's second generation wire program, which is to develop the technology necessary for U.S. companies to scale-up continuous production of coated conductor with sufficient quality for industrial-scale commercial manufacturing.

**FY 2004 Performance and FY 2005 Plans:** We focused our fabrication effort in FY 2004 on improving the texture and critical current of ISD-based coated conductors using SrRuO3 (SRO) as the buffer layer. This approach is based on the demonstrated improvement in biaxial texture using perovskite buffer layers and on our goal to develop a simplified architecture that takes full advantage of the simplicity and efficiency of ISD. In this activity, YBCO was deposited directly on SRO that was on MgO, which decreased the number of layers in the conductor and simplified its fabrication. Some effort was also devoted to the deposition of thicker YBCO films to enhance the critical currents. By closely coordinating the fabrication process with multiple characterization efforts, we improved our understanding of the ISD fundamentals and achieved a nearly three-fold increase in $I_c$. As a result, we produced short-length samples with transport $J_c$ >0.75 MA/cm$^2$ and $I_c$ ≈100 A/cm-width (at 77 K in self-field) for YBCO on ISD MgO substrates with a single-layer SRO buffer. This coordinated effort involved Raman microspectroscopy in systematically examining YBCO films to develop metrics for correlating conductor performance with deposition methodology and parameters; studies of epitaxial growth and interfacial reactions between buffer layers at Argonne's Electron Microscopy Center (EMC), funded by the DOE-Office of Science; and focused ion beam (FIB) analyses at both ANL-EMC and the University at Albany to examine the thickness and crystal chemistry of different layers of the ISD architecture. Processing improvements were also aided by extensive microstructural characterization and texture evaluation that were performed using an atomic force microscope (AFM) and a General Area Diffraction Detection X-ray unit. Due to these coordinated efforts, we can now reproducibly fabricate ISD-MgO-based coated conductors with improved performance and sharpened in-plane (ϕ-scan FWHM ≈5°) and out-of-plane texture (ω-scan FWHM ≈3°).

The FY 2005 plans are to: (1) utilize our coordinated characterization approach to identify the key current-limiting features in ISD-based coated conductors; (2) understand and optimize individual processing steps in the deposition of buffer and superconductor layers to further improve current carrying capability on short-length ISD-based samples; (3) use chemical and microstructural analyses to guide improvement of $J_c$ for YBCO films with thickness >2 μm; (4) investigate Dy-123 as the superconductor coating on ISD architecture; (5) apply the ISD process to moving substrates; (6) continue measurement and modeling of residual stresses/strains and evaluation of strain tolerance to characterize the effects of various processing parameters on the mechanical reliability of coated conductors; (7) continue collaboration with our industrial partners to solve critical issues in coated conductor scale-up (e.g., by integrating magneto-optical imaging, electron microscopy, Raman and X-ray methods to establish a characterization protocol).

**FY 2004 Results:** Reduced funding in FY 2004 had a significant impact on the breadth of our ISD fabrication activities. In particular, processing of long-length ISD tapes using the facilities at LANL's Research Park was completely curtailed. Key results are: (1) Studies using X-ray diffraction and AFM surface analysis showed that the optimal inclination angle for ISD MgO films is ≈35°. (2) Biaxial alignment was improved through the homoepitaxial MgO layer (≈0.25 μm) and SRO buffer (≈0.1 μm). We achieved in-plane texture of ≈5° and out-of-plane texture of ≈3° for YBCO grown on SRO buffered MgO template films. (3) Transport $J_c$ >0.75 MA/cm$^2$ and $I_c$ ≈100 A/cm-width were measured for YBCO on ISD MgO substrates using SRO single-buffer-layer architecture. (4) We fabricated thicker YBCO films (thickness ≈1.6 μm) with $J_c$ ≈0.6 MA/cm$^2$. In FY 2003, we were depositing YBCO films that were usually ≈0.3 μm in thickness. (5) YBCO was grown with its c-axis tilted using SRO buffer on ISD MgO. An anisotropy of ≈1.6 was detected between transport $J_c$ measured in longitudinal and transverse directions. Reproducibility of the ISD process improved. (6) We used Raman microspectroscopy to examine the onset and extent of a-axis-oriented grain growth in YBCO films. We devised Raman mapping strategies that provide both depth and spatial profiles for effects such as cation disorder, c-axis verticality, and impurity phase excretion, and we correlated these results with processing conditions. (7) We measured and numerically modeled residual stresses in YBCO coated conductors, and evaluated their effect on strain tolerance. The residual stresses in the YBCO film were measured by optical interferometric technique and were observed to be tensile in nature. A correlation of the analytically predicted and experimentally observed strain tolerance suggested that the measured tensile residual stress in the YBCO film decreases the strain tolerance of the coated conductor. The results of the modeling indicated that residual stress in the YBCO film is influenced only by the relatively thick substrate and not by the thin buffer layers. (8) In collaboration with LANL, we evaluated the angular dependent in-field performance of YBCO coated conductor fabricated using ISD-MgO architecture.

**Research Integration:** We have been working closely with SuperPower (SP), American Superconductor Corp. (AMSC), and Universal Energy Systems, Inc. (UES). The SP program focuses on integrating coated-conductor fabrication and characterization technologies developed at ANL and LANL with those pursued by SP. Early in the year, ISD substrates fabricated at ANL were sent to SP for YBCO deposition by MOCVD technique. Due to severe reduction in funding, MOCVD on ISD architecture was postponed. Most of our interactions with SP in FY 2004 were in the area of coordinated characterization utilizing MOI, Raman, FIB-SEM, and TEM to identify defects that influence superconducting properties in long-length tapes. Details of this interaction are given in our summary entitled "Coordinated Characterization of Coated Conductors". In our collaboration with AMSC, we worked on the optimization of their TFA precursor conversion process. Results of our collaborative effort with SP and AMSC are presented in two separate talks by our industrial partners and in ANL's talk on coordinated characterization. Our interaction with UES focuses on the ISD process. The UES program is funded by the Air Force Office of Scientific Research. In our collaboration with UES, ISD substrates were provided to UES for YBCO deposition by a MOD process. The YBCO coated samples were characterized at ANL using a variety of tools. In collaboration with LANL, we evaluated the angular dependent in-field performance of coated conductors that were fabricated using the ISD technique. Collaborations are also underway with University at Albany to evaluate the thickness and chemistry of different layers of the ISD architecture (using FIB and SIMS techniques). We also sent ISD substrates to University of Kansas (Prof. Judy Wu) for a study on the effect of miscut angle on the superconducting properties of YBCO films. Through regular teleconferences and team meetings with our collaborators, we coordinate all of the experiments, discuss the results, and establish plans for future work. ANL's program is heavily leveraged by the DOE-Office of Science's fundamental investigation of grain boundaries and by its electron microscopy center. ANL's interactions with industry and universities yielded many publications and talks at conferences during the past year.

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| **Project Title:** | **Applied R&D of 1st and 2nd Generation HTS Conductors** |
| **Organization(s):** | **Oak Ridge National Laboratory** |
| **Presenters:** | M.J. Gouge (ORNL) |
| **FY 2004 Funding:** | $150 K |

**Project Purpose and FY 2004 Objectives:** The purpose of this R&D project is to investigate the performance of prototype HTS conductors with a goal of design optimization for a broad range of practical ac and dc applications. For HTS transmission cables and other T&D devices, this involves examining the performance of single tapes and prototype cables with respect to AC loss and quench and stability when applying short-circuit fault currents of different magnitude and duration. Emphasis in 2004 was on over-current testing of HTS tapes with various stabilizer configurations, completion of HTS tape burn-out experiments, ac loss characterization of $2^{nd}$ generation HTS tapes and the impact of magnetic substrate materials on the inductance of $2^{nd}$ generation HTS cables.

**FY 2004 Performance:** From the 2003 peer review the following plans were projected for FY 2004:

- Impact of various YBCO conductor substrates and stabilization layers on ac losses and over-current tolerance will be studied. Status: Over-current and burn-out tests were conducted on BSCCO and YBCO tapes with various stabilizers and bare and insulated surfaces. AC losses were measured in 4- and 10-wide YBCO tables with different metal substrates.
- Normal zone propagation and stability margins will be measured in a series of copper-stabilized, YBCO coated conductors with different copper thicknesses and joining techniques. Status: not done due to R&D equipment in use by a higher priority SPI project.
- A 1-Tesla HTS coil will be made with YBCO conductor and tested to determine operating envelope and stability margins. Status: deferred to FY 2005 due to program funding reductions in FY 2004.
- Plan to make a YBCO cable with ~4-mm wide 2G tape. Status: not done due to higher priority, prerequisite work on impact of ferromagnetic substrates on 2G cable inductance and ac losses.

**FY 2005 Plans:** Normal zone propagation and stability margins will be measured in a series of copper-stabilized, YBCO coated conductors with different copper thicknesses and joining techniques. A 1-2-m-long 2G power cable will be made from 4-mm-wide, stabilized YBCO tapes. A 1-Tesla HTS coil will be made from YBCO conductor and tested at 30-80 K to determine the operating envelope as a function of (I, B, T), stability margins and quench propagation characteristics.

**FY 2004 Results:** A series of over-current experiments were performed with BSCCO and YBCO tapes. The 20-cm-long HTS tapes were covered with layers of Cryoflex™ dielectric tapes (thickness from ~0.1-1 mm) and bath-cooled in liquid nitrogen. Over-currents were supplied by pulsing a 3-kA, 30-V dc power supply. Electromechanical and thermal limitation of over-current pulses were measured on BSCCO and YBCO tapes. With pulse lengths as short as 35 ms, it is found that the BSCCO and YBCO tape made by AMSC can be pulsed to at least 1 to 1.2 kA range without being damaged electromechanically. Longer pulses at moderate over-currents indicated that both HTS tapes can be heated above room temperature (300 K) range without suffering from degradation. However, severely degraded HTS or burn-out of the tapes were observed when the pulse duration was further lengthened by as short as 10 ms which produced peak temperatures significantly above room temperature. The heating of the tapes accelerates as the temperature and the resistivity of the tape gets higher. Thus, a prudent design peak temperature of the HTS tape for short-circuit fault over-current could be 200 K or lower. When an additional Cu strip of about the same dimension was added to the HTS tape both the over-current magnitude and duration limitations were found to be about doubled. This is apparently due to the shunting function and the added heat capacity of the Cu strip. On the other hand, for ac applications one should be careful in adding Cu to the HTS tape, as the additional ac loss could be excessive. Thermal analysis of the heat absorption during the over-current pulse and the cooldown after the pulse indicates that the heat dissipation from the HTS conductor to its surroundings via the Cryoflex™ insulation in the simulated cable construction is a slow diffusion process. The time constant is on the order of 1-2 s during the pulse and 8-15 s after the pulse. Thus, there may not be vapor formation in the liquid nitrogen even if the HTS is heated to 150-200 K range during the over-current pulse. In a related experiment, burn-out measurements were performed on 1st and 2nd generation HTS wires in a liquid nitrogen bath to test their stability; dc heating pulses of 1 minute duration were applied. Tests were performed on bare wires and with up to ten layers of Cryoflex™. These tests were conducted by applying current above the critical current and holding it constant for up to one minute. If during this period of time the voltage remained constant, the tape was considered stable under that operating condition. At some applied current, the surface cooling of the tape by the liquid nitrogen bath was not sufficient to balance the heat generation at the conductor, which results in a voltage rise and an unstable condition is reached. The measurements showed that while a single layer can have a significant effect on the thermal stability of both 1st and 2nd generation wires, additional insulating layers have little effect on stability. Simulations performed on 1st generation wire, using the flux flow method to model the current transition within the conductor, resulted in theoretical burn-out measurements that coincided with experimental results. Electrical measurement of ac transport losses of 10-mm and 4-mm-wide YBCO on NiCrW substrates (with a nominal $I_c$ of 100 A per cm width) found that the total ac loss scales inversely with the square of the total conductor critical current. When the contribution of the ferromagnetic losses of the substrate are considered, the influence of the NiCrW substrate is not as significant as that seen in YBCO samples with Ni-5at%W substrates. The measured loss was compared to ac loss models. From the testing of the 1.25-m copper-laminated YBCO cable, the impact of NiW substrates on cable ac losses and inductance was examined through the construction of a pair of prototype cables made from 4.8-mm-wide stainless-steel BSCCO and with/without 4.8-mm-wide NiW substrates. Finite element modeling and experimental measurements will be compared. Modeling shows that the cable inductance increases by 10% at low currents <1 kA and approaches a lower asymptotic limit as the current approaches operating values >3 kA.

**Research Integration:** There is also a close interaction with AMSC and SuperPower staff working on 2nd generation conductor under CRADAs with ORNL. Tapes with different substrates and stabilizers as well as support components like low temperature solder are provided by CRADA partners. SPI CRADA partners like Southwire are leveraged to wind prototype cables. Results from the HTS burn-out experiments with BSCCO and YBCO tapes were presented last fall at the 2003 Cryogenic Engineering Conference and will be published in 2004. Papers on the HTS tape over-current testing, magnetic substrate impact on the inductance of YBCO cables and substrate material impact on YBCO conductor ac losses are in preparation to be presented at the 2004 Applied Superconductivity Conference. Results are also communicated to peers working in the DOE SPI projects so conductor performance can be optimized for the particular constraints of a given application.

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| **Project Title:** | **RABiTS Substrates Research and Development** |
| **Organization(s):** | **Oak Ridge National Laboratory** |
| **Presenters:** | A. Goyal, F.A. List, and M. Paranthaman (ORNL) |
| **FY 2004 Funding:** | $900 K (DOE to ORNL) |

**Project Purpose and FY 2004 Objectives**: To develop a basic understanding of fundamental issues related to coated conductor development for high-temperature and high-field applications based on the RABiTS process. The primary objectives for FY 2004 were:

1) Utilize rolling mill with clean room facility to develop a better understanding of experimental parameters affecting surface finish and texture development in Ni-based alloys.
2) Work with outside vendors to obtain improved coils with reduced defects.
3) Fabrication of long lengths of Cu-based substrates and development of suitable architectures for Cu-based substrates which can support high-$J_c$, thick YBCO films.
4) Perform percolation calculations using experimentally achievable texture in RABiTS substrates and perform such calculations as a function of applied magnetic fields.
5) Develop methods aimed at separating the a-axis and c-axis tilt components from the total misorientation measured in EBKP to better understand how misorientation at GB's affects $J_c$.
6) Continue magnetization studies aimed at a better understanding of AC losses in low alloy (alloys which are not completely nonmagnetic) substrates.
7) Develop robust, reel-to-reel buffer architectures on NiW substrates with optimized buffer layer thicknesses.
8) Develop high-rate, solution based buffer layers on NiW RABiTs substrates.
9) Fabricate double-sided RABiTS-based substrates.

**FY 2004 Performance and FY 2005 Plans**: In FY 2004, most milestones were achieved as planned. The ORNL rolling mill facility with a class 1000 clean room was made fully operational this year. A number of modifications were made to obtain wide, rolled substrates with good surface quality. We have worked on a limited budget with outside vendors to improve coil fabrication. We have fabricated long lengths of sharply-textured Cu substrates and new fully conductive architectures have been developed for Cu substrates. Percolation calculations using the presently achievable texture in RABiTS substrates show a reduced $J_c$ dependence on number of grains along the width. Furthermore, the $J_c$ dependence on width becomes even more insignificant in applied fields. We have developed crystallographically consistent methods to separate the in-plane and out-of-plane misorientation components from the total misorientation at grain boundaries. We have studied in detail processing issues which can lead to delamination of oxide buffers on powder metallurgy derived NiW substrates. We have fabricated solution-based LZO/$CeO_2$ buffers on NiW substrates as well as double-sided buffers.

FY 2005 plans include:

1) Fabrication of long lengths of Ni-5at%W substrates via the powder metallurgy route with sharp texture and transfer of technology to the industry and optimization of buffer layer thicknesses on Ni-5at%W substrates fabricated via the powder metallurgy route
2) Use thermal desorption as a tool to assess and control the tendency for interfacial carbon monoxide formation for various substrates fabricated using different processing routes
3) Research texture development in higher tungsten containing substrates, particularly the nonmagnetic, Ni-9.3at%W substrate
4) Research texture development in strengthened and conducting Cu-based alloy substrates

5) Develop suitable all-conducting buffer layer architectures on strengthened and conducting, Cu-based substrates
6) Develop simpler buffer layer architectures for NiW substrates involving either non-vacuum techniques or change in architecture
7) Develop methods to separate in-plane and out-of-plane misorientations from EBKP measurements in materials with lower crystal symmetry such as YBCO and correlate $J_c$ with grain boundary assemblages in YBCO films on RABiTS in terms of in-plane and out-of-plane misorientations
8) Perform filament subdivision studies using laser-scribing w.r.t. to percolation and ac losses on YBCO/RABiTS samples 10 cm to 100 cm in length. Correlate results obtained with suitable calculations involving percolation and ac losses.

**FY 2004 Results**: The ORNL rolling mill facility with a class 1000 clean room was completed. Significant research and subsequent modifications to the mill were required to perform rolling at high speeds and still maintain an excellent surface quality. Technical staff from AMSC routinely visited ORNL to perform week-long rolling runs. All of AMSC's substrates for scale-up to a 4-cm-wide process were slit from substrates fabricated using this facility in FY 2004. We have worked with outside vendors to develop improved powder metallurgy based Ni-3at%W and Ni-5at%W starting coils.

We have fabricated long lengths of Cu substrates of various thicknesses using our rolling mill facility. Approximately 1000 m of 1-cm-wide Cu substrates were fabricated. Conductive buffer layer architectures have been developed for use in Cu-based substrates.

Percolation calculations have been updated using the presently achievable texture in long-lengths of RABiTS substrates. Typical true in-plane textures of ~5º full-width-half-maximum are now routinely obtained by AMSC and ORNL. With this sharper in-plane texture, the dependence of $J_c$ on number of grains across the width of a conductor is reduced. We have also extended the calculations to determine the $J_c$ as a function of number of grains in the conductor in the presence of applied fields. It is found that in the presence of applied fields, the dependence of $J_c$ on number of grains across the width of a conductor is reduced significantly.

A long standing objective in the coated conductor community has been to get a better understanding of the in-plane and out-of-plane misorientations of grain boundaries present in coated conductors. The total grain boundary misorientation in large areas of the textured substrates has been characterized using electron backscatter Kikuchi diffraction (EBKD) for almost 10 years now. However, so far it has not been possible to separate the in-plane and out-of-plane misorientation components from the total misorientation as measured using EBKD. Using the properties of Rodrigues Space, we have successfully been able to separate the in-plane and out-of-plane misorientations in a crystallographically self-consistent manner for cubic materials. Grain boundary maps of the total, in-plane and out-of-plane misorientations in large areas of the RABiTS substrate were made. The misorientations were then correlated to both the measured true phi and the $J_c$ of YBCO grown epitaxially on these substrates.

A study was conducted on the magnetic properties of a series of biaxially textured $Ni_{1-x}W_x$ materials with compositions x = 0; 3; 5; 6, and 9 at.% W. The quasi-static dc and ac hysteretic loss W was determined to support estimates of the ferromagnetic contribution to the overall ac loss in potential ac applications. The alloys were prepared by either vacuum casting or powder metallurgy methods, and the hysteretic loss tended to be lower in materials that were recrystallized at higher temperatures. Some samples were progressively deformed (0.4% bending strain) to simulate winding operations; this increased the hysteretic loss, as did sample cutting operations that create localized damage. In ac magnetization measurements, the effects of ac frequency and dc bias field on the ferromagnetic loss were determined.

Development of reel-to-reel RABiTS using powder metallurgy derived Ni-3at%W substrates was found to result in delamination of oxide buffers at the alloy/seed layer interface. A significant research effort was focused in determining the fundamental cause of the delamination. Among the factors considered were: oxygen nonstoichiometry of the seed layer, barrier layer, and the cap layer; formation of a volatile tungsten oxide at the interface of NiW and $Y_2O_3$; stresses in the film from a higher rate of deposition; and morphology of the deposited layers such as columnar grains with porosity between columns that may increase oxygen diffusion to the alloy/oxide interface. It was found that none of these factors strongly affected the delamination. The strongest correlation with delamination was found to be with the presence of carbon in the powder metallurgy derived substrates. Although the amount of carbon in the substrates was not enough to prevent ~100% cube texture formation, the level was high enough to cause delamination problems. It is found that upon annealing the PM derived NiW substrates in a low partial pressure of oxygen or water, the carbon content is significantly reduced. No delamination of buffer layers is observed on PM NiW substrates in which the carbon has been reduced significantly via appropriate annealing procedures.

Using the sol-gel alkoxide precursor route, we have grown 50-100-nm-thick epitaxial LZO layers in a single coat directly on PM derived, Ni-W substrate. Solution based processing of thin films also offers the possibility of double sided coating for enhancing the overall engineering critical current density using a reel-to-reel dip coating process. Smooth, epitaxial, crack-free buffer layers with double-sided coatings were also produced. Using the metal-organic decomposition (MOD) approach, we have successfully developed a method to grow epitaxial $CeO_2$ cap layers on LZO-buffered Ni-W substrates.

**Research Integration:** Three CRADA teams are working directly with ORNL staff members to develop the science and technology base for coated conductors. These teams are led by American Superconductor Corporation, Oxford Superconducting Technology, and MetOx. Critical issues in each of these CRADAs are the development of better textured substrate materials and better characterization of the substrates with respect to texture as well as to ac losses. Cu-based substrates coupled with conductive buffer layers are also becoming an interest in light of applications requiring a stabilizer. Percolative aspects of current flow, nature of grain boundaries in RABiTS substrates, and fundamental limitations to obtaining high $J_c$'s in long samples are topics of great interest to all CRADA partners as well to the superconductivity community in general.

Substrate materials fabricated in this project provide substrates for internal ORNL projects. Both metal substrates and buffered substrates are sent to CRADA partners as well as many universities and national laboratories. All YBCO on RABiTS samples sent to collaborators from ORNL use substrates fabricated in this project. Sample exchanges this year include the following organizations: Sandia National Laboratories, National Renewable Energy Laboratory, University of Houston, California State University, and University of Cincinnati. Interactions were had with the following companies: American Superconductor, Oxford Superconducting Technology, MetOx, Ametek, Hamilton Precision Metals, and N. Ferrara, Inc. This project has resulted in a number of publications and invention disclosures in the last fiscal year.

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| **Project Title:** | **Non-Vacuum Techniques for HTS Coated Conductors** |
| **Organization(s):** | **National Renewable Energy Laboratory** |
| **Presenters:** | Raghu Bhattacharya (NREL) |
| **FY 2004 Funding:** | $400 K (NREL) |

**Project Overview:** The U. S. Department of Energy's vision is, "Low-cost, high performance YBCO coated conductors will be available in 2005 in kilometer lengths. For applications in liquid nitrogen, the wire cost will be less than $50/KA-m, while for applications requiring cooling to temperature of 20-60 K the cost will be less than $30/KA-m." One of the important critical needs to achieve this goal is to develop a simple low-cost technology for producing HTS and also buffer layers for low-cost metal substrates. Our project offers non-vacuum electrodeposition, dip coating and spray deposition processing technologies, which are potentially low-cost, long length and continuous processes. At present, we are working on development of HTS and buffer layers employing all these non-vacuum technologies. The YBCO is the primary HTS material system under investigation. The realization of biaxially textured "thick" oxide superconductor films with high transport current is the primary objective for the program. The overall approach for the preparation of non-vacuum HTS tape employs the electrodeposition or spray deposition of buffer layers and superconductor oxide films. Textured substrates, such as NREL's electrodeposited Ni/Ni-W, Ni/Cu, Ni-W/Cu, and other metal and metal oxides, are utilized, combined with appropriate buffer "cap" layers such as $CeO_2$/YSZ/ $CeO_2$. NREL is developing electrodeposited biaxially textured buffer layer for YBCO coated conductor in collaboration with other National Laboratories. NREL is developing an electrodeposited Cu stabilizer in collaboration with SuperPower Corporation (industrial partner). NREL is also assisting Oxford Superconducting Technology (industrial CRADA partner) in developing Bi-2212 conductor for a HTS MRI system. The superconducting properties of Bi-2212 was significantly enhanced by NREL developed MgO nano-particle incorporation. NREL provides technical communications support to DOE headquarters staff for the DOE Superconductivity Program for Electric Power Systems. The principal communications support is the maintenance of the DOE Web site for the superconductivity program.

**FY 2004 Objectives:**

- Investigate non-vacuum techniques for producing biaxial textured buffered metallic substrates.
- Demonstrate $J_c > 10^6$ A/cm$^2$ at 77 K for YBCO superconducting film using electrodeposited seed buffer layer.
- Explore techniques for improving Bi-2212 by nanoparticle additions.
- Technical communications for the DOE HQ's staff.

**FY 2004 Performance and Results:**

- Electrodeposited Ni seed buffer layers were developed on textured Ni, Ni-W, and Cu substrates.
- Biaxially textured YBCO was prepared on electrodeposited Ni seed layer with current density of 2 x $10^6$ A/cm$^2$ at 77 K.
- Developed a "melt-quench-melt-growth" (MQMG) process, which facilitated an open reaction and eliminated loss of material during processing.
- MgO nano-particles incorporated Bi-2212 tapes showed more than 60% better superconducting properties at high magnetic field and also a significant improvement (> 33%) was observed at zero field.

- Prepared 70 µm thick Cu layer by electrodeposition process to be used as a stabilizer on YBCO coated conductors.

**FY 2005 Plans:**

- Prepare electrodeposited biaxially textured buffer layer (innovative and simplified) for YBCO HTS. Electrodeposit non-magnetic Ni-W layer for HTS YBCO.
- Demonstrate $J_c > 10^6$ A/cm$^2$ at 77 K for YBCO using the NREL developed buffer layer.
- Investigate non-vacuum techniques (especially electrodeposition technique) for producing YBCO superconductor.
- Work with Oxford Superconducting Technology on NREL/OXFORD CRADA. Assist Oxford Superconducting Technology on HTS MRI system.
- Prepare electrodeposited Cu stabilizer on YBCO-coated conductor in collaboration with SuperPower Corporation.
- Technical communications for the DOE Headquarters' staff.

**Research Integration:** NREL and University of Colorado working together on electrodeposition and spray deposition process. NREL and Oxford Superconducting Technology have CRADA towards the development of HTS MRI system. NREL established new collaborative effort with SuperPower Corporation. NREL is also working with other national laboratories; especially ORNL and LANL, on YBCO coated conductors.

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| **Project Title:** | **Ex-Situ Processing of YBCO Precursors** |
| **Organization(s):** | **Oak Ridge National Laboratory** |
| **Presenters:** | H.M. Christen, D.F. Lee, and F.A. List (ORNL) |
| **FY 2004 Funding:** | $850 K (DOE to ORNL) |

**Project Purpose and FY 2004 Objectives:** The purpose of this project is to understand and explore means to fabricate high performance YBCO by the ex-situ technique. Our primary objectives for FY 2004 are:

1) Investigate reel-to-reel (R2R) Pulsed Electron-Beam Deposition (PED) of YBCO precursors.
2) Develop a R2R slot die coater for solution precursors.
3) Explore YBCO conversion characteristics and performance of various types of precursors.
4) Investigate differences in solution and physical vapor deposition (PVD) precursors responsible for different reaction rates, and increase the reaction rate of PVD precursors.
5) Identify pinning centers and processing parameters responsible for different field dependencies in samples converted in different systems.
6) Add and develop both reduced- and low-pressure R2R capabilities for precursor conversion.
7) Process double-sided precursors.

**FY 2004 Performance and FY 2005 Plans:** In our quest to explore new industrially scalable options for the deposition of precursors, we have implemented R2R systems for PED and for slot-die solution deposition (April 04). In the PED process, significant initial stability issues were overcome to yield precursors exceeding 1-µm thickness in meter lengths. In the area of solution precursors, we have developed a hybrid MOD precursor capable of sustaining high $J_c$'s. Meter-lengths of MOD precursors (>1-µm thickness) were deposited using our slot die coater. Due to a budget reduction, however, we were not able to develop and upgrade our R2R conversion systems to enable reduced- and low-pressure processing.

Significant progress in increasing the conversion rate of PVD precursors has been made. Modified deposition conditions for e-beam evaporated precursors resulted in a ten-fold increase in c-axis YBCO conversion speed over the previous e-beam precursor. In addition, a similar increase in conversion rate has also been found for PED precursors. In the area of conductor performance, the strong magnetic-field dependency of $I_c$ found in our R2R "atmospheric" system was eliminated by adjustments to the dry annealing temperature profile. This finding has significant implication on tape manufacturing where a tendency may exist to over-anneal the product to ensure complete conversion and spatial uniformity. In addition, double-sided buffers in short lengths have been fabricated, and some potential issues associated with buffer architecture and deposition have been identified. Various YBCO precursors have been converted on such substrates, and epitaxial films have been obtained.

Our FY 2005 plans focus on:

1) Continuing efforts to understand the effects of pressure on ex-situ conversion rate of various precursors.
2) Developing and installing a multi-source PED system to increase deposition rate of R2R PED precursors.
3) Increasing the conversion rate and performance of thicker PVD precursors.
4) Evaluating the feasibility of enhancing intra-granular Jc and pinning through nanoparticle inclusions using scalable ex-situ methods.
5) Obtaining high Ic/cm and low ac losses through conductor design such as double-sided and filamentary coated conductors
6) Evaluating issues related to the conversion and performance of high volumetric large-area conductors

7) Applying our ex-situ capabilities to aid in the continuing development of RABiTS, which is aimed at new alloy substrates, alternative buffers, and improved texture.
8) Working collaboratively with ANL and NIST on phase development of various precursors using ANL's R2R Raman Spectroscopy, NIST's in-situ XRD expertise, and ORNL's R2R X-ray diffraction capabilities.

**FY 2004 Results:** In the past year, we have been able to modify the deposition conditions of e-beam "$BaF_2$" precursors to yield higher reaction rates. Under previous deposition conditions, typical rates ranged from 0.6 Å/s to 2.5 Å/s, depending on the conversion system, with higher rates resulting in the development of random YBCO with few cube-textured grains. In contrast, our modified precursors sustain reaction rates as high as 10 Å/s with the formation of little or no random YBCO, and $J_c$'s >1 MA/cm$^2$ for ~1-µm-thick films.

PED is a potentially simple and stable method for PVD precursor deposition. Motivation for the exploration of this process comes from the initial observation that laser-ablated precursors on short-length samples yield $J_c$ >1 MA/cm$^2$ (1.4-µm thickness). To cost-effectively utilize the advantage of ablation from a single source, our PED system was modified for R2R operation. Initial trials revealed two potential problems: instability in source operation (missed pulses), and substantial decrease in the deposition rate per pulse with time. By adjusting the operation parameters, the instability limit was increased from tens of thousands of successively fired pulses to several million. In addition, studies of the relationships between target mounting, growth rates, and stoichiometry of transfer showed the importance of charge redistribution during precursor deposition, and allowed us to reproducibly increase the deposition rate. Short PED precursors (~1-µm thick) have been converted under various pressures, resulting in YBCO films with $J_c$'s greater than 1 MA/cm$^2$ (~120 A/cm-width). Furthermore, similar to the modified e-beam precursors, these PED precursors were found to be able to react at moderately fast rates.

A hybrid MOD precursor, containing both fluorine and nonfluorine containing phases has been developed. $J_c$'s in excess of 2 MA/cm$^2$ on 0.6-µm spin-coated short samples have been achieved. Like other solution precursors, this hybrid MOD precursor was found to be capable of being converted at higher rates than PVD precursors. Precursor films >1-µm-thick have been deposited using our R2R slot die coater, and the precursors are presently being evaluated using our various conversion systems.

We have preciously shown that samples converted in our R2R atmospheric-pressure furnace consistently resulted in films with strong magnetic field dependency, where the $J_c$ drops to ~15% of its self-field value at 0.5 T. In contrast, samples processed in other systems exhibited a drop to ~23% under the same 0.5 T applied field. We have traced the cause of this strong field dependence to excessive duration of high temperature dry annealing, which is inherent to the design of the R2R system. By adjusting the thermal profile, i.e., shortening the dry annealing time, samples from this atmospheric-pressure system now consistently exhibit a field dependency that is comparable to other systems.

Double-sided YBCO samples have been processed on RABiTS with the $CeO_2$/YSZ/LZO/NiW architecture. To avoid scratching of the substrate or buffer from our contact heaters, the RABiTS were fabricated under stationary conditions (short length). Results on converted samples indicated that both the top and bottom sides of the precursor films are epitaxial, and are fully converted without requiring addition times compared to single-sided samples.

**Technology Integration:** Results on ex-situ conversion of various types are of significant interest to AMSC, and our results obtained in the base program are routinely shared with AMSC. We have also collaborated with AMSC in that a significant fraction of conversion studies were performed on AMSC RABiTS. In the area of PED precursor work, substantial knowledge concerning the stability of PED has been transferred to Neocera. Work on solution precursor/buffer continues with SNL, and in-situ XRD analysis of solution reaction kinetics has been initiated with NIST. Research collaboration with University of Cincinnati on the development of MOD precursors has been successfully concluded with the graduation of a Ph.D. student. Collaboration with ANL on phase development using Raman, which was highly rated in FY03 review, continues on a reduced scale due to the delay in alternative precursor development owing to budget cuts. Throughout the year, our industrial CRADA partners were regularly briefed on our findings.

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| **Project Title:** | **Coordinated Characterization of Coated Conductors** |
| **Organization(s):** | **Argonne National Laboratory** |
| **Presenters:** | Kenneth E. Gray, Dean J. Miller, and Victor A. Maroni |
| **FY 2004 Funding:** | $520 K |

**Project Purpose and FY 2004 Objectives:** The purpose of this task is to develop, integrate, and implement a coordinated set of characterization methods to evaluate superconductivity in coated conductors and pinpoint the causes of degraded performance. Some methods examine intermediate stages of fabrication in a manner compatible with further high-temperature processing. These characterizations include measurements of local supercurrent transport, phase composition, microstructure, and epitaxy quality for YBCO coated conductors that range in size up to multi-meter-length tapes and that embrace the entire tape embodiment (substrate through cap layer). Our FY 2004 objectives included: (1) the establishment of Raman spectroscopy as an on-line process monitoring tool, (2) the integration of magneto-optical imaging (MOI) and Raman microscopy with transmission electron microscopy (TEM) assisted by focused ion beam (FIB) sample sectioning, (3) the extension of this integrated characterization package to long-length coated conductors supplied by our industrial partners, and (4) the development of seamless methods to monitor properties during/after sequential high-temperature treatments to improve superconductivity, e.g., optimizing oxygenation of coated conductors.

**FY 2004 Performance and FY 2005 Plans:** Performance in FY 2004: In collaboration with SuperPower, Inc. and Kaiser Optical Systems, Inc., we conducted design, concept development, and qualification testing of a fiber optic-based Raman microprobe embodiment that will soon be installed on one of SuperPower's coated conductor processing stands. We performed coordinated MOI, Raman microscopy, and electron microscopy analyses of selected high performance and low performance regions of meter-long YBCO CC tapes supplied by SuperPower. The insight gained from these complementary techniques is significantly enhanced by our use of FIB-based TEM specimen preparation. This integration elucidated several defects that could inhibit performance. In addition, we have made progress in our coordinated characterization methodology by developing new data collection and specimen preparation techniques. In collaboration with American Superconductor (AMSC), we used Raman microscopy to probe the details of phase evolution in the early stages of TFA precursor transformation. Using a novel scheme to reversibly change the oxygen concentration, we demonstrate that, below 77 K, the highest $J_C$ values in coated conductors from SuperPower as well as ISD from ANL occur at the highest (overdoped) oxygen concentration.

**Plans for FY 2005:** Our primary focus of effort in FY 2005 will be to apply our coordinated characterization of coated conductor approach to state-of-the-art coated conductor segments supplied by our CRADA partners—AMSC and SuperPower. A restoration of some of or the entire FY2004 funding cut is needed to fulfill our commitments to these CRADA partners. To the maximum extent possible we will conduct these analyses either *in situ* (e.g., using Raman spectroscopy) or in a manner that is compatible with further high-temperature processing (e.g., by "nondestructive" MOI and FIB-based excision of "micro specimens"). In the Superpower sample, we identified a defect that has a significant impact on performance. However, our coordinated characterization also reveals several other types of defects that we need to further evaluate by high-resolution SEM and TEM. We will also isolate specific defect structures to evaluate the local $J_c$ by magnetization methods. To improve $J_C$, we will attempt greater oxygenation of coated conductors using, e.g., ozone.

We will continue to work with SuperPower to follow through on the implementation of the fiber-optic Raman microprobe being installed at their facilities in Schenectady and with AMSC on the optimization of their precursor conversion process. We want to carry out more comprehensive TEM studies of precursor conversion of YBCO evolution to complement on-going Raman studies. Hopefully, FY 2005 funding levels will also permit us to reengage with ORNL on the $BaF_2$ process optimization work that we started in FY 2003.

**FY2004 Results:** Reduced funding in FY 2004 had a significant impact on the breadth of our characterization activities and on the number of specimens we could meaningfully examine. In particular, our productive and rewarding collaborations with national laboratory partners were greatly curtailed. We concentrated our efforts on meeting the characterization needs of our two principal industrial partners, AMSC and SuperPower. Segments of CC tapes supplied by SuperPower, along with comprehensive local $J_c$ data, were subjected to the integrated MOI/Raman/FIB-SEM/TEM methodology. MOI was used to explore the differences in high-, mid-, and lower-$I_c$ regions of a long-length tape, showing that local defects influence current flow in each case. Raman confirmed that the quality of the superconductor was degraded in the defected regions identified by MOI. TEM in those regions, aided by FIB-based specimen preparation, revealed that interactions at the buffer layer play a key role in performance. Detailed studies using energy-filtered TEM and STEM-based spectroscopy show that these interactions can be very subtle, reinforcing the need for coordinated characterization to identify such regions. We studied the effects of oxygen concentration on the temperature and magnetic field dependence of $J_c$ in coated conductors from SuperPower as well as ISD from ANL using a novel oxygenation scheme. We found that the most over-doped state always gave the highest $J_c$. In studies carried out in conjunction with AMSC, we performed Raman microscopy measurements on TFA precursor (and compositionally modified TFA precursor) specimens that were quenched during ramp up to the precursor conversion temperature. We were also able to detect the buffer layers during the early stages of precursor transformation.

**Technology Integration:** In FY04 we enhanced our interaction with Superpower and with the Electron Microscopy Center at Argonne to address a significant performance issue for long-length conductors. We implemented our complete coordinated characterization methodology, utilizing MOI, Raman, FIB-SEM, and TEM, to identify one specific defect that influences superconducting performance. The detailed microstructural information we provided also yielded new insight into the YBCO growth process on this SuperPower coated conductor architecture.

During FY 2004 our efforts to establish Raman spectroscopy as a viable/useful on-line diagnostic procedure for monitoring the progress of YBCO phase formation and the quality of the CC films were taken to yet another level with the design/development/testing and placement of a Raman probe on one of SuperPower's YBCO CC tape production lines. This accomplishment involved working closely with both SuperPower and Kaiser Optical Systems, and built upon our FY 2003 accomplishments which showed that meaningful Raman interrogations could be performed on moving tapes and that commercially available Raman hardware is fully adaptable for application at long-length coated conductor manufacturing facilities. We also continued to work with AMSC on the optimization of their TFA precursor conversion process, but at a reduced level of effort compared to FY 2003. Other Raman microscopy-based research on phase evolution in meter-length $BaF_2$-precursor tapes that was being performed in collaboration with ORNL, had to be curtailed due to the large funding reductions experienced in the Argonne program in FY 2004.

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| **Project Title:** | **Los Alamos Coated Conductor Development** |
| **Organization(s):** | **Los Alamos National Laboratory** |
| **Presenters:** | Vladimir Matias, Brady Gibbons, Leonardo Civale |
| **FY 2004 Funding:** | $2,100 K |

**Project Purpose and FY 2004 Objectives:** This part of the Los Alamos coated conductor development program is intended to accelerate the development, commercialization, and application of $YBa_2Cu_3O_y$ (YBCO) high temperature superconductors. Three focus areas are: internal scale up of the coated conductor (CC) fabrication processes based on IBAD MgO up to 10 meter lengths, development of new processes more suitable for manufacturing, and targeted collaborative R&D with US industry for development and characterization of long-length coated conductors. Specific objectives for FY 2004 under the CC development program were:

- Finish a modestly scaled CC fabrication (5-10 m) and characterization facility
  a) Produce lengths of over 5 meters with more than 200 A per cm-width;
  b) Produce 1 meter lengths of CC with less than 10% $I_c$ variation;
  c) Demonstrate IBAD template repair with measurable $I_c$ across repaired regions;
  d) Utilize ion scattering *in situ* diagnostics for diffusion barrier optimization;
  e) Implement YBCO reactive coevaporation
- Further collaborative relationships with industrial partners for the purpose of advancing the state of CC development and its commercialization in the U.S.
  a) Provide longer lengths (up to 10m) of IBAD-MgO templates to our industrial collaborators with in plane texture less than 8°.
  b) Provide access to facilities for targeted collaborative research in characterizing CC samples.

**FY 2004 Performance and FY2005 Plans:** The reel-to-reel systems at the Los Alamos Research Park are now producing CC's at a level of performance comparable to short length samples prepared in our Core Program. Electropolishing has produced several kilometers of smooth tape (2 and 4-mil tape) for internal IBAD MgO deposition and external development at our industrial partners. The ion beam assisted deposition (IBAD) system has produced 0.5 kilometer of IBAD-MgO with epitaxial MgO on top, in piece-lengths up to 10 meters. The in-plane texture is in the range of 6° – 8° full-width half maximum (FWHM). Ion scattering analytical equipment has been installed in the IBAD system for *in situ* surface analysis. This surface diagnostic tool has been used to optimize our $Al_2O_3$ diffusion barrier to be able to withstand temperatures above 900 °C without failure. A modified target rastering mechanism was installed in the pulsed laser deposition (PLD) system and has resulted in dramatically improved plume stability and resulting tape uniformity. In addition, a new continuous tape heater was installed that contains 9 separately controlled heating zones for optimal control of the temperature profile through the deposition zone. Fully processed CC's with over 200 A performance are now routinely obtained. Buffered and HTS-coated tapes have been provided to our collaborators. A deposition system for reactive coevaporation of YBCO on tapes is currently being installed. A system capable of measuring the local $I_c$'s (length scales of 1-10 cm) in lengths of up to 100 m of HTS coated conductor was finished and used to characterize several long tapes (10 m) from our industrial partners.

For FY2005, we plan to further demonstrate the promise of coated conductors by obtaining transport currents in excess of 500 A/cm-width in lengths of over 1 meter. This is to be accomplished by improving the reproducibility and uniformity of the processes and incorporating the advances of the LANL Core program into the continuous processing of IBAD MgO coated conductors. Short lengths of coated conductors with $J_c$ values in excess of $1 MA/cm^2$ will be also made by the reactive coevaporation of YBCO, which has great promise for low-cost and high-rate deposition. Up to 100 m piece lengths of HTS coated conductor from our industrial partners will be measured for positional $I_c$.

**FY 2004 Results:** In FY2004, significant results have been obtained in the areas of electropolishing, IBAD-MgO, PLD, electrodeposition of stabilizing layers, and continuous $I_c$ measurements of long length coated conductors.:

- Modifications to the electropolishing system currently allow for polishing of substrates up to 3 cm wide. Polishing of RABiTS templates was also initiated at the request of an industrial partner. A new system was installed for short length polishing with the goal of faster experimentation with a number of electrolytes.
- IBAD-MgO process speeds of over 100 meters/hour in a 10-cm deposition zone (laboratory scale) have been demonstrated.
- PLD buffer layer deposition has been demonstrated on several longer (> 5 m) lengths. Some of these buffered tapes have been supplied to our collaborators in industry, national labs and universities for development of their HTS processes. YBCO deposited continuously by PLD has shown in-plane FWHM values on the order of 2.8° - 3.5°, with $I_c$'s > 200 A. Our best tapes have a uniformity on a 1-cm scale of ~ ± 4.5% in $I_c$ for 20 cm long pieces, and ±7.8% over 1 meter.
- We have electroplated copper on our coated conductors to thermally stabilize the conductor and improve its mechanical robustness, without degrading its $I_c$. With the copper plating we are able to apply a current equal to 2.5 times the $I_c$ of the tape.
- We have characterized numerous coated conductors from our industrial partners for positional $I_c$ dependence (up to 10 meters long) and angular magnetic field dependence.

**Technology Integration:** On-going development of processes is responsive to the needs of CRADA collaborations and user facility operations. Central to this development is the expectation of free exchange of information and materials among the DOE laboratories and CRADA partners. At least half a dozen visits by and to our industry partners have been arranged in the past year. These have led to information and sample exchange. Tens of meters of coated tape have been sent to our partners. We have sample exchange with American Superconductor, MetOx, SuperPower, Oak Ridge National Lab, Sandia National Lab, Stanford University, and University of Wisconsin.

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| **Project Title:** | **All Solution Deposited YBCO Coated Conductors** |
| **Organization(s):** | **Sandia National Laboratories** |
| **Presenters:** | P. Clem, J. Voigt |
| **FY 2004 Funding:** | \$200 K Solution Buffers and YBCO Development<br>\$200 K YBCO Vacuum Conversion and Industrial CRADA |

**Project Purpose and FY 2004 Objectives:** The purpose of this project is development of economical, scaleable, solution film deposition techniques for continuous processing of 2nd generation coated conductor tapes. Sandia has a long history in sol-gel chemistry, scale-up of solution-deposited materials, and $BaF_2$- and trifluoroacetic acid-based (TFA) YBCO processing, and is applying this background to integration of high quality buffer layer and YBCO conductor process methods on commercial substrates. The solution deposition processes developed are inherently capable of continuous, 90-360 m/h deposition rates, and have promise to be the lowest cost method of producing 2nd generation coated conductors, if vacuum crystallographic quality can be attained. Towards this goal, we have substantially achieved all four of our FY2004 project milestones:

1) Develop high-rate solution deposition methods capable of producing YBCO films on RABiTS carrying (a) 1 MA/cm$^2$ at 0.5 μm and (b) 1 MA/cm$^2$ at 0.75-1.0 μm film thickness, deposited in a single coating.
2) Begin CRADA technology transfer and formal industrial collaboration related to solution-derived YBCO and buffer layer methods.
3) Optimize conversion and conversion rates of YBCO on single crystals and buffered substrates to enable 1 MA/cm$^2$, 1 μm thickness films with rapid pyrolysis and crystallization times (< 30 min).
4) Develop thin solution buffers on NiW capable of supporting MA/cm$^2$-quality films.

**FY 2004 Performance and FY 2005 Plans:** Summary of FY 2004 performance**:**

1) Collaboration with commercial and inter-laboratory partners to enable development and scale-up of solution-derived 2nd generation coated conductors: (i) a CRADA with American Superconductor Corporation (AMSC) for evaluation of Sandia solution buffers, and application of Sandia methods for optimization of AMSC processes, (ii) collaboration with Oak Ridge National Laboratory (ORNL) on solution deposition scale-up and vacuum conversion of solution-deposited YBCO, and (iii) collaboration with Los Alamos National Laboratory (LANL) on IBAD substrates of MgO and $LaMnO_3$/MgO, solution development of Cu-doped $SrTiO_3$ at LANL, and TEM of SNL YBCO/$SrTiO_3$/NiW. We have continued research on solution-deposited $SrTiO_3$ single buffer layer structures on NiW, followed by solution-deposited 0.25-0.75 μm YBCO.
2) Use of the SanDEA YBCO process to produce 0.5 μm, 1.2 MA/cm$^2$ films (60 A/cm $I_c$), and 0.75 μm, YBCO films on $CeO_2$//YSZ//$Y_2O_3$//Ni//Ni-W.
3) Finished the first year of a CRADA with AMSC on joint solution-deposited coated conductor research. Demonstrated high quality YBCO atop $SrTiO_3$/NiW buffer stacks.

We propose the following future research and development for FY 2005:

1) Increase thickness of 1 MA/cm2 YBCO to 2μm using fast deposition and process methods on RABiTS and IBAD substrates. Continue collaborations with ORNL, LANL, and AMSC to enable continuous, multimeter lengths of 200-400A/cm conductors.
2) Continue optimization of solution-derived buffer layers (FWHM, roughness) to replace vacuum deposited buffer layers. Work to attain vacuum-quality FWHM values.
3) Develop continuous, 0.3μm solution buffers toward industrial buffer layer technology transfer (CRADA). Apply industrial metrics and methods to enable process spin-off.

**FY 2004 Results:** Highlights of our progress include:

a. Development of new, solution-derived TFA-YBCO coating processes in FY2004 for production of 0.5-0.75 µm single-coat thickness YBCO films, at 90-144 meter/hour coating speeds, with 20 second organic burnout time. $MA/cm^2$-quality films have been produced in collaboration with ORNL on RABiTS substrates.

b. Investigation of vacuum conversion of TFA-YBCO with Fred List at ORNL and at Sandia. In contrast to traditional $BaF_2$ YBCO conversion rates of 1-2 Å/s, we have found conversion rates up to 40 Å/s in TFA-YBCO films, with conversion rates of 25 Å/s yielding high quality YBCO, which would enable 1 micron film conversion in 400 s, less than 7 minutes. Vacuum conversion has been performed on RABiTS and single crystals.

c. Demonstrated well-aligned $SrTiO_3$ buffer layers on AMSC NiW substrates, and deposited YBCO atop these with $MA/cm^2$ critical current densities. Collaborated with AMSC on solution YBCO, solution buffer layers, and vacuum buffer layer development.

**Research Integration:** Toward scale-up, we have three new collaborations with ORNL, LANL, and AMSC that have improved our program capabilities.

- AMSC: We have completed the first year of a CRADA and agreement to license with American Superconductor Corporation to explore areas of mutual interest, including solution deposition of YBCO and buffer layers on NiW. Sandia methods including $^{18}O$ in-diffusion experiments, focused ion beam sample sectioning, *in-situ* stress analysis, and $SrTiO_3$ buffers have been used to aid optimization of AMSC technologies. AMSC has provided substrates, precursors, and processing expertise for development of Sandia solution-derived YBCO/$SrTiO_3$/NiW conductors.
- ORNL: We have collaborated closely in FY04 with ORNL's ACCI facility to enable continuous (3 meter) high rate dip coating of our proprietary SanDEA TFA-YBCO deposition method, achieve 1.2 $MA/cm^2$ $J_c$ values on RABiTS, convert 0.75 µm YBCO films (0.5 $MA/cm^2$), and investigate vacuum conversion of TFA-YBCO precursors.
- LANL: We are working with LANL in three areas: (1) deposition of YBCO and buffer layers on their IBAD $LaMnO_3$ and MgO buffer layers, and (2) development of Cu-doped $SrTiO_3$ buffer layers on IBAD substrates, and (3) TEM analysis of YBCO/$SrTiO_3$/NiW conductor interfaces. Solution-derived epitaxial growth has been demoinstrated on LANL ACCI IBAD substrates.

# SPI RELATED RESEARCH SESSION

## Reviewers for SPI Session:

Shirabe Akita, CRIEPI
Mike Ingram, TVA
Julian Cave, IREQ Hydro-Quebec
Steiner Dale, Florida State University – CAPS
Patrick Duggan, Con Edison
Russell Eaton, Consultant
Ed Hahn, New York Power Authority
Shih-Min Hsu, Southern Company
Minwon Park, Korean DAPAS

## Review Projects for the SPI Session:

SPI Readiness Review Program
HTS Transformer: Waukesha/IGC-SuperPower Superconductivity Partnership Initiative Project
Development of Ultra-Efficient HTS Motor Systems
Cost Effective, Open Geometry HTS MRI System
Design and Development of a 100 MVA HTS Generator
High-Temperature Superconducting Power Cable
Development Status of Flywheel Electricity System
Waste Water Treatment with Magnetic Separation
Matrix Fault Curent Limiter: SuperPower, Inc., CRADA

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| **Project Title:** | **SPI Readiness Review Program** |
| **Organization(s):** | **ORNL, LANL, DOE** |
| **Presenters:** | M.J. Gouge (ORNL), S. Ashworth (LANL), P. Bakke (DOE-GO) |
| **FY 2004 Funding:** | $110 K (ORNL), $35 K (LANL) |

**Project Purpose and FY 2004 Objectives:** The purpose of this HTS program initiative is to support the Superconducting Partnership with Industry (SPI) program to help ensure SPI demonstration projects go as planned via a series of phased readiness reviews. The focus is on collaboration with the SPI team to identify potential failure modes; issues involving cryogenic temperatures, vacuum and high voltage dielectrics are a major concern. Expertise is obtained as needed from national laboratories, universities, and consultants. M. J. Gouge (ORNL) and Jim Daley (DOE) provided an overview of the proposed SPI oversight program at the January 2003 DOE Wire Development workshop and the program began in March 2003. The objective for 2004 is to provide at least one review of all active SPI projects. For complex or large-scale projects at transmission level voltages, such as the LIPA cable and SuperPower MFCL project, multiple reviews have been conducted.

**FY 2004 Performance and FY 2005 Plans:** All of the SPI projects will have been through at least one review cycle by August 2004. This phased readiness review program will continue in 2005 and 2006 as the SPI projects precede to final design, fabrication, assembly, and initial commissioning. We are encouraging all the SPI projects to develop risk identification and mitigation processes such as failure mode and effects analysis (FMEA) to manage risks including R&D and prototyping needed to enhance success at full-scale and design levels of voltage/current. Based on continuing issues with the design and performance of dielectric materials at cryogenic temperatures and at high voltage, more emphasis will be placed on R&D and risk mitigation in this area by the grid-based SPI projects. In 2005 a web-site will be implemented that would have lessons-learned from prior SPI projects, some general design guidance on high voltage, vacuum, etc. and a place where SPI participants can post comments or questions and get feedback. A High-Voltage Cryogenic Dielectric Workshop is being considered; it could be held just after the 2005 Wire Development Workshop. Participation by each SPI team facing high voltage component qualification would be expected and the agenda could include some overview talks on liquid nitrogen dielectrics, solid dielectrics, HV design practices, etc.

**FY 2004 Results:** M. J. Gouge (ORNL) and Don Gubser (NRL) participated in a 1-day review of the HTS coil and associated support structure for the 500-mm bore, reciprocating magnetic separator project at DuPont Superconductivity on March 10, 2003. M. J. Gouge (ORNL) and Russ Eaton (DOE) visited Waukesha Electric Systems in June 2003 to review the progress on assembly and cool-down of the 5/10 MVA transformer and to go over the plans for high-current and high-voltage electrical testing given the known issue of low partial discharge inception voltage in the HTS phase sets. M. J. Gouge (ORNL) and several other scientists from LANL, ANL, and CAPS participated in a 1-day technical advisory committee meeting and a 2-day conceptual design review of the HTS Matrix Fault Current Limiter (MFCL) project at SuperPower, Inc., on June 10-12 (this project was subsequently initiated as an SPI project in July). A detailed list of reviewer comments (chits) was assembled by SuperPower that will be tracked through focused development plans and subsequent design reviews. M. J. Gouge (ORNL) and Paul Bakke (DOE) participated in the Conceptual Design Review of the General Electric 7A6 HTS Generator on July 30-31, 2003, and provided technical feedback to GE program management. The MCFL review on October 14-15, 2003, included a report on design progress since the CDR in June, AEP substation study update, cryostat tests and over-current (low voltage) testing of the MFCL tubes at Nexans and matrix mock-up modules in the test cryostat at Florida State University (CAPS). A review of the Flywheel Project was conducted at Boeing facilities in Seattle on October 21-22, 2003. Boeing presented a comprehensive overview of their program, including the work that has been accomplished over the past several years and the future direction of the program. Much of the focus was on reviewing the 3 kW/10 kWh system where component testing resulted in a flywheel failure during spin test. The Open MRI System being developed at Oxford Superconducting Technology was reviewed on November

14, 2003, and Oxford staff provided an update on their trade-off evaluation between bare and sheathed BSCCO 2212 tape conductor. Additionally a team led by Steve Ashworth (LANL) reviewed the LIPA (AMSC/Nexans) and Albany (SuperPower/SEI) HTS cable projects in November-December 2003. A readiness review of the Ultera Cable Project was conducted by this same team on February 10-11, 2004, at Southwire Company, Carrollton, GA. The LIPA cable project 138 kV termination design was reviewed in March 2004. On May 3, 2004, an informal review of design issues was held at GE-CRD and on May 4 a MFCL project meeting of the Technical Advisory Board was held to go over results of high current testing at CAPS. A review of the follow-on HTS motor R&D project will be held at Rockwell Automation in August 2004.

**Research Integration:** Since the reviews contain a large amount of proprietary material, the results and recommendations are typically shared only between the project being reviewed, the reviewers, and DOE. The reviewers, to the extent possible, highlight or flag potential problem areas that they have learned from other project reviews. The web-site and proposed workshop mentioned above will be a way to share generic lessons-learned and design information.

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| **Project Title:** | **HTS Transformer: Waukesha/IGC-SuperPower Superconductivity Partnership Initiative Project** |
| **Organization(s):** | **Oak Ridge National Laboratory** |
| **Presenters:** | S.W. Schwenterly (ORNL), E.F. Pleva (WES), D.W. Hazelton (SP) |
| **FY 2004 Funding:** | $325K DOE to ORNL |

**Project Purpose and FY 2004 Objectives:** The objective of the current Phase II Superconductivity Partnership Initiative (SPI) project with Waukesha Electric Systems (WES), SuperPower, Inc. (SP), and Energy East, is to demonstrate the technical and economic feasibility of HTS transformers of medium (30 MVA) to larger ratings. An alpha-prototype 5/10 MVA, 3-phase, HTS transformer, with primary/secondary voltage ratings of 24.9/4.2 kV and 100-kV BIL has been designed, fabricated, and tested. ORNL's original FY 2004 objectives were to:

- Participate in completion of tests on the 5/10-MVA unit and its installation on the utility grid at the WES plant.
- Critique and provide technical input to the 30-MVA transformer reference design.
- Continue measurements of dielectric, thermal, and mechanical properties of candidate cryogenic electrical insulation materials for transformer design ratings of 30 MVA and above. Topics would include partial discharge, ac and impulse breakdown strength, tan delta, thermal shock resistance, thermal conductivity, and heat capacity.
- Investigate mechanical and electrical compatibility between various components of the insulation system.
- Investigate the incorporation of second-generation YBCO materials into the 30-MVA reference design, including ac loss, over-current capability, and fault current limiting issues.

**FY 2004 Performance and FY 2005 Plans:** Project activities focused on repair and testing of the 5/10-MVA transformer as described below. Various difficulties encountered and the ultimate high-voltage failure of the unit during the factory floor testing prevented the team from making further progress on the 30-MVA reference design. Electrical insulation tests continued on solid materials and epoxies. A new proposal for follow-on work in FY 2005-6 is under discussion. This 2-year interim project will supply further data required for design of the Phase-III prototype commercial 30-MVA transformer. The plan for this project basically continues with the above list of objectives. The 5/10-MVA unit is being disassembled and inspected during the remainder of FY 2004, in order to find the reasons for the failures and determine what material and design improvements are needed for successful operation.

**FY 2004 Results:** Cool-down and testing of the 5/10-MVA HTS transformer during summer of 2003 had shown good operation of the cryogenic system and successful short-circuit operation up to 1.4× rated current. However, heat loads from residual gas leakage and a high-resistance short around phase C limited operation times under high current to several hours. Also, recurrent plugging of the liquid nitrogen (LN) tank vent line had caused difficulties with refill. The unit was untanked for checkout and repair in August 2003. Leak measurements showed that new leaks had developed in the LN connections to the low-voltage (LV) leads. These were repaired with Stycast epoxy. Plugging of the LN tank vent line was traced to pinholes in the burst disc that evidently resulted from a partial inversion during a cool-down pressure excursion. The short circuit around phase C was found to result from contact between the inner radiation shield cylinder and the inner bore of the phase C coil set. A wedge was gently driven into the gap to deflect the shield inward from the coil bore, and G-10 insulation was inserted into the space and secured tightly. All three phases then had low excitation currents. After the transformer was reassembled, global leak checks showed more than an order of magnitude reduction in the LN system leak rate. Cooldown was carried out without incident in late October 2003. During November, the transformer was disconnected from all its utilities, loaded onto a flatbed truck, and transported while still cold about two blocks to the WES main plant for installation on their test floor. Normal temperatures and vacuum were quickly re-established at the new site. Preliminary electrical tests showed that no damage had occurred.

Testing on the transformer resumed in December with three-phase short-circuit tests. The tests done in June 2003 were repeated with 116 A (100% rating), 80 A, and 60 A line current on the HV windings. The coil temperature-time curves in these two tests showed very similar behavior, indicating that the short circuit around Phase C was not the source of the excess heating. A further extensive program of short-circuit testing showed that the transformer could run at 63 A continuously and at 85 A for several hours without overheating, which was adequate performance for installation in the WES substation. A major source of heating was from release of cryopumped nitrogen from the residual leaks when the coil temperatures rose above 40 K. However, the coils also appeared to generate excessive electrical losses, particularly on Phase A, which may have conductor damage. Operation at up to twice the rated operating current was carried out with additional cooling by circulating liquid helium in the auxiliary circuits on the coil cooling shells. The current was held for an hour at values of 74, 105, and 127 A with stable conditions. However, the HTS leads were approaching their maximum safe temperatures. The current was raised to 200 A for about 15 minutes and then to 230 A. After about 3 minutes at 230 A, the coil temperatures started running away even with maximum helium flow, and the power was shut off. The coils still operated properly at 60 A with normal cooling, indicating that no conductor damage had occurred from the over-current tests.

In late March 2004, three-phase open-circuit high-voltage tests were attempted. After about 2 minutes on the third voltage step, with 1368 V on the LV side and 8.2 kV on the HV side, a snap was heard and the voltage collapsed. The power supply fuses were blown and a spike in the tank vacuum was seen. Ratio tests showed that Phase B now had high excitation current. Megger tests at 500 V showed only 1 MΩ between the LV and HV windings, but a high value of 500-1000 MΩ between both windings and ground. Capacitance tests showed high dissipation factors, particularly between the LV windings and ground. However, dc resistance measurements on all windings showed no changes from previous values, indicating that the conductor had not been damaged. During further high-voltage tests on Phases A and C with Phase B shorted, another breakdown occurred during the step between 13 and 15 kV. After this, there was only a 22-Ω resistance between the HV and LV windings. The transformer is being disassembled and inspected for damage.

Materials testing at ORNL included measurements on 1) small samples of Stycast FT with simulated voids to understand the partial discharge inception voltage and signatures as a function of pressure in the void, 2) breakdown and partial discharge of solid filled epoxies for different gaps and volume for information on scaling at large gaps and volumes, and 3) the effect of naturally-occurring voids on breakdown and PD inception. Laboratory data indicates significant decreases in both breakdown strength and PD inception voltage as the gap and volume increases and when defects in the form of voids are present in filled epoxies. Voids were found to occur even when the epoxies are properly de-aired, as a result of shrinkage during the curing process. The cause of failure of the three phases cannot be clearly ascribed to voids until dissection has been accomplished to determine the actual cause of failure. However, previous cold partial discharge testing on the Phase B coils at the WES site appeared to indicate the presence of voids.

**Research Integration:** ORNL team members visited SP and WES on eight occasions to carry out repair and testing on the 5/10-MVA transformer. Several of these visits extended to as much as two-weeks. To provide low-voltage, high-current ac test power independent of the WES production test equipment, ORNL loaned a large, 3-phase variac bank to WES in February. Collaboration within the team continued to proceed smoothly, with each member contributing in its particular area of expertise. Papers and presentations on the 5/10-MVA cooling module design were given at the 2003 CEC/ICMC Conference, and on fabrication and testing of the 5/10-MVA unit at the 2004 IEEE-PES Summer Meeting.

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| **Project Title:** | **Development of Ultra-Efficient HTS Motor Systems** |
| **Organization(s):** | **Rockwell Automation** |
| **Presenters:** | Rich Schiferl |
| **FY 2004 Funding:** | $750 K |

**Project Purpose and FY 2004 Objectives:** The purpose of the project is to perform research in eight areas related to commercial viability of industrial motors with high temperature superconducting (HTS) windings. The eight areas were identified based upon the past work that Rockwell Automation had conducted on development and testing of HTS based motors up to and including the laboratory test of a 1600 hp motor. These research areas and objectives are listed below. Since this is the first year of reporting on this project, the overall project objectives are listed below.

| Research Area | Overall Objective |
|---|---|
| 1. Alternate HTS motor topologies | Investigate designs and verify with test a superconducting induction motor concept and a combination superconducting and permanent magnet motor concept. |
| 2. Alternate HTS wire technology applications | Acquire second generation conductor and coil samples and perform tests to simulate motor requirements. |
| 3. Eddy current heating in air-core, rotating machinery | Complete simulation model and verify with test rig to reduce losses in end regions. |
| 4. Adjustable speed drive integration / harmonic shielding for HTS motors | Complete simulation models and verify with comparison to HTS motor test data. |
| 5. On-board refrigeration system development | Conduct research to verify viability of on-board cryogenic system (on the rotor). |
| 6. Coil quench protection system development | Analyze quench event from 1000 hp motor and develop reliable quench monitoring and protection system for HTS motors. |
| 7. Composite torque tube advancement | Investigate the creep and fatigue phenomena associated with composite torque tubes in large scale HTS motors. |
| 8. Cryogenic persistent switch investigation for HTS field windings | Verify feasibility of using cryogenic persistent switch in HTS motors. |

**FY 2004 Performance, FY04 Results and FY 2005 Plans by research area:** Progress has been made in each of the research areas identified above. Below is a summary of the results and next year's plans.

**1. Alternate HTS motor topologies**

| FY04 Performance | FY04 Results | FY05 Plans |
|---|---|---|
| • Evaluated superconducting induction motor (SCIM) literature and potential options for open circuiting an HTS film. | • Initial model and thin film construction results showed SCIM construction will be problematic. | • Investigate alternate methods to open circuit HTS coils or films. Issue report on studies and tests. |
| • Literature search on permanent magnet (PM) performance at cryogenic temperatures. | • Some exotic PM materials retain performance at cryogenic temperatures. Tests on a common material showed 20% reduction in flux at cryogenic temperatures. | • Perform design study trade-off for PM vs. HTS content and issue report. |

**2. Alternate HTS wire technology applications**

| FY04 Performance | FY04 Results | FY05 Plans |
|---|---|---|
| • Provided wire and coil performance specifications for small HTS motor to 2nd gen wire vendor. | • Initial design of small HTS motor using 2nd Gen coils | • Build and test 2nd Gen HTS coil for motor application studies. |

**3. Eddy current heating in air-core, rotating machinery**

| FY04 Performance | FY04 Results | FY05 Plans |
|---|---|---|
| • Completed modeling of end region. Built test rig and verified performance with tests. | • Tests and models showed increased loss is a strong function of the location of the HTS field poles with respect to the end of the stator core. | • Complete report on tests and model verification. |

**4. Adjustable speed drive integration/harmonic shielding for HTS motors**

| FY04 Performance | FY04 Results | FY05 Plans |
|---|---|---|
| • Developed simulation model of HTS motor with medium voltage drive. | • Simulation completed and results compared to HTS motor test data. | • Verify simulation model with controlled test of HTS/motor and drive system. |

**5. On-board refrigeration system development**

| FY04 Performance | FY04 Results | FY05 Plans |
|---|---|---|
| • Evaluated cryocooler options and selected model for test rig. | • Purchase order placed for pulse tube refrigerator. CRADA with NIST under negotiation | • Complete system model with CRADA work. Build and test rotating cryocooler system. |

**6. Coil quench protection system development**

| FY04 Performance | FY04 Results | FY05 Plans |
|---|---|---|
| • Evaluate quench event and investigate quench prevention / protection options | • Quench event data reviewed and report written. | • Quench model development and choose best prevention option. Demonstrate solution and perform rotating exciter tests. |

**7. Composite torque tube advancement**

| FY04 Performance | FY04 Results | FY05 Plans |
|---|---|---|
| • Develop creep test method. | • Creep test rig designed and built for single sample. Tests initiated. | • Complete creep tests on multiple samples. Issue report on fatigue test needs. |

**8. Cryogenic persistent switch investigation for HTS field windings**

| FY04 Performance | FY04 Results | FY05 Plans |
|---|---|---|
| • Review switch options and characterize performance at cryogenic temperature. | • Electronic switch selected and some preliminary test data obtained. | • Complete test of persistent switch with HTS coil to prove performance. |

**Research Integration:** Modeling of the performance of a pulse tube refrigerator in a high-g environment will be conducted through a CRADA agreement between Rockwell Automation and NIST. Modeling results will be compared to test data.

| Project Title: | Cost Effective, Open Geometry HTS MRI System |
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| **Organization(s):** | **Oxford Instruments, Superconducting Technology** |
| **Presenters:** | K. Marken, G. Gilgrass (OMT) and T. Holesinger (LANL) |
| **FY 2004 Funding:** | $550 K (DOE), $550 K (Industry), $200 K (LANL), $200 K (NREL) |

**Project Purpose and FY 2004 Objectives:** The purpose of this Phase II Superconductivity Partnership Initiative project is to build and operate a prototype Magnetic Resonance Imaging (MRI) system using HTS coils wound from low-cost, dip-coated BSCCO 2212 tape conductor. The planned milestones for FY 2004 were: (1) complete precursor powder manufacturing upgrades; (2) complete prototype conductor processing line; (3) begin conductor fabrication (4) complete design of cryogenics system and magnet.

**FY 2004 Performance and FY 2005 Plans:** FY2004 Performance includes: (1) Precursor powder cost reduction and performance studies were completed. Powder process facility upgrades were completed, and powder manufacturing is underway. (2) Conductor configuration was selected, and prototype conductor processing line was completed, including coating, sheathing and heat treatment. (3) Conductor qualification is underway, conductor manufacturing to begin in August. (4) Magnet and cryogenic modeling and design work has continued with completion scheduled for September.

The project was formally amended in August of 2003 to extend the period of performance one year, with no budget increase. The new project completion date is May 2006. There has been no delay in the revised schedule.

For FY 2005 plans include (1) Complete manufacture of powder. (2) Complete manufacture of tape. (3) Complete magnet and cryogenics system manufacture and test.

**FY 2004 Results:** Substantial improvements were demonstrated in precursor powder processing, and these were incorporated in a scaled up manufacturing line. This progress includes advances in precursor materials, precipitation line, calcine furnace, milling and characterization tools. Present powders have both 60% lower costs and 30% higher critical current performance (>3500 A/mm$^2$ at 4.2K, self field) than previous powders.

Three conductor configurations were compared, and a decision regarding conductor type was made in February. The conductor will be sheathed dip coated tape, between 20 and 25 mm wide, batch heat treated. This decision dictated the need for a larger furnace to accommodate minimum batch size of 500 m tape; a furnace was purchased and put into operation in June. This decision also dictated the need to scale up the sheathing line, and the reworked line was put into service in June. The coating line was rebuilt to accommodate wider tapes (up to 25 mm) and longer lengths (up to several km), and has shown excellent thickness control over hundreds of meters. Our partners at NREL demonstrated a 30% increase in Jc values obtained in short samples by addition of nanoparticle MgO, and trials with long lengths using this method are underway at OST. Our partners at LANL provided substantial characterization support during this period, including $I_c$ testing as a function of temperature and field, powder characterization and optimization, and extensive microstructural work. Under subcontract, the Electromagnetic Technology Division at NIST has provided detailed measurements of critical current as a function of temperature, field, and angle with respect to field. These data are being used to refine the magnet design.

Design work has continued for the cryogenic systems and magnet.

**Research Integration:** This SPI team includes three industrial development partners (Oxford Superconducting Technology, SCI Engineered Materials, Oxford Magnet Technology), an industrial end user (Siemens Medical Solutions), and two national laboratories (LANL and NREL). This partnership vertically integrates a range of expertise and experience including powder synthesis, conductor design and fabrication, magnet and cryogenics design and manufacture, MRI imaging and analysis, and a broad range of analytical and characterization tools at the DOE Labs that complement the project objectives and activities. In addition this year we have partnered with the Electromagnetics Technology group at NIST for more extensive critical current characterization.

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| **Project Title:** | **Design and Development of a 100 MVA HTS Generator** |
| **Organization(s):** | **Oak Ridge and Los Alamos National Laboratories** |
| **Presenters:** | J. Fogarty (GE), R. Duckworth (ORNL), J. Waynert (LANL) |
| **FY 2004 Funding:** | $325 K (ORNL), $330 K (LANL) |

**Project Purpose and FY 2004 Objectives:** General Electric's Global Research in Niskayuna, N.Y., will design and develop a 100 MVA class high-temperature superconducting (HTS) generator, with designs through 250 MVA. The HTS rotor will be capable of retrofitting into existing generators. ORNL and LANL have entered into CRADAs with GE to provide assistance in several technology areas.

For FY 2004 ORNL will: complete measurements of total hemispherical emissivity of specified surfaces at temperatures between 30 K and 40 K with and without controlled surface contamination; measure transient behavior of short conductor samples in support of modeling of the HTS rotor coil; measure turn-to-turn impulse breakdown strength of candidate insulation materials at 77/300 K; perform accelerated pulsed aging tests on the selected insulation at 77/300 K; measure partial discharge initiation voltage (PDIV) for composite samples at 77/300 K.

For FY 2004 LANL will: continue characterizing the room temperature outgassing properties of materials supplied by GE; evaluate the impact of low temperature bakeout of composite materials on outgassing; provide list of possible getter materials; provide prescription for long-term vacuum maintenance; enhance thermal model for rotating heat pipe cooling and assemble experimental apparatus to verify model predictions; develop thermal model for passively pumped single-phase helium cooling loop; and model and measure thermal impact of over-currents in GE-provided HTS coil to predict temperature rise in rotor coil during over-current faults.

**FY 2004 Performance/FY 2005 Plans:** For FY 2004, ORNL measured the emissivity of silver-plated copper shield samples and hand-polished copper shield samples at 30 K. Evaluated emissivity degradation of surfaces with respect to air and water contamination. Conducted preliminary measurements of outgassing of rotor material and its impact on emissivity. Completed modifications to an existing apparatus and conducted preliminary measurements to characterize the transition of HTS conductors down to 30 K and in dc fields up to 4 T. Conducted measurements of turn-to-turn impulse breakdown dielectric strength for two candidate types of superconducting wire insulation at ambient and liquid nitrogen temperatures and completed PDIV measurements and accelerated pulsed aging tests on the candidate insulation at ambient temperature, and initiated experiments at liquid nitrogen temperature.

For FY 2004, LANL has developed an outgassing model incorporating readsorption; measured outgassing properties of 11 different materials requiring over 90 outgassing experiments; modeled and measured the impact of vacuum bakeout temperature and duration on outgassing of fiberglass composites; published a paper presenting the prescription for long-term vacuum maintenance; developed a complete thermal model of heat pipe performance as a function of rotation rate; designed and fabricated all the parts for a room temperature, rotating heat pipe apparatus to verify thermal model predictions; apparatus is partially assembled awaiting final heat pipe; developed a heat pipe wick that could maintain shape integrity through bending of the heat pipe; assembled and tested full-scale straight and bent heat pipes; assembled test rig with cryocooler and HTS coil from GE for measuring temperature rise during over-current fault.

**ORNL Plans for FY 2005**

1) Complete measurements of the total hemispherical emissivity of specified surfaces at temperatures between 20-40 K including surface contamination, whether it originates from a direct leak or outgassing of rotor materials placed in the vacuum space. Submit final report.
2) Complete measurement of transient composite tape resistances at different over-currents and applied dc fields up to 4 T. Submit final report.
3) Measure ac PDIV as a function of temperature for composite samples with voids. Submit final report.

4) Assist GE with design and testing of the HTS coil quench protection system.

**LANL Plans for FY 2005**

1) Extend CRADA with GE.
2) Continue outgassing and bakeout measurements as needed by GE and provide summary reports.
3) Complete rotating heat pipe experiments, update model as required. Submit final report.
4) Modify rotating heat pipe apparatus for passively pumped cooling loop. Complete passively pumped cooling loop experiments and compare to thermal model predictions. Submit final report.
5) Complete analysis of impact of $2^{nd}$ generation HTS conductor on GE rotor. Submit final report.

**FY 2004 Results:**

Significant progress has been made at ORNL during the year.

**Emissivity test rig** - Emissivities have been measured for silver-plated and bare copper shield samples between 25 K and 35 K. The impact of water and air contamination on emissivity has been completed for silver-plated copper samples and a follow-on study was conducted to correlate water contamination from leaks and materials in the rotor vacuum insulation that could impact the total refrigeration heat load.

**Dielectric testing** - Measurements of the turn-to-turn dielectric strength with respect to the impulse breakdown voltage were completed for two candidate types of superconducting wire insulation at ambient and liquid nitrogen temperatures. Accelerated pulsed aging tests and PDIV measurements on the selected wire insulation system were completed at ambient temperature and initiated at liquid nitrogen temperature. At ambient temperature the slope of the lifetime aging curve was found to decrease at a lower voltage which indicates a change in the aging mechanism(s). Further work will determine if different aging mechanisms are also found for the case of cryogenic temperatures and whether the rate of aging will decrease significantly when the tape samples are cooled to liquid nitrogen temperature.

Significant progress has been made at LANL during the year.

**Outgassing and bakeout measurements** - Models have been developed to facilitate understanding of performance; 11 different materials have been characterized, requiring over 90 different experiments.

**Heat pipe and passive cooling loop** - A detailed thermal model has been developed for both the heat pipe and the passively cooled single-phase helium loop; a room temperature experiment has been designed and fabricated. Assembly is awaiting the full scale heat pipe. A wick structure has been developed to maintain the geometric integrity of the wick after the heat pipe has been bent into the crank shape; straight and bent heat pipes have been assembled and tested.

**HTS coil over-current measurement** - HTS coil from GE has been instrumented and mounted in contact with a cryocooler. Preliminary measurements of temperature rise versus over-current have been made.

**Research Integration:** ORNL and LANL have regular teleconferences with GE staff to ensure that R&D objectives, efforts, and results are in accord with project objectives. The results are reviewed by GE staff. One technical poster on the emissivity measurements was presented at the *Cryogenic Engineering Conference* in September 2003. In addition, the exchange of information between ORNL and LANL has led to productive discussions with GE on the role of materials in the rotor vacuum space. ORNL will present papers on the high voltage tape insulation test configuration and results from generic insulation materials at the 2004 *Applied Superconductivity Conference* and the 2004 *Conference on Electrical Insulation and Dielectric Phenomena*. LANL has published the long-term vacuum maintenance prescription in *Advances in Cryogenic Engineering* and the details of the thermal model of the rotating heat pipe model will be presented at the 2004 ASME *Heat Transfer/Fluids Engineering Summer Conference.*

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| **Project Title:** | **Development Status of Flywheel Electricity System** |
| **Organization(s):** | **Boeing/Argonne National Laboratory** |
| **Presenters:** | Mike Strasik (Boeing) |
| **FY 2004 Funding:** | $367 K (Boeing)/($0 K) ANL |

**Project Purpose and FY 2004 Objectives:** The main purpose of this effort is to develop a 10-kWh flywheel energy system based on high-temperature superconducting (HTS) bearings. The first unit developed had a 3-kW motor/generator (M/G). The second unit developed has a 100-kW M/G. This effort started in FY1999. Due to DOE's funding limitations this year, the Boeing project received significantly lower funding than planned, and ANL didn't get any DOE funding at all. Specific objectives for FY 2004 were to complete the manufacturing of all components for the 100 kW/5 kWh UPS flywheel system, test all individual components at full speed, assemble the system, and fully test the UPS flywheel system at Boeing site with technical assistance from Southern California Edison's test personnel.

**FY 2004 Performance and FY 2005 Plans:** Due to funding limitations, limited progress was made in the FY 2004 objectives. All components of the 100 kW / 5 kWh flywheel UPS system were manufactured and also successfully tested up to 102% of the operating speed. The major accomplishment of this year was the successful spin-test verification of the redesigned aluminum hub/composite flywheel rotor. This fully verified the new Boeing hub/rotor design and modeling tools for predicting static and dynamic performance of the system. In addition, the Boeing flywheel test facility has undergone a major upgrade with the addition of two new larger air turbines to allow spin-testing of heavier components at higher speed. A larger air compressor became necessary to run the larger air turbines and was also acquired. The Boeing South Park Facility has been upgraded with dedicated 480 VAC, 200 Amp, 3-Phase power system for Flywheel testing, as well as a separate 480 VAC 30 Amp, 3-phase power system for voltage sag testing. The designs of the 480 VAC systems were in accordance with Southern California Edison recommendations for power quality testing of the 5 kWh / 100 kW flywheel UPS system. All modifications were inspected by the Sate of Washington and were certified for spin testing. All the facility modifications and upgrades (> $400K) were paid for by the Boeing Company. This additional capability at Boeing will result in substantial economical and logistical benefits to the program since we don't have to send hardware and personnel for spin testing at various facilities. Additionally, the Boeing flywheel spin-test facility will be one of the largest of this type in the U.S.

**FY 2004 Results:** Key results from the FY 2004 program are summarized below.

1) All components of the 100 kW / 5 kWh Flywheel UPS systems were manufactured.
2) All flywheel components were spin tested up to 102% of the operating speed (22,900 rpm).
3) The redesigned metal Hub/Composite Rim assembly was balanced and quill tested to 22,900 RPM (102% MEOS) and soaked for 15 minutes and thus met acceptance testing criteria per ANSI Space Flywheel Standard ANSI/AIAA S-096-200X.
4) Stainless steel cryostat for HTS stability bearing was manufactured, sealed, and tested at liquid nitrogen temperatures with no leaks on first seal attempt.
5) The cryogenic system including thermosyphon, GM cryocooler, and bearing cryostat was assembled and tested.
6) All control and monitoring systems for the flywheel system were assembled and successfully tested.
7) Electrical systems from Ballard Power Systems (BPS) and Ashman Technologies have been installed. These include the Motor Controller unit and the Utility Interface Unit.
8) The emergency dump load required to spin the system down in the event of an inverter system failure has been delivered.
9) The load bank required to support Southern California Edison utility testing has been selected and ordered.
10) The SAG generator electrical interface to the facilities electrical system was completed.

11) A separate test cell for spin test qualification was built within the Boeing test pit to provide in-house balancing and spin-testing of components

**FY 2005 Plans:** FY 2005 is the last year of the present SPI project. The 100 kW / 5 kWh UPS flywheel system will be assembled and fully tested by Boeing. Operational characteristics of the UPS system such as critical frequencies, vibration, rotational losses, power output, power quality, peak power capabilities, charge and discharge time, cryocooler performance, and vacuum level will be monitored and analyzed. Flywheel system will also be tested by Southern California Edison's Test personnel to verify power quality, sag, and performance characteristics required by a UPS system. A new task to design, build, and spin test 10 kWh composite wheel with the redesigned metal hub will be added to the FY 2005 project.

In FY 2005, ANL will (1) provide general consultation on overall testing of the system and components, based on ANL's previous experience with these types of devices; (2) participate in experimental tests of flywheel systems at Boeing; (3) provide thermal analysis to predict temperature development in the flywheel under different conditions; and (4) perform small-scale experiments toward developing a lower-cost, direct cooling system for the HTS bearing.

**Research Integration:** Boeing and its industrial partners, Praxair, Southern California Edison, Ashman Technologies, and Ballard Power Systems are very actively engaged in frequent phone teleconferences, on-site visits for testing, test planning, design, and progress reviews. Boeing Flywheel Organization is an active member of the Flywheel Rotor Safety and Longevity working group and is continuing to contribute to the ANSI Flywheel Standard, heading up the rotor NDE section. Boeing recently hosted this group's meeting at Boeing Flywheel Facility. Our successful working relationship with ANL has started in 1988 and has continued since. ANL serves in the role of general consultation on this SPI project. Boeing has already incorporated much of the ANL experience into the design process in the continuing development of the unique Boeing design. This research integration is expected to continue and will be useful in the design phase of the next generation flywheel as well. ANL has participated in design reviews and several lengthy experimental series at Boeing. Phone and Email exchanges have been made on a frequent basis on various features of the flywheel design. Boeing-made HTS samples have been sent to ANL for evaluation. Several papers with joint authorship have been published. It is expected that this level of exchange will continue throughout this project and the Phase-3 SPI.

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| **Project Title:** | **High-Temperature Superconducting Power Cable** |
| **Organization(s):** | **Oak Ridge National Laboratory** |
| **Presenters:** | David Lindsay (Southwire Co.), Jonathan Demko (ORNL) |
| **FY 2004 Funding:** | $1.7 million (DOE to ORNL) |

**Project Purpose and FY 2004 Objectives:** Southwire Company and ORNL have jointly developed, built, and demonstrated a series of cold-dielectric, high-temperature superconducting (HTS) power cables for this Superconductivity Partnership Initiative (SPI) project. The 30-m cable at Southwire's wire-manufacturing complex in Carrollton, GA, continues to run, accumulating over 26,000 hours at full load to date and running unattended over the last 36 months. This cable is rated at 12.4-kV, 1,250-A, 3-phase, 60-Hz, and 27-MVA. This cold dielectric cable was placed into full service in April 2000 for an extended testing period under actual industrial conditions. In a new cold dielectric cable concept called a tri-axial cable, ORNL has in 2004 worked with Southwire Company to research and improve the overall design and capabilities of the HTS cable system including:

- Design triaxial cable terminations for the 5-m tri-axial, 3-phase, 3,000 $A_{rms}$ cable to be tested at ORNL. This 5-m cable system is a prototype of the 200-m system to be installed at AEP.
- Fabrication and testing of a 1.5-m single-phase cable to evaluate a copper-clad HTS tape architecture, and a 3-m tri-axial cable made with brass-clad HTS tapes to study over-current response and heat transfer characteristics.
- Continued development and testing of cryogenic dielectric material including model cables and terminations. Tested cast and solid dielectric materials for high voltage strength, partial discharge, and thermal shock.
- Developing a cryogenic system specification for the American Electric Power (AEP) project. Estimates of the heat loads, operating pressure, temperature, and flow rate of liquid nitrogen are being prepared.
- Initial design of cable subsystems for a long-length cable installation at Columbus, OH, in partnership with Ultera and AEP.
- Continued research improving cryogenic system performance with industry.

**FY 2004 Performance and FY 2005 Plans:** The design of the 5-m tri-axial 3000 $A_{rms}$ cable and associated 3-phase terminations is being completed in summer of 2004. The 3-phase cable will be manufactured by Ultera (Southwire) and expected delivery to ORNL is in September 2004. Final assembly of the terminations, initial cooldown, and initial dc/ac testing will take place during the first quarter of FY 2005. The Southwire team participated in a successful SPI Readiness Review in February 2004. The issues identified by the independent review team are being addressed. The issue of cryostat performance and reliability is being worked with vendors.

**Plans for FY 2005:**

1) Complete electrical testing including high voltage qualification of the 5-m tri-axial, 3-phase, 3,000 $A_{rms}$ cable and terminations at ORNL.
2) Test model cables and terminations to higher ac voltages (up to 69 kV), investigate AC breakdown strength and partial discharge inception and examine scaling to higher BIL levels, and continue development and testing of improved dielectric tapes for use at higher voltages.
3) Complete design of the long length cable demo at AEP Columbus and begin long lead procurements.

**FY 2004 Results:** Significant progress has been made towards the project objectives during the year:

**30-m HTS Cable** - In April 2000, the cable was placed into extended service and has logged over 26,000 hours of full power operation since that time. The performance of the superconductor was measured annually since April 2001, most recently in June 2004. There has been no measurable change in the critical current of the superconductor providing further credence to the viability of this promising technology. There have been several cable outages due to the cryogenic system and this experience is being used in specifying technical requirements for the SPI cable project at the AEP Bixby substation.

**Cryogenic Dielectric Studies** - An aging mechanism of cryogenic cable dielectrics, partial discharge (PD), is being studied using a state-of-the art PD detection system. Several new insulation tape materials have been formulated with the goal of optimizing mechanical and electrical characteristics. Development was conducted on potential materials for the dielectric insulation in the 3-phase terminations that require high breakdown strength and high thermal conductivity at 77 K and 300 K. The development of cast dielectrics for use in cable auxiliaries was stopped due to technical difficulties with material properties and consistency. However significant information was gained on the area and volume effects for scaling solid dielectric materials to large-scale devices at room and liquid nitrogen temperature. A new focus on the use of solid dielectrics for use in these auxiliaries was implemented. For the new termination design, data has been obtained on flashover impulse strength and on partial discharge inception. A revised design using cryogenic-compatible solid dielectrics was implemented.

**Tri-axial Cable** - The tri-axial cable consists of three concentric superconducting phases made of BSCCO-2223 HTS tapes that are separated by layers of Cryoflex™ cold-dielectric tape, which provides the phase-to-phase electrical insulation. Copper tapes are placed next to the HTS tape for over-current protection. A copper braid is added as the grounding shield. The completed tri-axial cable is enclosed in a flexible cryostat and has circulating liquid nitrogen cooling the outside of the cable. In 2003 ORNL and Southwire started R&D on a compact, 3-phase termination rated for 3 $kA_{rms}$ per phase that will be a full-scale prototype of the cable to be installed at the AEP Bixby substation under the SPI program. Due to issues with cast and filled dielectric materials, a new design approach has been adopted using manufactured pieces in a larger cryostat. This higher capacity cable will include a comprehensive high current test program similar to the one conducted on the 1.3 kA cable, but expanded to include high voltage characterization. The cryogenic skid used for testing 5-m cables at ORNL has been upgraded to handle higher heat loads. This is necessary for testing triaxial cables as the refrigeration load is now for three phases.

**Short Sample Cables** - A 3-m-long tri-axial HTS cable made using brass-clad BSCCO HTS tape was fabricated and tested to evaluate the ac loss and overcurrent performance. In addition, a 1.5-m single-phase cable was wound with copper-clad HTS tapes. High voltage dielectric tape was applied to evaluate the ac loss, overcurrent and heat transfer characteristics of a simulated triaxial cable. A measurement of the thermal conductivity of Cryoflex dielectric in an open liquid nitrogen bath was also conducted.

**Second Generation Conductor Cable** - A 1.25-m-long cable was fabricated last year from second generation YBCO coated conductor. The dc performance and ac loss was measured on the second generation conductor cable. Over-current (thermal and E-M force effects) testing of second generation YBCO tapes was conducted. Investigations into the inductance of HTS cables with and without magnetic substrates are being evaluated in short cable sections.

**Research Integration:** The design, assembly, and operation of the cable test facilities at ORNL and the 30-m demonstration cable at Southwire have been totally integrated efforts drawing upon scientists, engineers, and technicians from Southwire, NKT, ORNL, and private industry. Private consultants, cryogenic equipment manufacturing firms, and superconducting materials suppliers have been used extensively during the project. Major components of the 5-m and 30-m cable systems were procured via competitive subcontracts. Four technical papers were presented at the *Cryogenic Engineering Conference* in September 2003. Four HTS cable technical papers are planned for the *Applied Superconductivity Conference* to be held in October 2004.

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| **Project Title:** | **Waste Water Treatment with Magnetic Separation** |
| **Organization(s):** | **Los Alamos National Laboratory** |
| **Presenters:** | Joe Waynert (LANL), Jon Bernard (DuPont/LANL) |
| **FY 2004 Funding:** | $60 K (DOE to LANL); $150k (DuPont to LANL; funds-in);<br>$100 K (DuPont matching funds) |

**Project Purpose and FY 2004 Objectives: Project Purpose and FY 2003 Objectives:** DuPont is leading the SPI development of a 500 mm HTS reciprocating magnetic separator. An HTS magnetic separator offers significant operational energy savings compared to conventional copper coil separators. The DuPont business plan calls for the development of new applications of magnetic separation that can benefit from the energy efficiency. DuPont and LANL established a CRADA in FY03 that capitalizes on LANL's experience in magnetic separation. DuPont has stationed a full-time employee, Jon Bernard, at the Los Alamos Research Park. After jointly assessing several potential market opportunities, DuPont and LANL agreed to focus on the removal of heavy metals in wastewater using high gradient magnetic separation (HGMS). LANL will work with DuPont to develop an in-situ ferrite formation process that incorporates the heavy metals in a ferrite crystal lattice. The ferrites, having a high magnetic susceptibility, are then readily removed as they pass near a magnetized matrix material.

The objectives for FY 2004 were to determine the controlling parameters and their associated ranges for the ferrite process; optimize the ferrite and HGMS processes for the pilot plant application (Leadville, CO); determine the scaling issues in transitioning from the laboratory to the pilot plant operations; and establish a pilot plant location that allows for testing and demonstration.

**FY 2004 Performance/FY 2005 Plans:** In FY 2004 LANL and DuPont performed over 100 separate experiments investigating the effects of magnetic field strength, superficial velocity, matrix fiber diameter, reaction time, bubbling air impact on reaction, varying seed to iron (II) ratio, matrix packing density, and matrix column length. Reasonable ranges of operation to maximize the amount of material captured before breakthrough have been determined. An agreement has been established to locate a 10 gallon per minute pilot plant at the Leadville Mine Drainage Treatment facility in Colorado. Scaling issues in transitioning from the laboratory to the 10 gpm plant have been identified. Conceptual designs are being developed.

LANL plans for FY 2005

1) Either extend the CRADA with DuPont or find another company to support the development of the HTS HGMS.
2) Design, fabricate, assemble, and verify operational capability of the HGMS pilot plant system at LANL before transporting the system to Leadville.

**FY 2004 Results:** Significant progress has been made at LANL during the year. In the past fiscal year, we demonstrated by benchtop chemistry that a magnetic product of suitable quality and magnetic response can be formed at 6$^{o}$C, the water temperature at Leadville. We have confirmed the magnetic product is stable enough for long term storage and will pass standard EPA heavy metal leaching tests. Using HGMS test facility at Los Alamos Research Park, we have optimized magnetic separation conditions, such as flow rates, matrix material, breakthrough volume, … and developed a detailed process for magnetic separation considering issues related to scale-up of the process. We have established a location that allows testing of a pilot plant magnetic separator.

**Research Integration:** LANL and DuPont have regular teleconferences to ensure that R&D objectives, efforts, and results are in accord with project objectives. The results are reviewed by DuPont staff. Information and techniques are regularly exchanged between DuPont and LANL. As a full time DuPont employee, Jon Bernard participates in weekly LANL magnetic separation team meetings. A partnership between LANL, Leadville Institute of Science and Technology and the Bureau of Reclamation has been established to promote and evaluate the HGMS system in the Leadville Mine Drainage Treatment plant.

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| **Project Title:** | **Matrix Fault Current Limiter: SuperPower, Inc., CRADA** |
| **Organization(s):** | **Oak Ridge National Laboratory, Los Alamos National Laboratory** |
| **Presenters:** | L. Kovalsky (SuperPower), J. Bock (Nexans), S.W. Schwenterly (ORNL) |
| **FY 2004 Funding:** | $115 K (DOE to ORNL), $20 K (DOE to LANL) |

**Project Purpose and FY 2004 Objectives:** The purpose of this project is to conduct R&D on specified components and provide technical design support to a SuperPower, Inc. (SP) team developing high temperature superconducting (HTS) technology for a Matrix Fault Current Limiter (MFCL). This device incorporates a series-parallel array of bulk HTS elements and inductors in a subcooled liquid nitrogen (LN) bath. Transition of the HTS elements into the normal state during a fault drives most of the current into the inductors and leads to a sudden increase in impedance that limits the fault current. ORNL's FY 2004 objectives are to:

- Assist with cryogenic subsystem R&D, design, fabrication, and testing
- Assist with high voltage subsystem R&D, design, fabrication, and testing
- Participate in conceptual and detailed design reviews
- Guide commercialization by participation on the Technical Advisory Board

**FY 2004 Performance and FY 2005 Plans:** The MFCL Project is broken into three major tasks, the Pre-Prototype/Alpha Prototype, Beta Prototype, and the Beta Field Evaluation. The pre-prototype is single phase and is rated at 8 kV/800 Arms. The Alpha prototype is single phase rated at 138 kV, with a current rating to be determined by the target application. The Beta prototype is a full 138kV three-phase system that will meet the entire host utility's requirements. The Pre-Prototype/Alpha Prototype development task runs for approximately 2.5 years. The Beta unit will be designed to meet a specific utility application requirement, and will be tested on the transmission grid at a utility host site to be determined. During FY 2004, ORNL carried out tests to simulate SP's cooling concept in an existing cryostat. ORNL personnel attended all project review and Technical Advisory Board meetings. In the summer of 2004, the cryostat will be modified to accept a SP-provided bushing for combined cooling and high-voltage tests in late FY 2004 and in FY 2005. Material testing will also be carried out on samples provided by SP.

**FY 2004 Results:** Preliminary cooling tests in sub-cooled LN were performed using an existing pressure cryostat. Liquid nitrogen at 77 K and 1 atm was circulated through a coil of copper tubing at the bottom of a bath of pressurized supercritical nitrogen. This coil simulates the cooling ring that is attached to the cryocooler in SP's design. Foam discs were placed above the coil to simulate the vacuum above the pressurized tank that would surround the MFCL array. A disc heater mounted below the coil simulated the array heat load. Two temperature sensors were mounted above and below a G-10 plate attached just above the coil. Initial tests at 3 atm and 5 atm supercritical nitrogen pressures indicated that the lower sensor (which is closer to the heater) stayed about 2 K warmer than the one above the plate for power inputs up to 300 W. Good temperature stability was obtained with no venting from the pressurized bath. Further tests were run with more sensors in this cryostat to give a more detailed temperature profile. A copper plate replaced the original G-10 plate. At power levels up to 300 W, temperatures were maintained between 83 K and 86 K below the copper plate, and ranged up to 93 K in the bath above the plate. A new cover flange has been made for this cryostat, to accept a 52-kV bushing that will be provided by SP. This bushing will have a high-current lead similar to that of the Pre-Prototype MFCL unit, allowing a realistic simulation of conditions in the MFCL cryostat. A CRADA between ORNL and SP is in the final stages of development and is expected to be approved by July 2004.

**Research Integration:** ORNL team members attended project review meetings in October 2003 and May 2004. Frequent contact was maintained with SP personnel by telephone and E-mail. Because the current collaboration between ORNL and SP is informal with limited budget, SP has supplied some of the hardware for the cryostat modifications.

# STRATEGIC RESEARCH SESSION

Reviewers for the Strategic Research Panel:

Michael Cima, MIT
Paul Grant, Consultant
Don Gubser, NRL
Fred Lange, University of California-Santa Barbara
Bill McCallum, Iowa State University
Siu-Wai Chan, Columbia University
David Norton, University of Florida
Bruce Strauss, DOE, Office of Science
Judy Wu, University of Kansas

Review Projects for the Strategic Research Panel:

Strategic Research on IBAD MgO-Based Coated Conductors
Wire Development Group: Improving the Understanding and Performance of HTS Wire.
AC Loss Studies in Coated Conductors
ORNL-American Superconductor Strategic Research
Phase Relations of High $T_c$ Superconductors
RABiTS-Based Strategic Research
Understanding and Improving Pinning in Coated Conductors
Development of High $I_c$ Ex Situ Processed RBCO Coated Conductors
Nucleation and Growth of YBCO by the $BaF_2$ Process and AC Losses of YBCO Films

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| **Project Title:** | **Strategic Research on IBAD MgO-Based Coated Conductors** |
| **Organization(s):** | **Los Alamos National Laboratory** |
| **Presenters:** | Paul Arendt, Steve Foltyn |
| **FY 2004 Funding:** | $1.4 M |

**Project Purpose and FY 2004 Objectives:** This project is the Core Research part of the Los Alamos effort to improve both the performance of and commercial prospects for coated conductors based on ion-beam-assisted deposition of MgO (IBAD MgO) and pulsed-laser deposition (PLD) of YBCO. The objective is to conduct research focused on improving the performance ($J_c$, $I_c$) and/or reducing the cost of this conductor approach, in line with the overall DOE goal of minimizing cost/performance (C/P).

IBAD MgO offers several benefits in the production of coated conductors: The ion-beam assisted layer itself is very thin and can be deposited at high rate, resulting in excellent texture at a low cost; the total thickness of non-superconducting layers is also minimal, reducing "overhead" in the IBAD MgO architecture; and, finally, both texture and $J_c$ of the YBCO layer are approaching the level obtained on single-crystal substrates, maximizing $I_c$ through the full range of superconductor thickness.

Last year we reported several important developments. These included texture improvements resulting in IBAD/YBCO $J_c$ levels that are equivalent to those on single-crystal substrates, initial analysis of the roles of barrier and buffer layers, replacement of $SrRuO_3$ with $SrTiO_3$ for the PLD buffer layer, observation of the role of substrate smoothness in facilitating the deposition of high-$I_c$ thick films, and continuous processing of cm-wide tapes with $I_c$ values of 265-425 A.

For this year we made a major change in the Core Program, reducing our effort in the continuous processing of meter-long tapes, and focusing on more basic and long-range issues aimed at reducing C/P of IBAD-based coated conductors. These issues include: process modeling to further refine and facilitate the transfer of IBAD MgO to industry; analysis of extended I-V curves to determine whether IBAD samples are likely to benefit from additional texture improvements; addressing the question of intrinsic vs. materials limitations to conductor $I_c$; modifications aimed at improving REBCO performance in a magnetic field; and continued cost reduction efforts for barrier and buffer layers.

**FY 2004 Performance and FY 2005 Plans:** Substantial progress was made on each FY 2004 objective. An IBAD texturing model has resulted from ion-channeling and damage experiments on MgO single crystals. Extended I-V curves of YBCO-on-IBAD MgO samples established a texture range for the onset of strongly-coupled behavior. Process optimization allowed us to reproducibly meet our goal of $I_c > 400$ A at a YBCO thickness of $\leq 1.5$ μm. We also found several ways to improve the field-dependence of coated conductors. And finally we developed a method to systematically analyze the effect of impurities diffusing from the metal substrate. Manpower resource limitations required the goal of providing meter-lengths of buffered IBAD MgO to industrial partners to be removed. This was compensated in part by our technology transfer efforts to help SuperPower start up their own IBAD MgO template pilot line and by the Research Park providing buffered lengths of template to other industrial partners.

In FY 2005, the Core Program will continue its effort to reduce C/P of coated conductors based on IBAD MgO. This work will enhance commercial viability by improving economics and broadening the range of product applicability. Our activities will address every aspect of the IBAD MgO architecture. The first goal is to routinely achieve in-plane IBAD MgO texture of < 5° FWHM, which will give a large margin for process drift in long-length manufacturing. We will continue optimization of the nonsuperconducting layers, leading to reduced thickness, increased rate, and broader processing windows. We will also continue work begun last year to understand and engineer flux-pinning defect structures for higher performance in magnetic fields that are characteristic of DOE applications. A new area will be to follow up on some early and promising work on alternate approaches for texturing materials with ions – this offers the possibility of a simpler process and a wider range of useable materials. Another new area will be to investigate the often-observed phenomenon of texture sharpening of a heteroepitaxial layer relative to the underlying layer. This little-understood effect already offers 6 degrees or more of in-plane texture improvement over the starting RABiTS or IBAD MgO template – understanding and controlling the effect will advance the efficiency and reproducibility of all coated conductor processes.

**FY 2004 Results:**

- Produced many ~ 1.5 μm-thick samples with $I_c$ > 400 A/cm-width
- Demonstrated thicker films with $I_c$(75 K) > 1000 A/cm-width
- Found several ways to increase $J_c$ by a factor of 2-5 in fields > 1 T(75 K, B||c).
- Experimentally verified mechanism responsible for biaxial texturing of IBAD MgO that may allow for a more robust manufacturing process.
- Determined diffusion coefficients for substrate elements in alumina barrier layers.
- Measured the effects of transition metal impurity concentrations on superconducting properties to establish requirements for barrier layers.

**Research Integration:** During FY2004 we began the transfer of IBAD MgO technology to SuperPower. On site visits and sample and material exchanges resulted in substantial progress being made and we anticipate that the full transfer of IBAD MgO in the coming year will be both smooth and rapid, based on SuperPower's success with earlier IBAD technologies. In addition we participated in focused collaborations with Oak Ridge, Argonne, and Brookhaven National Laboratories, resulting in joint publications with ANL and BNL. We have also hosted a visiting staff member from Cambridge University, which has resulted in joint publications.

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| **Project Title:** | **Wire Development Group: Improving the Understanding and Performance of HTS Wire.** |
| **Organization(s):** | **Los Alamos, Argonne and Oak Ridge National Laboratories American Superconductor Corporation<br>University of Wisconsin** |
| **Presenters:** | Alex Malozemoff (AMSC), Eric Hellstrom (UW) Leonardo Civale (LANL) and David Larbalestier (UW) |
| **FY 2004 Funding:** | |

| | DOE-EERE | AMSC |
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| LANL | \$375 K | |
| ORNL | \$225 K | |
| UW | \$262 K | |
| ANL | \$150 K (initially authorized – only \$80 K available) | |
| AMSC | | \$535 K |

**Project Purpose and FY 2004 Objectives:** The Wire Development Group (WDG) is a unique multi-institutional collaborative effort focused on advancing the materials science underpinning advanced HTS (BSCCO and YBCO) conductors for energy and magnet applications in the US and international marketplace. The WDG combines the expertise and resources of three DOE national laboratories (ANL, LANL and ORNL) and a leading university program in applied superconductivity (UW-Madison) with the world's leading entrepreneurial company (American Superconductor – AMSC) developing and manufacturing both first (BSCCO-1G) and second (YBCO coated conductor – 2G) generation HTS wire and wire products. Robust long-length 1G wire is commercially available today and is being used in an expanding range of applications. This project aims at extending the state-of-the art performance of the 1G conductor to improve its price/performance and to maintain the U.S. position as the world-wide leader in commercial HTS wire development and manufacturing. During the past year, this project has also undertaken the task of enhancing the performance of 2G wires, focusing specifically at the operating conditions (T,H,θ) of targeted commercial and military applications. Specific objectives of the past year were:

1) Improve the understanding of the BSCCO-2223 formation process,
2) Evaluate routes to increasing BSSCO-2223 phase purity in 1G wire and enhancing $J_c$,
3) Develop a low-temperature scanning laser microscopy (LTSLM) capability and combine it with transport MO studies to identify and characterize local sources of dissipation in 1G and 2G HTS conductors,
4) Evaluate over-pressure (OP) processing for 1G wire production,
5) Bring WDG experience and capabilities to bear on materials science and superconducting properties of 2G wire – specifically in enhanced pinning.

**FY 2004 Performance and FY 2005 Plans:** Progress was made on most FY04 objectives (see results below), resulting in significant performance improvements in both 1G multifilamentary conductors and 2G films. A major new initiative to broaden WDG activity into 2G wire was undertaken, focusing on detailed characterizations of the microstructure and field dependence of ex-situ processed YBCO films. A temporary interruption of funding limited the effort on Objective 2 above and delayed purchase of equipment, e..g. for Objective 3. Because of a major increase in performance in non-OP processed 1G wire, the focus of Objective 4 was shifted from long-length production to optimizing the OP process for additional $J_c$ increases using the same wires. Our efforts in FY05 will remain focused on continued improvements in the processing, materials chemistry, and characterization of 1G wire, and the characterization and optimization of pinning and current limiting mechanisms (CLMs) in 2G wires prepared with ex-situ techniques. Specific areas of research include:

1) Enhance our understanding and control of BSCCO-2223 phase formation in 1G wires to further improve phase purity, eliminate CLMs and open new paths to increase $I_c$, including optimized OP processing,
2) Combine detailed $J_c$-anistropy and microstructure measurements with new processing to introduce pinning and improved grain boundary structure to optimize 2G wire performance at the operating conditions of temperature, field and field orientation for targeted applications,
3) Implement and refine new analytical techniques such as LTSLM for probing current flow and dissipation in 1G and 2G conductors, identifying CLMs and opening new paths for $J_c$ enhancement.

**FY2004 Results:** Key results include:

- The role of BSCCO-2212 intergrowths as CLM's in HTS wire was studied, and a new "anticorrelation" was found between $J_c$ and the 2212 SQUID index. These results explain increases in $J_c$ achieved during the final stages of heat treatment.
- A critical current of 202A (480A/cm-width at 77K sf), a new record, was achieved in a 1G wire using overpressure processing (OP). Another new record $I_c$ of 190A (450A/cm-width) was obtained in a 4.2x0.21 $mm^2$ wire cross-section without OP. Work to apply OP to these wires has been initiated.
- Localized dissipation was observed along YBCO grain boundaries by LTSLM, and correlations with local grain boundary orientation are studied.
- Temperature, magnetic field H, and field orientation dependent measurements of $J_c$ were performed on PVD-$BaF_2$ YBCO conductors on RABiTS with the goal of establishing correlations with controlled process variations. Fast-processed films may exhibit significantly reduced anisotropy (<2 for the $J_c$ ratio for fields parallel or perpendicular to the tape plane at H=1 T, 77 K). The angular dependence of field angle typically exhibits only a minor peak for fields parallel to the c-axis. A simple scaling of low-temperature, medium field (e.g., 2 T) $J_c$ values and the self-field $J_c$ at 77 K was observed, with remarkably weak dependence on high-field pinning characteristics.
- $J_c$ anisotropy of MOD-based 2G wires was measured as a function of magnetic field orientation and temperature. Rare-earth nanodots in MOD YBCO films, detected by TEM, were shown to significantly improve the in-field performance from 26 – 77K with themagnetic field oriented in a range around the perpendicular to the tape plane. The dominating contribution of planar defects was identified for the magnetic field oriented in a range around parallel to the tape plane.

**Research Integration:** The WDG remains a vibrant example of effective inter-institutional, university-lab-industry collaborations, which has helped establish US scientific leadership in HTS wire development, as well as unquestioned world leadership in 1G HTS wire production by a US company. During the last year, new members have been added to the core WDG group to enhance the expertise in the 2G wire area. Trimesterly meetings, frequent individual visits, emails, phone calls, and intra-organizational sample exchanges insure rapid coordinated progress by exploiting the unique skills at the different sites. A sensible balance of proprietary technology and publishable results is maintained. An atmosphere of trust supports a positive and enthusiastic esprit de corps. The expertise and cooperation in the group allows new challenges, including 2G wire development, to be rapidly addressed. Key lab and university results are tech-transferred effectively to AMSC, enabling rapid introduction of new developments to the AMSC production of robust long-length wire.

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| **Project Title:** | **AC Loss Studies in Coated Conductors** |
| **Organization(s):** | **Los Alamos National Laboratory** |
| **Presenters:** | Steve Ashworth |
| **FY 2004 Funding:** | $300 K |

**Project Purpose and Objectives FY2004:** This project had the objective to study aspects of the ac losses of BSCCO tapes and YBCO coated conductors. Specifically, we aimed to;

1) Measure ac losses in state of the art BSCCO 2223 tapes in the 20-40K temperature regime.
2) Assemble predictive equations for the losses in this temperature range to aid in machine design.
3) Determine conductor temperature rises for BSCCO 2223 tapes in the 20 - 40K temperature regime exposed to large fluctuations in applied field when carrying dc currents (ie 1T increase in 1second).
4) Measurement of losses on coated conductor samples with ac transport currents and ac magnetic fields. The aim being data generation for prospective design studies.
5) Measurement of losses with fields at various angles to the conductor, with the aim of determining the effect of ab plane and c- axis 'peaks' in IC.
6) Measurement of the effect of conductor interaction (stacks, arrays) on ac losses.
7) Low loss coated conductor studies
8) Study cryo-stabilization of coated conductors under ac conditions

**FY2004 Performance and FY2005 Plans:** A high quality (Ic>100A/cm width)1 cm wide coated conductor sample has losses of order 1W/m at 60Hz in a 30mT perpendicular ac field. This needs to be reduced by 2 – 3 orders of magnitude for widespread use in power applications.

We consider this to be the most pressing problem in ac losses in HTS.

This year's effort has been concentrated on measuring, understanding and working to reduce the ac losses in coated conductor as required by some of our stated objectives from last year. Effort on BSCCO-2223 has been reduced in favor of work on this problem, the rationale being that techniques for the reduction of coated conductor losses need to be implemented, or at least shown possible, if the development of coated conductor for power applications is not to be called into question. All other problems were considered to be subsidiary to this.

We consider that progress has been made on this problem, if initially in a negative sense by demonstrating that the simple route of cutting filaments or striations into the conductor will not work without also imposing transposition of the resulting filaments. We have also though made some progress in developing novel conductor architectures which may result in lower losses.

**In 2005** we plan to continue the quest for a low ac loss coated conductor. We will

- Further developing novel architectures, with significantly more integration with the LANL coater conductor effort.
- Introducing a modeling capability into the US to further our understanding of the magnetic field behavior in the conductors.
- Work with US industrial partners to provide data on their conductor samples.
- Make the results of our own innovation available to those partners.

A specific, measurable and highly challenging objective will be to develop a conductor design;

1) with ac losses in perpendicular ac magnetic field an order of magnitude lower than the 'bare' 1cm wide conductor
2) with reduction in dc critical current of less than 10% from the 'bare' conductor

3) in principle manufacturable by a continuous process.

**FY2004 Results:** In measurements we;

- Reduced the complexity of making calorimetric measurements of losses due to combined fields and currents, doing away with the need for hand assembled thermocouples and thermal insulation.

  This reduced the time required to change samples from about 1 day to less than an hour. This was achieved by replacing the styrofoam and silicone sealant previously used to thermally insulate the sample with an alcohol (IPA) bath. This is frozen in place in the cryostat and acts as the required thermal insulation. After use the alcohol is simply allowed to evaporate and the sample is recovered. This also allows us to make measurements on complex surfaces (cables or coils) which were previously difficult to measure.

- Introduced a system for measurement of magnetic losses which 'captures' all the signal in cases where the field is applied perpendicular to the conductor. Most workers in the field do not do this.

  This entailed utilizing a map of the magnetic field around a conductor sample to build magnetic pick up coils encompassing all the 'lossy' field. Analysis if the derived data then required an understanding of how ac magnetic fields act to require voltages from power supplies.

- Showed that cutting 'striations' into coated conductors does not in fact reduce the ac losses as many workers are assuming, this is an artifact of measuring on small samples.

  Understanding this is essential to focus effort where needed in reducing losses in coated conductors.

- Introduced a system for continuous measurement of losses on long (meter) length samples, for comparison with dc position sensitive critical current measurements.

In working to reduce losses we;

- Measured striated / patterned samples from collaborators or produced at LANL, measuring losses due to simultaneous fields and currents. This is not routinely done at any other laboratory in the US and only two other labs worldwide have this capability.
- Investigated a number of novel adaptations (ie other than 'striations') of the coated conductor to reduce losses. Some of these did indeed reduce the losses, but not by anywhere near enough and with other penalties (eg making the conductor difficult/impossible to wind).
- Made measurements on the interaction of 'windings' of coated conductor.
- Conceived and made first measurements on a novel conductor design based on striations which does have the potential for lower loss – without twisting or transposition.

**Research Integration:** In the past year we have made extensive measurements on patterned coated conductor samples from IGC-Superpower as part of an ongoing CRADA. We have also begun working with USAF and Long Electromagnetics on low loss conductors for Air Force applications and have a DARPA funded project (including American Superconductor) on low loss conductors.

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| **Project Title:** | **ORNL-American Superconductor Strategic Research** |
| **Organization(s):** | **Oak Ridge National Laboratory/American Superconductor Corporation** |
| **Presenters:** | A. Goyal, M. Paranthaman (ORNL), and U. Schoop (AMSC) |
| **FY 2004 Funding:** | $925 K DOE-OETD to ORNL; matching funds at AMSC |

**Project Purpose and FY 2004 Objectives:** The objective of this research is to develop a basic material sciences understanding of the fundamental issues related to fabrication of RABiTS templates for high critical current coated conductor wires (second generation – 2G). This understanding will assist in the development of a reliable, low-cost manufacturing process based on a 4 – 10-cm-wide reel-to-reel process. The program is also focused on characterizing and understanding issues related to ac losses and stability effects in wires and cables made with RABiTS-based 2G wires. FY 2004 plans included:

1) Fabrication of pilot line quality (10-cm wide by 100-m long) alloy substrates using the ORNL rolling mill facility with clean room.
2) Demonstration of scalable continuous processing of the MOD-YBCO on RABiTS through implementation of 4-cm-wide process.
3) Assistance by ORNL to AMSC's production of 20-m lengths of 2G wire with an Ic of 250 A/cm from the 4-cm-wide manufacturing process.
4) Characterization of buffers, using microstructural techniques such as TEM, SIMS, EBSP, SEM, Auger Spectroscopy, etc., to optimize the buffer layer stack for long length production of 2G wire.
5) Correlation of texture to $J_c$ to facilitate the improvement of the texture of AMSC alloy substrates. Analyze the importance of out-of-plane misorientation with respect to $J_c$.

**FY 2004 Performance and FY 2005 Plans:** Major progress has been made in demonstrating a, reproducible, low-cost manufacturing process for a commercial 2G conductor. Increased understanding of the fundamental properties of the substrate and each buffer layer allowed the implementation of an improved, highly stable manufacturing process at AMSC. These improvements led to AMSC's successful fabrication of a series of 4 consecutive runs of continuously processed 10-m lengths with outstanding performance (250-270 A/cm-w at 77 K). Other studies were directed to understanding of substrate components on ac losses, conductor stability, and the investigation of high risk approaches with the potential reward to drastically improve performance or reduce cost. Several approaches to define suitable buffer stacks on nonmagnetic substrate materials were investigated. FY 2005 Plans include:

1) ORNL assistance to AMSC in producing pilot line quality (4 cm wide by 100 m long) alloy substrates using the ORNL rolling mill facility with clean room,
2) Improvement of RABiTS template manufacturing process reliability through fundamental characterization of the buffer layer properties.
3) Reduction of the substrate/buffer manufacturing cost through improved understanding of the interactions of buffer deposition rates and intrinsic properties.
4) Detailed analysis of the role of RABiTS template texture and manufacturing defects as current limiting mechanisms in long length, 4-mm-wide YBCO wires.
5) Analysis of the uniformity and reproducibility of long length, 4-cm-wide RABiTS templates produced in a high-rate reel-to-reel manufacturing process.
6) Development of new, low-cost template architectures that are applicable to Ni-5at%W as well as nonmagnetic Ni-9at%W and NiCrW substrates

**FY2004 Results:** Close collaboration between AMSC and ORNL has produced significant progress in the development of a reproducible, robust reel-to-reel fabrication process for MOD-YBCO/RABiTS wires and the development of practical conductor architectures. Key Results include:

- 250-270 A/cm-width performance, uniformity and reproducibility of 10-m continuously processed 2G wires based on RABiTS templates confirmed the quality of the RABiTS template and reel-to-reel manufacturing process.
- The microstructure of AMSC buffers was studied in detail using a combination of SEM, TEM, X-ray diffraction and SIMS, in a collaborative program of ORNL with Sandia National Laboratory. This provided an improved understanding of the function of each layer in term of diffusion properties and interface reactions. A model was developed explaining the buffer properties for the current $Y_2O_3$/YSZ/$CeO_2$ architecture.
- Grain boundary assemblages in AMSC substrates were studied with electron backscatter Kikuchi diffraction and X-ray microdiffraction techniques. The total misorientation at each grain boundary was separated into in-plane and out-of-plane contributions. It is found that grain boundary maps of the in-plane misorientation correlate better with the $J_c$ levels attainable for YBCO films grown epitaxially on these substrates compared to grain boundary maps of the total misorientation.
- The properties of substrate materials were investigated to determine their effect on conductor properties. Total ac losses of 1-cm- and 4-mm-wide YBCO/$CeO_2$YSZ/$Y_2O_3$/Ni/NiCrW sample were found to scale inversely with the square of the total conductor critical current. It was confirmed that the contribution to the ferromagnetic losses from the substrate was reduced for Ni/NiCrW compared to Ni-5at%W substrates.
- Several buffer architectures were investigated for the nonmagnetic NiCrW and Ni9at%W substrates. Since direct deposition of oxide buffer layers on NiCrW is not thermodynamically favored, we have investigated two approaches for the seed layer:
  - TiN seed layers were used in a $CeO_2$/LMO/MgO/TiN architecture. 0.8-μm-thick MOD YBCO films were grown on these samples with critical current densities of 1.8 $MA/cm^2$. Extensive structural and chemical characterization was performed on TiN-based architectures.
  - Ni-9at%W coatings were deposited on both Ni-5at%W and NiCrW alloys to test the viability of this approach to reduce the magnetic contribution of the template. This approach may allow the use of the standard buffer layers comprising of $CeO_2$/YSZ/$Y_2O_3$ on the nonmagnetic substrates.
- The effectiveness of Cu stabilizers, required to protect against a 10× overcurrent in thermally isolated YBCO conductors, was studied. Centimeter-wide YBCO samples with 50 microns of copper stabilizer survived overcurrent pulses for 35 ms without significant degradation. This overcurrent resulted in a peak temperature of 280 K.
- The ORNL rolling mill facility with clean room was used to fabricate wide substrates for AMSC in this period. Homogeneity of the textured substrates was confirmed by X-ray techniques at ORNL. Increased processing width followed by a final slitting to conductor size is a necessary contribution to a cost effective manufacturing process.

**Technology Integration:** Close collaboration and interaction between ORNL and AMSC has resulted in significant advancement in process understanding and subsequently in production processing at AMSC. Regular weekly conference calls, frequent sample exchanges, CRADA meetings, joint development and joint materials evaluation and testing have resulted in significant and rapid progress over the course of the last year. Technical staff from AMSC routinely visited ORNL to perform week-long rolling runs. AMSC views ORNL as their fundamental RABiTS template research laboratory. An even closer interaction is envisioned for future work. Several joint publications and many joint presentations have resulted from this work.

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| **Project Title:** | **Phase Relations of High $T_c$ Superconductors** |
| **Organization(s):** | **NIST, Ceramics Division, Gaithersburg, MD 20899** |
| **Presenters:** | W. Wong-Ng and L.P. Cook |
| **FY 2004 Funding:** | $250 K |

**Project Purpose and FY 2004 Objectives:** Our principal 2004 project objective is to develop a critical phase equilibrium database for Ba-R-Cu-O (R=Y, lanthanides) second generation RABiTS and IBAD coated conductor applications. In addition to phase diagram studies of the Ba-R-Cu-O systems, subprojects include phase transformation determination of $Ba_2RCu_3O_{6+x}$ (213), and characterization of the "*ex-situ* $BaF_2$ process" of $Ba_2YCu_3O_{6+x}$ (Y-213) formation. To investigate the interplay of phase equilibria and kinetics in the Ba-Y-Cu-O-OH system, we have collaborated with ORNL, ASC and BNL to determine the occurrence of melt in association with the defluorination process, and to follow the phase formation of the Y-123 phase in precursor films using high temperature x-ray diffraction (HTXRD). An understanding of the interfacial reaction of Y-213 phases with the buffer layers is critical to the development of coated conductor tapes. Consequently, another objective is to collaborate with ORNL and LANL to investigate the phase equilibria of the multicomponent systems representing the interaction of $Ba_2YCu_3O_{6+x}$ with selected buffer materials. Additionally, by mixing a small lanthanide ion with larger R in R-213 solid solutions, flux-pinning and melting properties can be tailored and optimized. In collaboration with LANL and the AFRL at Wright-Patterson (AFRL-WP), we continued to characterize the high $T_c$ mixed lanthanide solid solutions, including flux-pinning studies. Finally, in order to provide thermodynamic data for the challenging Mg-B system, we continued to pursue both experimental and theoretical studies of $MgB_2$.

**FY 2004 Performance and FY 2005 Plans:** An advisory team for our phase equilibria research activities was formed to ensure relevancy, efficiency, and impact of our work. Based on various interactions with the team members, we have continually refined our FY 2004 objectives. We have successfully applied our experimental procedure and specialized apparatus to construct phase diagrams of the Ba-Gd-Cu-O, Ba-Dy-Cu-O and Ba-Yb-Cu-O systems under controlled atmosphere conditions. In collaboration with BNL and Caltech, an understanding of the trend of orthorhombic to tetragonal phase transformation temperature was obtained. We have investigated the solid solution range of the $Ba_{2-x}(R,Y)_{1+x}Cu_3O_z$ phase, where R= Sm, Eu and Gd. This year we have also successfully constructed a steam furnace for controlling water vapor pressure, an important step in our investigation of the role of $Ba(OH)_2$-related liquid in low-temperature melting of the Ba-Y-Cu-O-OH system. In collaboration with ORNL, we have made significant progress in understanding the mechanism of phase evolution of the $BaF_2$ films (prepared using both e-beam evaporation and TFA methods) by a combined use of HTXRD and TEM. In collaboration with LANL and ORNL, we continued to study the phase equilibria of the multicomponent systems representing the interaction of $Ba_2YCu_3O_{6+x}$ with $CeO_2$ and $SrTiO_3$ buffer materials.

The FY 2005 plan builds upon FY2004 progress. We will continue our interactions with the 'phase equilibria advisory team', and our collaborations with ORNL, ASC, and BNL on the the $BaF_2$ subproject, with LANL and AFRL-WP on the mixed-lanthanides subproject, and with ORNL and LANL on superconductor/buffer interaction subproject. We will also continue to study phase equilibria of the Ba-R-Cu-O systems under reduced oxygen pressures. For the $BaF_2$ project, emphasis will continue to be placed on both modeling and experimental work related to melting equilibria in the multicomponent Ba-Y-Cu-O-F-OH system and pertinent subsystems. In collaboration with ORNL, we will use combined HTXRD and TEM to compare the mechanism of phase evolution of the R-213 superconductor films as a function of different stoichiometries. These films will be prepared using both e-beam and TFA methods.

**FY 2004 Results:** Key results from the FY 2004 program are summarized below:

1) The phase diagrams of the Ba-R-Cu-O (R=Gd, Dy and Yb) systems in 0.1 % $O_2$ have been constructed and compared with other members of the Ba-R-Cu-O systems. A trend in the diagrams was observed.
2) The $Ba_{2-x}$(R, Y)1+x$Cu_3$Oz systems (R=Sm, Eu and Gd) have been characterized. The size of the solid solution region varies with the oxygen partial pressure as well as the size of R (with AFRL-WP and LANL).
3) The phase formation mechanism of Y-213 during the "$BaF_2$ process" was determined to depend on precursor type (i.e., Y2O3 vs YF3), as well as precursor stoichiometry. A barium oxyfluoride superlattice phase was confirmed to be involved in the phase formation process (with ORNL).
4) Further studies confirmed earlier evidence of low-temperature melts in the F-rich region of the Ba,Y,Cu//O,F reciprocal system. Phase equilibria of the intermediate $BaF_2$-$CuF_3$-$YF_3$-CuOx region was successfully studied. The low temperature DTA event occurring in this region was determined to be due to a solid state phase transition in yttrium oxyfluoride.
5) Phase diagrams of the Ba-Y-Cu-O-F-OH binary systems, including $Ba(OH)_2$-$Y_2O_3$, $Ba(OH)_2$-CuO, $Ba(OH)_2$-BaO, and $BaF_2$-BaO, have been initiated using a specially constructed vapor pressure furnace.
6) Phase equilibria for pseuodobinary systems of $Ba_2YCu_3O_{6+x}$ with buffer materials $CeO_2$ and $SrTiO_3$, together with selected subsystems, were determined (with LANL).
7) The orthorhombic to tetragonal phase transition temperature of $Ba_2RCu_3O_{6+x}$ was characterized and successfully modeled (with BNL and Caltech). The observation that the smaller the ionic radius of R, the higher the transition temperature, was found to be related to the effect of strain.
8) Study of the effect of BaR2CuO5 on the superconducting properties of 213-films was initiated (with AFRL-WP).
9) Enthalpy of formation and vapor pressure of oxygen-free $MgB_2$ were determined (with Ames Lab).

**Technology Integration:** To ensure the relevance of our phase equilibrium studies, we work closely with other national laboratories, with universities, and with industry. We have formed a "phase equilibrium advisory team" which includes members from the superconductor industry, government laboratories and universities: ASC, IGC, Oxford Instruments, ORNL, LANL, BNL, AFRL-WP, Columbia University, and University of Houston. We are currently collaborating on the $BaF_2$ project with ORNL, ASC, and BNL, and with other scientists of the NIST Ceramics and Metallurgy Divisions and the Center for Neutron Research. We are collaborating with LANL and AFRL-WP on the mixed lanthanide projects, with ORNL and LANL on study of interaction of Y-213 with buffers, with Florida State University on a phase equilibria study of Pb-free 2223, with BNL and Caltech on phase transformations of R-213, and with Ames Lab on $MgB_2$ studies.

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| **Project Title:** | **RABiTS-Based Strategic Research** |
| **Organization(s):** | **Oak Ridge National Laboratory** |
| **Presenters:** | A. Goyal, S. Sathyamurthy, and T. Aytug (ORNL) |
| **FY 2004 Funding:** | $900 K (DOE to ORNL) |

**Project Purpose and FY 2004 Objectives:** To develop a basic understanding of and practical synthesis paths for epitaxial buffer layers and YBCO superconductors on biaxially textured metal tapes for improved coated conductor performance. The primary objectives for FY 2004 were:

1) Develop all solution buffer architectures that are compatible with MOD TFA YBCO
   a. Achieve over 200 A/cm-w on solution LZO seeds
   b. Develop two-sided LZO layers
   c. Extend to 4-cm-wide substrates
2) Continue fundamental studies of epitaxial growth of both PVD and solution buffers on textured substrates, including copper and copper alloys.
   a. For copper-based substrates, develop a fully conductive architecture.
3) Achieve high-$I_c$ YBCO films on Cu or Cu-alloy templates by *in-situ* or *ex-situ* approach.
4) Enhance flux-pinning in YBCO films on RABiTS through practical, growth-controlled pinning centers in the films

**FY 2004 Performance and FY 2005 Plans:** We have developed a simple, solution based buffer layer architecture using $La_2Zr_2O_7$ (LZO) as a barrier layer to nickel diffusion. LZO buffers were grown epitaxially on biaxially textured and strengthened Ni-W metal tapes by a scalable sol-gel alkoxide precursor route, yielding 50-100-nm-thick epitaxial LZO layers in a single coat directly on Ni-W up to 4-cm wide. Using the metal-organic decomposition (MOD) approach, we have successfully developed a method to grow epitaxial $CeO_2$ cap layers on LZO-buffered Ni-W substrates. Results of YBCO films grown on all solution $CeO_2$/LZO buffered Ni-W substrates will be presented.

As an alternative RABiTS architecture, we have developed combinations of $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) and Iridium (Ir) metal that provide effective diffusion barriers for both inward oxygen and outward substrate cation diffusion. Since both LSMO and Ir are conductive materials, we have assessed the feasibility of LSMO/Ir structure as a conductive buffer interface on Ni-W substrates. High current YBCO films grown by PLD on Ni-W are fully electrically connected to the substrate tape.

We have explored Cu-based substrates as RABiTS templates since they are nonmagnetic, have high thermal conductivity, and high electrical conductivity, which could be exploited for conductor stability provided a fully conductive buffer architecture is developed. Based on our findings on Ni-W substrates, we have begun development of conductive buffer layers using Ir-based architectures on biaxially textured Cu tapes.

We have incorporated second phase, nano-particles in YBCO films grown epitaxially on RABiTS substrates. Several different nano-particle species have been attempted. Detailed transport, magnetization and microstructural characterization were performed and these results will be presented.

**The FY 2005 plans are:**

1) Continue fundamental studies of epitaxial growth of simplified buffers on textured nonmagnetic substrates, including nickel alloys, copper and copper alloys and demonstrate high $I_c$ YBCO films.
2) Perform studies aimed at an all solution route to buffers that are capable of sustaining a high quality and thick (>1 μm) YBCO layer by a scalable superconductor process, such as evaporated $BaF_2$ precursors or a TFA-derived MOD process.

- High $I_c$ of 200 A/cm on all solution buffers
- Demonstrate MOD layer on nonmagnetic Ni-W9at.% substrates.

3) Produce meter lengths of solution buffers using both slot-die coating and reel-to-reel dip-coating capable of sustaining 1-µm-thick YBCO films with $J_c$ over 1 MA/cm$^2$.
   - Optimize double-sided YBCO coating on all-solution buffers
4) Continue detailed studies on incorporation of practical pinning centers in YBCO *in-situ* and *ex-situ* films on RABiTS. Identify pinning centers using TEM studies and correlate to measured superconducting properties such as irreversibility field, $J_c$ versus field, and angle at various temperatures.

**FY 2004 Results:**

**<u>All solution buffers based $CeO_2$/LZO/Ni-W substrates</u>** - Under *ex-situ* YBCO process conditions, we have found that a 100 nm thick LZO protects the metal substrate from oxidation as well as that of the standard three-layer buffer architecture. About 80-120 nm MOD LZO provide good metal diffusion barrier, no delamination, and adequate template for growing thick YBCO films. To date, 10- to 20-cm-long LZO buffers were produced by dip coating. MOD LZO buffers were successfully grown on non-magnetic Ni-W9at.% templates for feasibility of deposition on Ni-W9at.% substrates. Highly textured MOD $CeO_2$ caps were grown on LZO-buffered Ni-W substrates and YBCO films with good properties were obtained.

**<u>Demonstration of high current density YBCO films on conductive LSMO/Ir/Ni-W substrates</u>** - Using PLD YBCO films, we have demonstrated *ideal* electrical coupling to the metal substrate. Electron microscopy shows a complete absence of unwanted insulating oxide interfaces. For 0.2-µm-thick YBCO films self-field critical current ($J_c$) values exceeding $2 \times 10^6$ A/cm$^2$ at 77 K were obtained on a Ni-W RABiTS template. Critical current ($I_c$) values for 1-µm-thick YBCO coatings exceed 100 A/cm at 77 K. Using a $CeO_2$ cap layer, a buffer layer stack was made compatible with the $BaF_2$ ex situ process, yielding $I_c$ >150 A/cm (77 K) for a 1-µm-thick YBCO coating.

**<u>Conductive buffer layer studies on copper</u>** - Feasibility of two different epitaxial buffer layer architectures, LSMO/Ir and LSMO/Ir/TiN, were explored as a conductive buffer interface on Cu templates. Preliminary results show that YBCO can be grown on these buffer architectures.

**<u>Strongly enhanced flux-pinning in YBCO films on RABiTS</u>** - We have incorporated second phase nano-particles of various kinds in YBCO films grown epitaxially on RABiTS substrates. During growth, a fine distribution of nano-particles (2-5 nm) precipitates homogeneously in the YBCO films, as determined by TEM. This produces significant enhancements in the transport behavior, including increases in self-field $J_c$, less sensitivity to field, increases in the irreversibility field, and significantly enhanced angular dependence of flux pinning at 77 K.

**Research Integration:** This project is related to the objectives of our CRADA partners that are working directly with ORNL. These teams are led by American Superconductor Corporation, MetOx, Neocera, Oxford Superconducting Technology, and SuperPower. The materials science base for buffer layers for YBCO coated conductors also involves collaborations with universities and other national laboratories, including University of Tennessee, University of Florida, University of Kansas, University of Wisconsin-Madison, University of Houston, NREL, LANL, and SNL. Numerous publications (including a Web-based posting of the FY 2003 ORNL annual report) and presentations help assure transfer of information to industry.

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| **Project Title:** | **Understanding and Improving Pinning in Coated Conductors** |
| **Organization(s):** | **Los Alamos National Laboratory** |
| **Presenters:** | Leonardo Civale, Judith Driscoll |
| **FY 2004 Funding:** | $550 K |

**Project Purpose and FY 2004 Objectives:** The objective of this project is to investigate the mechanisms that determine the supercurrent in coated conductors (CC), and to use that knowledge as a guide to explore practical methods for nano-engineering of pinning defects and process optimization of high performance CC. The approach is to characterize the transport properties as a function of magnetic field strength (H) and orientation (Θ), and temperature (T). We then correlate these properties with the structural characteristics of the samples in a variety of rare earth (RE)-123 films on single crystal substrates and CC of different architectures.

This project started in FY 2003, and that first year we focused on the comparison of the angular dependence of the critical current density ($J_c$) at liquid $N_2$ temperature in YBCO films grown by pulsed-laser deposition (PLD) on ion-beam-assisted deposited MgO (IBAD MgO) and on single crystal substrates. We identified the H-Θ regions where $J_c$ is dominated by various types of pinning centers. We found that the sources of pinning are similar in CC and films on single crystal substrates, and that the in-field $J_c$ in our CC can be higher than in equivalent films on single crystal substrates. We also performed initial studies at lower T, and on CC of different architectures provided by our industrial partners SuperPower and American Superconductor.

The goals for FY 2004 were to extend the measurements and analysis to lower temperatures, study films thinner than 1 μm, explore $J_c$(H,Θ,T) in CC with different architectures, perform $J_c$ measurements with current flowing in different directions in the ab-plane, grow films with rare earth substitutions, and introduce columnar defects at different angles in YBCO films on single crystal substrates.

**FY 2004 Performance and FY 2005 Plans:** Substantial progress was made on each goal. Extensive $J_c$(H,Θ,T) studies in the range 4 K < T < $T_c$ ~ 90 K allowed us to develop a H-Θ-T diagram of the dominant pinning mechanisms for films of thickness ranging from 0.2 μm to 6 μm. We extended our studies to CC of different architecture, mixed RE-123 compositions, second phase additions, and growth methods and conditions, on samples from Los Alamos as well as from our partners. We found systematic differences that are fingerprints of the CC processing method and architecture and that can be clearly correlated with the structural properties.

We successfully developed at Los Alamos several ways to engineer the microstructure in order to enhance the in-field $J_c$, either by introduction of additional correlated disorder (e.g., dislocations) or random pinning (e.g., strain associated with ion size variance). Our industrial partners also pursued alternative approaches to the introduction of additional pinning; we investigated $J_c$(H,Θ,T) in several of their samples and provided them with valuable feedback.

The last goal, the introduction of columnar defects, was modified. The reason is that we have unexpectedly been able to produce and/or study samples with additional extended defects at several orientations, generated by a variety of methods that are scaleable to industrial production. We decided that the study of the pinning due to these defects was technologically more relevant than the initially planned heavy-ion irradiations.

In FY 2005, we will continue our effort to further improve the in-field performance of CC. We will pursue this goal in several ways. One main focus will continue to be the nano-engineering of pinning-inducing defects. We expect to optimize the deposition conditions and density of $BaZrO_3$ inclusions, and explore alternative nanoparticles. We also plan to optimize our successful approach to pinning enhancement by tuning the buffer layer deposition conditions in order to create surface outgrowths. Finally, we will continue our exploration of RE substitutions, following our initial encouraging results on compositions with low variance in the RE ion size. Based on the results of the above-mentioned alternatives, we will select the most appropriate one and implement it in the continuous long-length process. In terms of measurement capabilities, we will make full use of our in-plane current rotation system, and we will incorporate measurements in non-maximum Lorentz force configurations, in order to explore the CC performance in realistic current/field distributions for various applications.

**FY 2004 Results:**

- We developed a H-Θ-T map of the dominate pinning mechanisms in PLD/IBAD MgO CC in the temperature range from $T_c$ to ~ 26 K.
- We found that $J_c$ for H//c can be scaled over wide ranges of H-T. This allows us to predict $J_c$ values for arbitrary (H,T), based on a few parameters.
- We determined the influence of the film thickness on the relative importance of the correlated and uncorrelated pinning mechanisms.
- We observed significant improvements in the in-field $J_c$ in CC of mixed RE-123 compositions grown by various methods (including samples from SuperPower and AMSC).
- We have been able to introduce epitaxial $BaZrO_3$ nanoparticles in YBCO PLD films, which generate additional c-axis correlated defects that in turn produce remarkable improvement of the in-field $J_c$.
- We introduced additional strong pinning c-axis dislocations by modifying the growth conditions of the STO buffer layer.
- We introduced tilted correlated defects by two different methods, which produce a $J_c$(H,Θ,T) that is asymmetric with respect to H//c.
- We found that the laminar growth associated with MOD films (from AMSC) results in a large density of planar defects parallel to the ab-planes, which dominates pinning in a wide angular range around H//ab.
- We demonstrated that a superstructure of $Y_2BaCuO_5$ (211) extended planar defects parallel to the ab planes produces a tunable matching pinning effect (collab. with Air Force Research Lab.).
- We explored the influence of the IBAD MgO structure on the in-plane anisotropy of $J_c$.

**Research Integration:** During FY2004 we performed measurements of $J_c$(H,Θ,T) on CC fabricated by SuperPower, Inc., American Superconductor, and the Air Force Research Laboratory, resulting in joint publications and conference presentations. The information learned from these collaborations is critical for studying the pinning mechanisms arising from different deposition techniques. During her stay at Los Alamos as a visiting staff member, Dr. Judith Driscoll was on sabbatical leave from the University of Cambridge, UK.

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| **Project Title:** | **Development of High $I_c$ Ex Situ Processed RBCO Coated Conductors** |
| **Organization(s):** | **Oak Ridge National Laboratory, Los Alamos National Laboratory, and The University of Wisconsin** |
| **Presenters:** | T. Holesinger (LANL), M. Feldmann (UW), and R. Feenstra (ORNL) |
| **FY 2004 Funding:** | $250 K DOE to ORNL; $250 K DOE to LANL; $150 K DOE and AFOSR-MURI to UW |

**Project Purpose and FY 2004 Objectives:** This project represents a cross-institutional, collaborative research effort targeting the development of $YBa_2Cu_3O_7$ (YBCO) and/or RBCO coated conductors (R is a rare earth element or mixture thereof) based on the ex-situ conversion of evaporated, $BaF_2$-type precursors. The purpose is to generate a materials science basis for continued properties improvement in ex-situ coated conductors through structure-property-chemistry correlations. FY 2004 objectives included achieving a better understanding and control of transient liquids during the conversion process, faster conversion rates, high $I_c$ (≥400 A/cm-width) with thickness and $J_c$ optimization, and a better understanding of the relation between flux pinning and microstructure. The last objective is closely coupled with the American Superconductor Corporation (AMSC) led Coated Conductor Wire Development Group (CC-WDG). Each of the three collaborating teams participates in this CC-WDG.

**FY 2004 Performance and FY 2005 Plans**: Significant progress towards FY 2004 objectives and milestones was made. Specific milestones for FY 2004 were to: 1) increase the processing rate of PVD precursors from 1-2 Å/s to 10 Å/s, and 2) raise the $I_c$ performance of YBCO films on a metallic substrate to 400 A/cm-width at 77 K (self-field). TEM and SEM were used to characterize fully and partially processed YBCO coatings. Signatures of liquid phase formation were identified. The existence of two distinct growth modes was established. EBSD (Kikuchi electron backscatter diffraction) was used to examine in detail grain boundary structures and local YBCO orientations through the thickness of a film by repeated imaging and ion milling. The ability of YBCO to overgrow substrate grain boundaries (GBs) and create novel GB networks was discovered. A new "fast modified" process was developed for the conversion of thick PVD-$BaF_2$ precursors in the range of 10 Å/s. YBCO films of variable thickness were grown by the fast conversion process on RABiTS substrates provided by AMSC. A nearly linear increase of $I_c$ with d was obtained. Angular and temperature dependent $J_c$ measurements were performed in variable magnetic fields. It was observed that the angular dependence of $J_c$ is processing dependent and can be controlled to reduce the anisotropy (this is covered in the CC-WDG summary).

Research plans for FY 2005 are to continue the collaborative research towards higher $I_c$ in ex- situ coated conductors. With respect to CC-WDG objectives, an enhanced emphasis will be given to the relationships between flux pinning and the processing of PVD-$BaF_2$ YBCO films. The microstructural origin of the process dependent $J_c$ anisotropy will be investigated. A promising route to study and improve flux pinning is to substitute one or more rare earths for Y. We will investigate the ramifications of these substitutions for several R elements, bearing in mind that minor variations in the overall process may have an impact on the liquid-mediated growth and $I_c$ performance. Evaluation of the efficacy/ compatibility of R substitution is considered timely. We will attempt to raise $I_c$ to values >500 A/cm at 77 K by increasing $J_c$ for films of medium thickness (1.5-2 μm). Using the new through-thickness imaging capability, we will continue study of current-limiting mechanisms in YBCO coated conductors.

**FY 2004 Results**: Key results from the FY 2004 collaborative research are summarized below:

1) Continuation of the study of the bimodal growth process in ex-situ YBCO coated conductors showed that this growth mode is not limited to thick films (d >2 μm), but may occur in thinner coatings (e.g., 0.8 μm) as well. The bimodal structure is evidence of the variable role of transient liquids during the conversion process. Barium-rich secondary phase layers were often observed between the large, laminar YBCO grains. However, exceptions to this latter effect were observed as well. Such films still exhibited bimodal microstructures without the intercalated Ba-rich phases, had lower out-of-plane misalignments, and produced higher than average $J_c$ values.
2) A new set of processing conditions and procedures was developed for the synthesis of thick YBCO coatings. The improvements involve all stages of the production process, starting from the precursor deposition (by electron-beam evaporation), through a newly inserted, low-temperature oxidation anneal, to the high-temperature conversion. This new process enables faster conversion rates in the range of 5-10 Å/s, compared to 1-2 Å/s previously.
3) The efficacy of this new, "fast modified" process for raising Ic was tested for YBCO films of variable thickness on ORNL and AMSC RABiTS substrates. A significantly reduced dependence of $J_c$ on the YBCO thickness d was observed. In the range 0.5-1.3 μm, Ic increases linearly with d to values >300 A/cm (77 K). This represents a significant improvement over FY 2003's best result (240 A/cm), measured for 2.5-μm-thick YBCO coatings. The present $I_c$ values are higher and obtained for films of half the thickness.
4) Ion milling, coupled with SEM and EBSD, has been used to visualize through-thickness, YBCO grain boundary structures in coated conductors and their registry with the underlying template. A remarkable feature of the liquid-mediated growth mode is the ability of YBCO grains to completely overgrow GB's of the substrate template, both in the case of IBAD and RABiTS. A new GB network is thus formed in the YBCO and this network may evolve through the film thickness. Analysis of this behavior for films produced by the "fast modified" process reveals interesting GB network modifications which depend on the original precursor thickness. The role of these modifications in enhancing $J_c$ is currently under investigation.

**Research Integration:** This research group represents a tight inter-lab, university, and industry collaboration in YBCO coated conductor research, where each partner brings a unique expertise to the collaboration. Ex-situ conversion is a promising deposition process for large-scale commercial deployment as illustrated by our industry partner, American Superconductor Corporation. Work on flux pinning in ex-situ PVD-$BaF_2$ YBCO coated conductors is closely integrated with CC-WDG efforts in flux pinning of AMSC MOD-$BaF_2$ YBCO. Additional external collaborators include: NIST-Gaithersburg (phase development) and NIST-Boulder (strain effects), Stanford University and other participants in the MURI project (information exchange), and Institute de Ciencia de Materials de Barcelona, Spain (granularity effects).

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| **Project Title:** | **Nucleation and Growth of YBCO by the $BaF_2$ Process and AC Losses of YBCO Films** |
| **Organization(s):** | **Brookhaven National Laboratory** |
| **Presenters:** | M. Suenaga and D.O. Welch |
| **FY 2004 Funding:** | $500 K |

**Project Purpose and FY 2004 Objectives:** The purpose of this project is 1) to develop synthesis methods/protocols, which are suitable for the fabrication of $YBa_2Cu_3O_x$, YBCO, coated conductors, through the development of an understanding of the mechanisms, kinetics, and thermodynamics of a- and c-axis nucleation in the $BaF_2$ process for YBCO thick films. 2) Another purpose of this project is to perform small-scale ac loss measurements which assist in the development of understanding of the currently known or expected ac losses in electric utility devices using HTS conductors. Our objectives for FY 2004 were to continue the study of the nucleation mechanisms in thick YBCO films by investigating the effects of variations in the growth conditions on the c-axis nuclei densities in the films. We also planned to emphasize our nucleation study on the films on buffered metallic substrates. These substrates were to be provided by American Superconductor Corp., AMSC. Also, we began a component of this program devoted to the theory and modeling of the thermodynamics and kinetics of nucleation and growth in the $BaF_2$ process, focusing especially on factors which control a- and c-axis nucleation.

**FY 2004 Performance and FY 2005 Plans:** YBCO thick film processing: a) We have developed a new and very simple optical microscopy technique to measure directly areal densities of YBCO nuclei in fluorinated precursor films on a substrate. We used this technique to study the relationship between the nuclei densities and critical current densities of YBCO films, primarily on buffered metallic substrates from AMSC. A simple thermodynamic model for the nucleation was also developed to describe some of the experimental observations. b) Theory and modeling efforts focused on the use of semiempirical atomistic and statistical thermodynamic methods to estimate thermophysical properties pertinent to the epitaxial nucleation of YBCO in the $BaF_2$ process. Also, in collaboration with W. Wong-Ng (NIST) and H. Su (Caltech), the systematic variation of the temperature of the orthorhombic-to-tetragonal transition in the family of RE-123 compounds was investigated. c) A collaboration was initiated with M. Cima (MIT) to investigate the roles which fluorine plays in the nucleation and growth of YBCO in the $BaF_2$ process. d) A simple method for the measurements of ac losses of YBCO in perpendicular magnetic fields was developed with J. R. Clem (Ames Laboratory). This technique was employed to measure the losses of YBCO films on buffered metallic substrates from AMSC and Superpower/IGC.

In FY2005: 1) The growth of thick (> 2 μm) YBCO films on buffered metallic substrates will be continued and will emphasize the control of the growth conditions to achieve the consistency of the properties of the films. In this effort, our new technique to determine the YBCO nuclei densities and our theoretical understanding of the factors controlling c- and a-axis nucleation will play important roles for the development of the clear relationship between the processing conditions and the properties of YBCO thick films. 2) Theory and modeling will be focused on delineating processing conditions which result in appreciable a- and randomly oriented axis nucleation. 3) ac losses of YBCO films on metallic substrates will be continued emphasizing the effects of stacked films and non-uniform macroscopic flux penetration on the losses. 4)The collaboration will also be continued with M. Cima at MIT on the modeling of nucleation and growth kinetics and nanoscale structure evolution in the case of MOD-derived precursors for comparison with the behavior for the precursors by an e-beam deposition method used at BNL.

**FY 2004 Results:** Key results from the FY 2004 program are summarized below.

1) **YBCO nucleation and growth**

   a) ***YBCO nuclei densities and growth conditions***

   We developed an experimental method for direct measurements of areal densities of YBCO nuclei in fluorinated precursor films which are on $CeO_2$ buffered metallic and single-crystalline $SrTiO_3$ substrates. The aerial density of YBCO nuclei was measured by polarized light microscopy after the nuclei have grown to the surface of the film. The density was found to depend strongly, not only on processing conditions, but also on the type of the substrate. We have also established the correlation between the areal density of the nuclei and the nucleation of the randomly and/or a-axis oriented YBCO grains in the films. A model, which is based on classical nucleation theory, correctly predicts some aspects of the functional dependence of the nuclei density with processing parameters. It is shown that the c-axis-oriented nucleation dominates if the average distance between the nuclei is a few times or greater than the film thickness of the precursor. The formation of randomly oriented grains is interpreted to be a result of collective interactions among the c-axis-oriented nuclei which are initially formed. By controlling the nuclei densities, $J_c$ (self fields) of ~/ > 1 MA/$cm^2$ was achieved for 2 μm thick YBCO films on buffered metallic substrates from AMSC.

   b) ***Modeling of Thermodynamics, Kinetics, and Mechanics***

   A combination of atomistic modeling and the use of scaling-relations based on ionic-crystal theory was used to estimate the lattice energy, surface energy, and elastic moduli of the $(Y,Ba)(O,F)_2$ precursor in the $BaF_2$ process and to estimate the interfacial energies between the precursor, YBCO, and a $CeO_2$ substrate. These results were used to estimate the dependence on the degree of oxygenation of the nucleation barriers for c-axis and a-axis nucleation. As part of an exploration of the comparative processing behavior of YBCO and family of REBCOs, the systematic variation of the thermodynamics of oxygen content and order was studied by atomistic simulation and the results compared with experimental data obtained by W. Wong-Ng and L. Cook (NIST) for the temperature of the orthorhombic-tetragonal oxygen ordering transition, thus yielding an understanding of the systematics of oxygenation in these superconductors.

2) **AC losses**

   An ac loss measurement method, which used a planar pick-up coil, was developed using a YBCO film from S. Foltyn/LANL. This method does not require calibration for the losses and it was shown that the correct losses were measured as long as the diameter of the coil was greater than ~3 times of a specimen diameter. Also a specimen can be as much as 1 mm above the coil for correct loss measurements. The latter allows the use of this technique to study the effect of stacking the films and this is important for applications of YBCO coated tapes in electric devices.

**Research Integration:** Our studies in FY04 were performed as informal collaborations with the staffs at LANL, MIT, NIST, AMSC, and Superpower. We would like to point out that the results of the work in this program can take some “incubation period” before their value becomes apparent to industry. For example, the concept of subatmospheric pressure processing in the $BaF_2$ process, which we introduced a few years ago, is now an indispensable modification in the fabrication of YBCO coated conductors by this process.

## UNIVERSITY RESEARCH SESSION

### Reviewers for the University Panel:

Ken Gray, Argonne National Laboratory
Vic Maroni, Argonne National Laboratory
Leonardo Civale, Los Alamos National Laboratory
Terry Holesinger, Los Alamos National Laboratory
Vlad Matias, Los Alamos National Laboratory
Hans M. Christen, Oak Ridge National Laboratory
Dominic Lee, Oak Ridge National Laboratory
Mariappan Paranthaman, Oak Ridge National Laboratory

### Review Projects for the University Session:

Microstructure and Mechanics of Superconductor Epitaxy via the Chemical Solution Deposition Method
Enhancing YBCO Performance Through Fundamental Process Evaluation and Characterization
Epitaxial Electrodeposition of Metal and Metal Oxide Capping Layers for RABiTS-Based Second Generation Coated Conductors
Systematic Evaluation of Jc Decrease in Thick Film Coated Conductors
Conversion of Oxy-Fluoride Based Coated Conductors
Buffer Layer Growth and the Thickness Dependence of Jc in Coated Conductors
Stanford In-Situ High Rate YBCO Process: Transfer to Metal Tapes and Process Scale Up

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| **Project Title:** | **Microstructure and Mechanics of Superconductor Epitaxy via the Chemical Solution Deposition Method** |
| **Organization(s):** | **University of California, Santa Barbara** |
| **Presenters:** | F.F. Lange |
| **FY 2004 Funding:** | $150 K |

**Project Purpose and FY 2004 Objectives:** The purpose of this project is to study chemical solution deposition methods for single buffer-layers in YBCO/RABiTS superconductor wires. The study focuses on the development of microstructure during epitaxy and the mechanical phenomena that produce cracks during dip coating, pyrolysis, crystallization and epitaxy. The primary objectives for FY 2004 are:

1) Investigate and develop the precursor chemistry for LaMnO3 and MgO buffer-layer systems for deposition onto the RABiTS Ni substrates.
2) Utilize spin coating for the chemical solution deposition of LaMnO3 and MgO buffer-layers onto RABiTS Ni substrates.
3) Investigate the effect of deposition and processing conditions of $LaMnO_3$ and MgO on buffer-layer critical thickness.

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**FY 2004 Performance and FY 2005 Plans:** Two buffer-layer compositions, $LaMnO_3$ and MgO, are currently being developed for use with RABiTS Ni-alloy substrates. MgO has been selected as a buffer-layer for its low oxygen diffusion coefficient and good lattice match to RABiTS Ni-W alloys exhibiting no S superstructure. $LaMnO_3$ has been selected due to a low oxygen diffusion coefficient, apparent deposition ability, based on PLD methods, on RABiTS Ni substrates and a good lattice match to YBCO.

Solution precursors for $LaMnO_3$ and MgO have been investigated and characterized using powder X-ray diffraction. Solutions of La acetate/Mn acetate dissolved in acetic acid and either water or methanol have been chosen as the preferred candidates for $LaMnO_3$. Powder X-ray diffraction of $LaMnO_3$ precursors heated under Ar-5%$H_2$ (required to prevent Ni from oxidizing) with differing levels of $p_{H2O}$ (required to produce the $LaMnO_3$) allow the orthorhombic $LaMnO_3$ phase to be synthesized. Two precursor solutions are currently under investigation for MgO. One is a Mg ethoxide in a mixture of ethanol and acetic acid, and the other is a Mg 2-ethylhexanoate in toluene. Heat treatment under Ar-5%$H_2$ resulted in the synthesis of MgO phase as determined by powder x-ray diffraction.

The solution deposition of $LaMnO_3$ and MgO precursors has produced epitaxial films on various substrate materials when heat treated above 800°C. Epitaxial films of (101) $LaMnO_3$ has been achieved on (100) $SrTiO_3$, however, for the same atmospheric conditions, deposition of $LaMnO_3$ on Ni-alloy substrates have produced different results. Namely, $LaMn_2O_5$ has been identified besides the orthorhombic phase, $LaMnO_3$; $LaMn_2O_5$ is first observed at 800 °C. In addition, the lattice constants for the '$LaMnO_3$' phase produced on the Ni substrate suggest that it might incorporate NiO. Continued work into variations of heat treatment conditions, and atmosphere is under study to achieve a single phase epitaxial regime.

MgO has been successfully deposited on MgO and (100) $SrTiO_3$ substrates. Deposition of MgO precursors onto RABiTS Ni-alloy substrates has produced weak XRD peaks for epitaxy for current conditions.

Variations in precursor solution chemistry and thin film heat treatment have been investigated to increase the critical film thickness of $LaMnO_3$ films. Studies using $LaMnO_3$ deposited on Is substrates have resulted in critical film thickness increases when using high boiling point solvents such as polyvinylpyrrolidone or glycerol as well as slow heating rates. Film thicknesses of 230 nm have been achieved with $LaMnO_3$ on Si substrates.

*FY 2005 Plans*

- Continue research into epitaxy through chemical solution deposition of $LaMnO_3$ and MgO single buffer-layers on RABiTS Ni substrates.
- Research and develop other possible candidate materials for single buffer-layer superconducting wires, that limit the oxidation of the Ni substrate during YBCO epitaxy, and limit the diffusion of Ni to the superconductor.
- Continue research into improving thin film mechanical properties including the critical film thickness of chemical solution deposited oxide films.
- Develop a high rate solution process for the candidate buffer-layer materials.

**Research Integration:** The University of California, Santa Barbara has two research collaborations with ORNL and Sandia NL:

- ORNL: We have collaborated closely with ORNL, through Amit Goyal, in investigating the viability of $LaMnO_3$ and MgO buffer-layers via face-to-face conversations at two Society meetings, phone calls, and email correspondence. Current collaboration activities center around the use of RABiTS Ni-alloy substrates for deposition of $LaMnO_3$ and MgO thin films. Future work and collaboration will revolve around modifying the spin-on precursor system to a slot dip-coating system for the deposition of $LaMnO_3$ and MgO thin films as well as the deposition of YBCO layers on top of the $LaMnO_3$ and MgO architectures.
- Sandia NL: Paul Clem has helped us to initiate an investigation of a new MgO precursor, namely, magnesium ethoxide in trifluoroacetic acid and methanol. Initial experiments show that this precursor solution wets SrTiO3 single crystal substrates, but does not wet Ni substrates.

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| **Project Title:** | **Enhancing YBCO Performance Through Fundamental Process Evaluation and Characterization** |
| **Organization(s):** | **Albany NanoTech – University at Albany – State University of New York** |
| **Presenters:** | Manisha Rane and Kathleen Dunn |
| **FY 2004 Funding:** | $75 K (started Sept. '03) |

**Project Purpose and FY 2004 Objectives:** The main goal of the program is to develop a fundamental understanding of the mechanisms which cause defects in thick YBCO films grown on multi-layered buffered, metal substrates. To elucidate these mechanisms, Albany NanoTech (ANT) utilized its expertise in film deposition and characterization using state-of-the-art processing tools and analytical characterization methods to evaluate current standards of control over film quality and performance. We have made significant progress on both of our FY2004 milestones:

- **Process Comparisons:** Evaluate ability to control characteristics of thick films prepared by Aerosol Assisted Deposition (AAD) and Metal Organic Deposition (MOD) processing methods by developing and fabricating a significant number of samples produced internally and by our national laboratory partners. Study the relationship between film microstructure, defects, thickness, YBCO deposition process used, and the critical current density ($J_c$)
- **Evaluation of Multilayer buffers:** Influence of metal substrate and multi-layer buffer layers on the subsequent growth and performance of thick YBCO layers

**FY 2004 Performance and FY 2005 Plans:** We have pursued two methods toward accomplishing FY 2004 objectives: (i) Partnership with national laboratories and industries to acquire a large number of coated conductors on a variety of templates in order to obtain relevant samplings of each type for diversified characterization, and (ii) continued internal research on the development of AAD and MOD techniques. A summary of our work includes:

- Evaluation and identification of problems associated with growth of thick YBCO on single crystal STO substrates. As the film grows thick microstructural defects such pores, a-axis grains and second phase particles start forming resulting in the degradation of the current carrying performance of the superconductor. These defects were directly observed through Focused Ion Beam (FIB) cross-sectional and plan-view imaging and their composition was determined through X-ray diffraction (XRD), Energy Dispersion Spectroscopy (EDS) and Monte-Carlo simulations.
- Delineation of microstructural differences between reel-to-reel deposited ISD-MgO tape and ISD-MgO layers on stationary substrates and probed microstructure and metal diffusion issues on subsequent deposited YBCO/buffer films. Plan-view imaging revealed a roof-tile-shaped structure for the MgO films while columnar grains nearly perpendicular to the substrate surface were observed by FIB. FIB data was also correlated to magneto-optical images (MOI) of the YBCO layer. Cracks were observed in the MgO layer. Ni diffusion profiles studied by Second Ions Mass Spectroscopy (SIMS) depth profile suggested that no Ni was diffused into the YBCO layer.
- Evaluation of YBCO films on buffer/metal substrates synthesized by the MOD-TFA process. We have investigated the fluorine concentration depth profile and microstructural evolution in precursor films as a function of the heat treatment times and conditions. A number of samples, quenched at various stages of the heat treatment process, were investigated by Nuclear Reaction Analysis (NRA) for fluorine depth profile, by Rutherford Backscattering (RBS) for film composition and density, and by Focused Ion Beam (FIB)

microscopy for top view and cross sectional interface imaging. The knowledge gained from this work is being used by AMSC to optimize processing conditions for high $I_c$, thick YBCO films.

- Performed depositions of YBCO films from aqueous nitrate solutions, by a rapid growth AAD technique. Non vacuum processing, at low oxygen partial pressure and high substrate temperature regime, was found to be favorable for 1 to 5 μm-thick YBCO film growth. Identification of the process parameter range leads to YBCO film deposition with a/c-axis oriented grains. In addition a low cost TFA-MOD process from trifluoroacetates precursor solution was also developed to prepare 1 μm-thick YBCO films through spin coating, followed by calcination and firing and compared to AAD films.

We propose the following future research and development for FY 2005:

- Process comparison: Continue comparison studies of YBCO deposited by various techniques on multilayer buffers to develop knowledge of the preferred orientation via innovative electron and ion microscopy (SEM, HRTEM, FIB), surface techniques (SIMS, XPS, AFM), and depth profile techniques (XPS, NRA).
- Improve flux pinning: Evaluate the effects of second phase inclusions such as the Y211 phase, ytrria, or other oxide and non-oxide nanoparticulate inclusions to enhance flux pinning. The effectiveness for various methods to incorporate such inclusions will be carefully monitored through microscopic and spectroscopic studies.
- Lower ac losses: Study patterned YBCO layers with linear striations by removing strips of the superconductor through laser ablation in order to investigate reduction in hysteretic loss and identify composition changes taken place during ablation.
- Low cost processing: Develop and improve internal non-vacuum YBCO deposition schemes for faster processing and preparation of thick (1-5 μm), c-axis films on buffered substrates. Perform associated structural, chemical, and electrical characterization.

**Research Integration:** To better understand the relationship between film microstructure, defects, thickness, YBCO deposition process, we have established collaborations with national labs and industrial partners including Argonne National Lab. (ANL), Air Force Research Lab. (AFRL), UES, Inc., IGC-Super Power, American Superconductor (AMSC), and Wright State University (WSU) that have improved our program capabilities by providing processed films for microstructural characterization.

- ANL, UES: We are working with ANL and UES on characterization of YBCO layers on growing and stationary substrate MgO films and multi-layer buffers. We are collaborating with ANL on evaluating local texture at various stages during buffer growth, transfer of texture from buffer to conductor, and the resulting effect of conductor's electrical performance.
- AFRL: We continue to collaborate with AFRL on striation of YBCO layers through laser ablation, and delineation of the microstructural difference between striated and non-striated areas. Additional techniques to pattern long YBCO tapes are being evaluated.
- AMSC: We have collaborated closely with AMSC to obtain coated conductors prepared by solution based processes using metal trifluoroacetate (TFA) precursors. Our plans for FY 2005 are to continue this partnership, our target is to evaluate fully processed thick (1 - 2 μm) YBCO films with $J_c > 2$ MA/cm$^2$.

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| **Project Title:** | **Epitaxial Electrodeposition of Metal and Metal Oxide Capping Layers for RABiTS-Based Second Generation Coated Conductors** |
| **Organization(s):** | **University of Missouri-Rolla** |
| **Presenters:** | Jay A. Switzer |
| **FY 2004 Funding:** | $150 K |

**Project Purpose and FY 2004 Objectives:** The goal of the proposed project is to apply recent advances in epitaxial electrodeposition of metals and metal oxides to develop a new epitaxial substrate coating process and high rate manufacturing technology for commercial lengths of YBCO. A high throughput, non-vacuum technology is proposed that would extend the operating temperature of commercial high field superconductors up to 77 Kelvin, and enable broad new markets. This approach, if successful, would address three of four key research areas: improved wire fabrication, production of high engineering current density tapes, and lower cost of wire fabrication. Epitaxial electrodeposition has been developed in the past three years to deposit films and epitaxial nanostructures of both metals and metal oxides. This research will be performed in partnership with Sandia National Laboratories (SNL), Microcoating Technologies (MCT), and Oxford Superconducting Technology (OST). We have substantially achieved all of our FY2004 project milestones, in addition to beginning work on a FY2005 milestone on the electrodeposition of epitaxial CuO. The FY2004 milestones are listed below:

1) Electrodeposit Ni and Cu2O on Cu(001) single crystals and Cu(001) RABiTS.
2) Characterize films by XRD pole figures, STM/AFM and EBSD.
3) Determine effects of additives on roughness.

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**FY 2004 Performance and FY 2005 Plans:** Films of $Cu_2O$, Ni, and CuO were deposited onto Cu(001) single crystals and Cu RABiTS. The $Cu_2O$ films were deposited from a solution of 0.4M $CuSO_4$, 3M lactate ion, with the pH adjusted to 9.0 with 5M NaOH. The films were deposited at room temperature, at a current density of 10 $\mu A/cm^2$, to a total thickness of about 1 µm. The orientation of the film was primarily [001]. The [111] pole figure showed four sharp spots at a tilt angle of 54.7 degrees, consistent with cube-on-cube epitaxy. There was little or no evidence of a fiber texture. The SEM of the film showed that it was highly faceted. Preliminary work showed that by switching the deposition bath to one based on tartrate ion at pH 13-14, the film was very much smoother.

Films of Ni were deposited onto Cu RABiTS from a Watts bath consisting of 60 g/L $NiSO_4$, 10 g/L $NiCl_2$, and 10 g/L $H_3BO_3$. The deposition was performed at room temperature, at an applied potential of -0.7 V vs. AgCl, to a total thickness of 1 µm. The film orientation was [001]. The pole figure showed four sharp spots at a tilt angle of 54.7 degrees. The surface roughness was measured by AFM to be about 15 nm rms.

Films of CuO were deposited onto Cu RABiTS from a solution of 0.2M $CuSO_4$, 0.2M L-tartaric acid, and 2.5M NaOH. The deposition was performed at a temperature of 30 degrees, at an applied potential of +0.4V vs. SCE, to a total thickness of about 1 µm. X-ray diffraction $\theta$-$2\theta$ scans show that the CuO film grows in the [010] direction on Cu(001). X-ray pole figure analysis indicates that the CuO film has two equivalent epitaxial domains with orientation relationships of CuO(010)[001]||Cu(001)[110] and CuO(010)[001]||Cu(001)$[1\bar{1}0]$. Scanning electron microscopy reveals that crosshatch patterns of CuO with 25 nm wide and 150 nm long orthogonal features are formed on top of the substrate. Preliminary results showed that the crystallographic orientation and chirality of the film can be controlled through the use of chiral complexing agents. The resistivity of the electrodeposited CuO film is 21 Ω-cm at 300K and the activation energy for the resistivity is 0.12 eV.

For FY2005 we would like to extend our work on the use of additives to control the crystallographic orientation and roughness of the electrodeposited $Cu_2O$, Ni, and CuO. For example we have found that using tartrate ion to complex the Cu(II) produces much smoother $Cu_2O$ films, and that the hand of chiral CuO films can be controlled by changing the enantiomer of tartrate ion used in the deposition bath. We would like to develop new deposition waveforms that will allow us to electropolish the films during deposition. We would also like to extend our portfolio of electrodeposited oxides to include highly-conducting $PbO_2$ and $Tl_2O_3$, and superconducting $KBaBiO_3$.

**FY 2004 Research Results:** most of the research results were summarized above. X-ray pole figures are shown in Fig. 1 for an epitaxial film of $Cu_2O$ on a Cu RABiTS. Fig. 2 shows an SEM micrograph of a CuO film deposited onto a Cu RABiTS. The orthogonal microstructure of the CuO film may lead to a reduction of critical currents if the 90 degree grain boundaries are transferred to the superconductor overlayer. The smoothest $Cu_2O$ films with a cube-on-cube epitaxial relationship were deposited at pH 13 using tartrate ion to control the morphology.

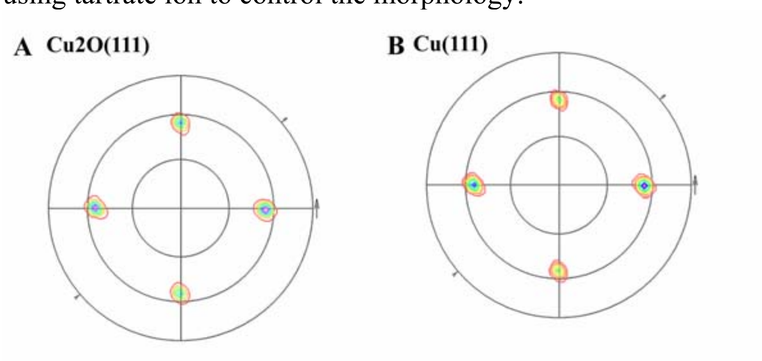


**Fig. 1. (111) Pole Figures of Electrodeposited $Cu_2O$ and Cu(001) RABiTS**

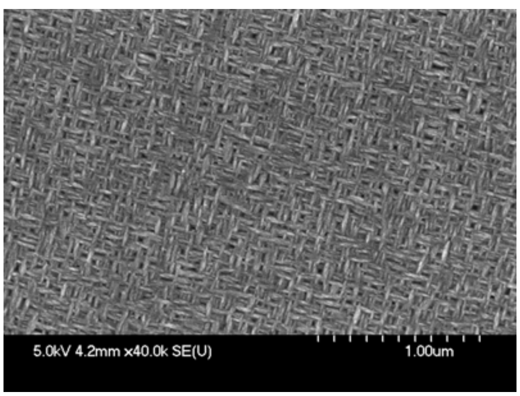


**Fig. 2. SEM Micrograph of Electrodeposited CuO on a Cu(001) RABiTS**

**Research Integration:** Our main interaction has been with Dr. Amit Goyal of Oak Ridge, who has provided us Cu RABiTS for our deposition studies. We have deposited epitaxial Ni, $Cu_2O$, and Cu onto these substrates. He and Dr. Paul Clem of Sandia have also provided input on the desired microstructures and orientations. Our $Cu_2O$/Cu RABiTS samples will be sent this year to Paul Clem for sol-gel coating of YBCO superconductors.

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| **Project Title:** | **Systematic Evaluation of Jc Decrease in Thick Film Coated Conductors** |
| **Organization(s):** | **University of Houston** |
| **Presenters:** | Jianming Zeng, Alex Ignatiev |
| **FY 2004 Funding:** | $75 K |

**Project Purpose and FY 2004 Objectives:** The original objectives of the project were significantly curtailed due to budget reductions. The purpose of this project however, remains as addressing the thickness dependence of $J_c$, in thick film YBCO coated conductors. To accomplish this we are fabricating and characterizing a series of thick film YBCO samples (from 0.5 to 8 μm thickness) on oxide and RABiTS substrates by high growth rate photo-assisted MOCVD. The oxide substrates, although not commercially viable, play an important role in helping to better elucidate the $J_c$ vs. thickness problem by partially eliminating the question of quality of cube texturing of the substrate.

The FY-04 objectives of the project under its significantly reduced scope from the original proposed work are to fabricate a series of thick YBCO samples (from 1μm to 8 μm) on $LaAlO_3$ substrates. This objective was fully met with over 20 different samples of thick film YBCO made ranging in thickness from 1.5 μm to 15 μm.

**FY-04 Performance and FY 2005 Plan:** Thick YBCO film growth yielded a series of YBCO films with thicknesses mainly from 3 to 10 μm thickness. Some thinner films were grown as were several films of up to 15 μm thickness. The YBCO films were grown by photo-assisted MOCVD on $LaAlO_3$ (LAO) substrates utilizing both single precursor liquid source delivery and multiple precursor solid source delivery. Both systems gave similar quality films and both have been able to grow thick films. The growth rates used were conservative at about 0.2 – 0.3 μm per minute. Higher growth rates have previously been shown to be effective, and will be used in future work.

The intriguing part of the work is that the thick film samples grown by photo-assisted MOCVD have all exhibited extremely high crystalline quality. SEM micrographs for nominally 10 μm thick YBCO samples show high film density throughout the film thickness with a minimum of observed macro-defects. XRD data reveals a high degree of atomic ordering both in plane and out of plane as shown by pole figure data with a FWHM of ~1.5°. Selected are electron diffraction data show extremely high crystalline quality YBCO and excellent crystalline orientation between the YBCO and the $LaAlO_3$ substrate. TEM bright field data indicates some stacking faults at the YBCO-substrate interface with, however, a sharp interface between the YBCO and the substrate. In addition, the top surface of the YBCO samples is seen to be well structured with no defects, supporting the SEM data of high-density YBCO films. Such data indicating extremely high crystalline quality YBCO films is not unexpected for growth of YBCO on crystalline oxide substrates, although this has not been previously exhibited for such thick film samples. The $J_c$ data for these high quality thick films, however, is consistently low: ~ 2 – 5 x $10^5$ A/cm$^2$. The high degree of crystalline quality, the high film density and the absence of voids and large defects in the films indicate that poor film microstructure cannot be responsible for the low $J_c$ values. However, on the other hand, the extremely high crystalline quality of the MOCVD-grown films may be responsible for the low $J_c$ through the lack of pinning centers in the films much like in high quality single crystal bulk samples, i.e., the photo-assisted MOCVD YBCO films are too good.

**FY 2005 Plan:** The FY-05 plan will e modified to add to the proposed schedule of further characterization of thick films grown on oxide substrates and extending thick film growth to metal substrates, the attempt at several approaches to increase pinning centers in the MOCVD–grown thick films. These will be done in collaboration with groups that have studied pinning center enhancement in bulk YBCO materials by radioactive decay techniques, and those that have expertise in pinning center generation by ion implantation techniques. It is expected that this additional effort will not only help clarify the supposition of too good of crystalline quality for MOCVD grown thick YBCO films, but also will identify viable approaches to enhance pinning and hence $J_c$ in thick film YBCO for use in commercial coated conductor wire fabrication. This additional reprogramming of effort in FY-05 is expected to be accommodated under additional industry support, and under a request for additional government funds.

**Research Integration:** The advancement of MOCVD processing for coated conductor applications has been closely integrated from the beginning with industry through a partnership with Metal Oxide Technologies Inc. (MetOx). We have successfully transferred the photo-assisted MOCVD growth technology to MetOx for wire development, and have continued to transfer technology to MetOx for advancement of their coated conductor wire effort. We will within this program, move the thick film YBCO growth and optimization technology to MetOx, and under partial funding support from MetOx will work toward identifying commercially viable techniques for enhancing $J_c$ in MOCVD-grown YBCO coated conductors.

ORNL: We will begin to supply thick film samples to ORNL for additional microstructure characterization and corroboration of HTS properties, and will fabricate and send for characterization, thick film YBCO samples on RABiTS substrates supplied by ORNL. In addition, we expect to jointly investigate increased pinning techniques for YBCO thick films.

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| **Project Title:** | **Conversion of Oxy-Fluoride Based Coated Conductors** |
| **Organization(s):** | **Massachusetts Institute of Technology, Brookhaven National Laboratory** |
| **Presenters:** | M.J. Cima, Masaki Suenaga |
| **FY 2004 Funding:** | $200 K |

**Project Purpose and FY 2004 Objectives:** Direct measurements of HF pressure in equilibrium with the film during the $BaF_2$ process are needed for accurate process design and control. It is the HF partial pressure that governs the rate at which the film composition is changing and is, therefore, an important factor in controlling the composition/time trajectory of the film. Establishing the composition/time trajectory of both MOD-derived and e-beam derived films for a given set of conditions is another goal for the project. These studies will provide a fundamental understanding of the *ex situ* process for producing coated conductors. FY 2004 objectives of our project were:

1) Establish modified Knudsen cell technique
2) Make modified Knudsen cell measurements on MOD films
3) Make modified Knudsen cell measurements on pure $BaF_2$ films to compare with MOD films

**FY 2004 Performance and FY 2005 Plans:** Thanks in part to a successful collaboration with BNL, we have completed all the objectives of FY2004. MIT has extensive experience with MOD-derived YBCO coated conductors and BNL has experience with e-beam derived YBCO, so both parties have much to gain from this collaboration and we will continue it into the future. Below is a list of our successes in 2004.

1) We have constructed a modified Knudsen cell and measured $P_{HF}$ of MOD derived films using this cell. The measured $P_{HF}$ varies from 0.02 to 0.2 Pa with temperature and extent of reaction. The pressures when $YF_3$ is still present are 0.028 to 0.17 Pa with temperatures between 525ºC and 575ºC, respectively. Further reaction gives much lower pressures of 0.02 to 0.06 Pa with temperatures of 575ºC and 625ºC, respectively. Measured $P_{HF}$ were used to calculate $\Delta G$ of the reaction and compared with the literature values. The measured results are different from the estimated values of pure reactants obtained from literature values. This indicates that the literature data for pure reactants is not appropriate and that the actual reaction is more complex.
2) $P_{HF}$ of the decomposition of $BaF_2$ films were also measured. It was hoped that such measurements could be used to judge the accuracy of our method. $P_{HF}$ of the reaction is much smaller than that measured on YBCO films described above and not within our range of sensitivity. Increasing temperature increases the $P_{HF}$. Ba loss was, however, observed during heat treatment, making measurement difficult. We believe this is the result of reaction with the substrate. The measurement accuracy is not high due to low $P_{HF}$ and Ba loss. Yttrium fluoride decomposition is now being investigated as a control reaction.
3) A preliminary F/Ba trajectory of e-beam derived YBCO films from BNL was determined. The F/Ba ratio of the green film is close to 2 and does not show significant change below 700ºC. This indicates that $BaF_2$ in e-beam derived films does not decompose below 700ºC even though at those temperatures $BaF_2$ in MOD derived films can decompose without YBCO formation.
4) Given the completion of FY 2004 targets, work was begun on FY 2005 objectives. $BaCeO_3$ is a known reaction product between YBCO and $CeO_2$, however, no method for quantifying the extent of the product over the entire film has been demonstrated. We have prepared ~20 nm thick cube-textured $CeO_2$ films on YSZ substrates using a new nitrate-based MOD process. No off-axis grains were detected in these films and the in-plane texture is similar to that of the YSZ substrate. Critical current measurements will be made on these films to verify they can produce mega-amp current densities, and then the films will be removed to examine the substrate for $BaCeO_3$ using an x-ray fluorescence method.

5) Publications:
   "Reactions of oxyfluoride precursors for the preparation of barium yttrium cuprate films," Physica C 403 (2004), 191.
   "Determination of HF partial pressure during *ex situ* YBCO formation," submitted to Physica C.

In summary, our FY 2004 work provided a unique method to measure $P_{HF}$ over the precursor film by using a modified Knudsen cell. It was found that $BaF_2$ in MOD derived films can decompose without YBCO formation below 700ºC, even though $BaF_2$ in e-beam derived films is stable at those temperatures. Finally, with FY 2004 objectives met, progress was made on the FY 2005 goal of establishing a protocol to quantitatively analyze the reaction between YBCO and a $CeO_2$ buffer layer.

With appropriate external guidance to maximize our programmatic impact, we propose the following future research and development for FY 2005:

- More $P_{HF}$ measurements will be performed, especially on e-beam derived film. Precise thermodynamic analysis will give us more information on the reaction path from decomposed film to YBCO coated conductor. The degree of reaction in and out of the partial melt zone will be measured for MOD/e-beam derived films to obtain the reaction path. The amount of melt in the partially reacted film should dictate the extent of reaction with the substrate, which has a negative impact on electrical properties.
- F/Ba trajectory vs. property relationship will be analyzed for both MOD and e-beam derived films so that the heating profile can be modified effectively. F/Ba ratio is one of the most important factors controlling the amount of the melt and the release of HF gas into the atmosphere. HF gas affects the morphology of YBCO crystals and their electrical properties. The F/Ba trajectory required to obtain the highest performance will be proposed.
- A protocol will be established for the quantitative measurement of reaction with buffer layers. These measurements will be compared to film performance to determine exactly how substrate reactions affect electrical performance.
- It is believed the removal of fluorine is the rate-limiting step in the growth of $BaF_2$ derived YBCO films. To test this theory, the growth rate of the YBCO layer will be compared to the removal rate of fluorine.

**Research Integration:**
MIT has collaboration with BNL to address the difference between e-beam derived and MOD derived precursor films. This collaboration has consisted of two face-to-face meetings, one video- conference, many exchanged samples, and measurements being performed at each site.

| Project Title: | Buffer Layer Growth and the Thickness Dependence of Jc in Coated Conductors |
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| **Organization(s):** | **University of Wisconsin - Madison** |
| **Presenters:** | Chang-Beom Eom, Alex Gurevich, David Larbalestier |
| **FY 2004 Funding:** | $250 K |

**Project Purpose and FY 2004-2006 Objectives:**

***I. Buffer layer studies***: Our primary objectives were

1) To understand the mechanisms of in-plane texture improvement of YBCO films on specific buffer layers such as $SrRuO_3$
2) To control the mosaic spread of both out-of-plane and in-plane texture using a single buffer layer and to identify the optimum buffer layer, deposition technique, and deposition parameters to obtain the largest improvement of in-plane texture
3) Use MOD routes to deposit buffer layers on Ni(W) RABiTS and identify and understand the origin of and develop methods to eliminate buffer-layer defects by tracking individual buffer defects into the YBCO to determine how they affect the superconducting properties of the YBCO.

***II. Jc(t) Experiments***: Our primary objectives were:

1) To measure the Jc(t) dependence of a baseline set of ex situ $BaF_2$ films converted in a variety of ways at ORNL using both RABiTS and IBAD substrates and to develop hypotheses about how the observed behavior depends on process methodology
2) To improve the Jc(t) dependence through feedback to processing science and to decisively impact the production of >500A/cm width CC.

**FY 2004 Performance and FY 2005 Plans:**

**I. Buffer Layer Experiments**

The initial plan for IBAD-MgO buffer layer studies was to optimize the deposition parameters of various buffer layers on single crystal substrates. We have grown epitaxial $SrRuO_3$ (SRO), $SrTiO_3$ (STO), $CaTiO_3$ (CTO), $Y_2O_3$ and $CeO_2$ buffer layers on epitaxial Ni films by PLD with *in situ* high pressure reflection high energy electron diffraction (RHEED). A second aspect of the plan was to obtain YBCO/buffer ($SrRuO_3$), and $SrTiO_3$/IBAD-MgO seed template layer samples from Quanxi Jia at LANL and characterize by AFM and x-ray diffraction to investigate the in-plane texture improvement. Jia has fabricated five different samples: a. IBAD-MgO/Ni-alloy, b. $SrRuO_3$/IBAD-MgO/Ni-alloy, c. $SrTiO_3$/IBAD-MgO/Ni-alloy, d. YBCO/ $SrRuO_3$/IBAD-MgO/Ni-alloy, e. YBCO/ $SrTiO_3$ /IBAD-MgO/Ni-alloy. AFM images shows SRO layers grow in step flow mode with smoother surface morphology which indicates planarization during the SRO layer growth. We have also set up a high resolution x-ray optics with a four-bounce monochromator in our four-circle x-ray diffraction system in order to determine the crystalline qualities and textures of each layers. For FY2005 we plan to investigate the correlation between the textures, surface morphologies and microstructures to determine the mechanism of in-plane texture improvement. We will also measure $J_c$(H) as a function of temperature for the YBCO samples on SRO and STO buffer layers.

Chemical Buffer Layer work focused on depositing La-Mn-O sol gel solutions to form LMO layers on $Y_2O_3$ seed layers on textured Ni(W) using lanthanum and manganese acetylacetonates (La-acac, Mn-acac). Because these metal acacs have low solubility in methanol and glycol, we developed, in consultation with Paranthaman (ORNL), a pyridine/propionic acid mixture as a new solvent. This dissolved much larger amounts of the acacs, allowing us to make a 0.4M solution (0.4M La and 0.4M

Mn), which was a factor of 10 higher in concentration than was possible with the methanol + glycol solvent. Studies are now being pursued by UW graduate student Kartik Venkaratam, while he spends a summer at ORNL with Paranthaman. For FY2005 we will continue depositing LMO using the sol-gel technique, experimenting with different cation concentrations and different spinning rates when depositing the solution. The LMO films will be studied using pole figure analysis to determine the phase composition and texture, and by scanning electron microscopy to investigate their microstructure.

**II. Critical current density- Thickness studies of CC**

We made extensive studies of $J_c(t)$ in the YBCO for $BaF_2$ films made by Feenstra (ORNL) using an older, "slow" and a newer ,"fast" conversion process. The slow process allowed a maximum of ~200 A/cm at ~2 μm thickness, while the faster process allowed up to ~300 A/cm at same t. $J_c(t)$ was approximately flat through thickness for both processes, while TEM analysis by Holesinger (LANL) showed a marked bimodal microstructure in the "fast" films. Magneto optical and EBSD analysis at UW showed that 40-50 μm YBCO grains were growing on the template, even when the template was IBAD-YSZ with sub-μm grain size. Thus the observed $J_c(t)$ performance is a combination of granular effects that lower overall $J_c$ while providing higher local flux pinning from planar defects arising from the new, liquid-present route. To shed further light on these strong process-dependent results, we performed a study of $J_c(t)$ on 1 μm-thick AMSC CC ($I_c$ ~270 A/cm). Unlike the $BaF_2$ films, they appear not to develop liquid during YBCO conversion and exhibit a rising $J_c$ at smaller t, consistent with models of a more 2D-like vortex behavior at small t. To help understand these complex behaviors, we are now modeling the flux pinning in a more real, multi-scale network. Careful growth of "uniform" PLD microstructures of YBCO will be used for model testing. For FY2005 we plan to separate the connectivity and pinning aspects of $J_c$ and to develop a full model of flux pinning in the 2D-3D crossover regime that will allow prediction of how best to juggle the connectivity ($J_c$-decreasing) and flux pinning ($J_c$-increasing) contributions to our 500 A/cm goal.

**FY2004 Results:** Key results include:

- Development of controlled growth of various oxide buffer layers using *in situ* high pressure RHEED
- Development of an understanding of $J_c(t)$ in high current tapes made both by the PVD-$BaF_2$ and by the MOD-TFA routes
- Development of a new flux pinning model that incorporates multi-scale pinning interactions and analyses their influences on the 2D-3D crossover

**Research Integration:** The whole effort is strongly interactive with scientists at AMSC, LANL and ORNL. $BaF_2$ studies are very tightly integrated between ORNL scientist Feenstra and UW postdoc Feldmann. Gurevich (UW) takes the data developed by Feldmann and UW student Kim as input for new theory. UW student Venkataraman is working on MOD buffer layers with Paranthaman (ORNL) and spending the summer at ORNL to better learn techniques. PVD buffer layer studies are tightly integrated between UW postdoc Das and LANL scientist Jia. The global impact of the work is discussed at the trimesterly meetings of the CC-WDG.

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| **Project Title:** | **Stanford In-Situ High Rate YBCO Process: Transfer to Metal Tapes and Process Scale Up** |
| **Organization(s):** | **Stanford University** |
| **Presenters:** | H.-Y. Zhai, J.-U. Huh, J. Storer (LANL) |
| **FY 2004 Funding:** | $100 K |

**Project Purpose and FY 2004 Objectives:** The objective is to further the goal of the Stanford high-rate electron-beam deposition process. The process is capable in principle of meeting the cost/performance (C/P ratio) requirement of $10/kA-m desired for coated conductors, and if the process can be scaled up a realistic goal for this process is a C/P ratio of $1/kA-m. The research is aimed at solving the remaining technical problems of the approach and characterizing the process requirements. There are two tasks:

**Task 1 -** Explore Scale-Up Issues of Stanford's High-Rate Electron-Beam deposition process in Collaboration with Los Alamos National Laboratory. This task is concerned with determining the required deposition temperature and oxygen activity for a given deposition rate in the Stanford chamber, and then assist the effort at LANL in transferring the Stanford Process to the system at LANL. Initially the rate will be the present value of 100 Å/s. Higher rates will be explored as success is demonstrated. The target critical current density is a $MA/cm^2$ and greater.

Making the process more robust is another objective. This will use RE metals added to the copper evaporation source to enable the Atomic Absorbtion (AA) of the RE to monitor and control the combined flux, as well to possibly reduce the number of sources from three to two.

**Task 2 -** Collaboration with Los Alamos National Laboratory on the application of Stanford's High-Rate Process on IBAD-MgO (LANL) tape. This task is concerned with determining the electrical characteristics of the Stanford Process deposited on the LANL IBAD—MgO tape. Specifically:

1) Deposition of 123 YBCO (RE123) using our existing process on metal substrates (tape) provided by LANL. Our process so far requires a high temperature. A goal will be to work with LANL to improve the diffusion and buffer layers, and to lower the temperature by additions to the liquid flux being used.
2) Structural characterization of samples by XRD, and electrical characterization including resistivity and $J_c(T,H)$
3) Provide best samples to LANL for further characterization.

The target electrical characteristics are a critical current density of a $MA/cm^2$.

**FY 2004 Performance and FY 2005 Plans:** The arrival of the Post Doctoral researcher in April, 2004 marked the real start of this project.

**Task 1:** As the LANL facility comes on line we will collaborate in determining the process parameters, in terms of Temperature, oxygen activity, O*, and rate, etc. We have been collaborating in an effort to make the process more robust in terms of monitoring and controlling the fluxes, and reducing the number of thermal or e-beam sources from three to two. This effort could have the additional benefit of making use of RE elements to maximize the high field pinning. Copper is difficult to flux monitor using AA (Atomic Absorption). Adding or combining a RE to the copper in the same source and monitoring the AA of the RE would also control the Cu flux. This is possible because of the similarity of the vapor pressures of Cu and a number of the RE's. We are investigating several options: 1. Trace of RE in Cu—monitor the AA of the RE. A few % RE in Cu would have no effect on the YBCO superconducting performance. This would still require three sources. 2. Complete replacement of Y by RE. This results in only two sources. 3. Mixture of RE's in Cu, either with Y (three sources), or without Y (two sources). In a limited number of experiments so far the predictive equation governing the relative fluxes has been roughly validated for the case of Nd in Cu. We will continue these tests with larger sources which will have more constant flux ratios over longer times consistent with film growth. We will deposit films of REBCO using our chopped-ion-gauge monitors and trial and error determination of T and O*. This will allow us to better assess the feasibility of this approach, and to test the properties of the REBCO superconductor made with the high rate with liquid assist. We will continue the assessment of the combined RE in Cu method for other RE which satisfy the requirements of AA ( ground state transition in the range of available TDLs, transition probability favorable for absorption), vapor pressure close to Cu, and superconducting properties suitable for Coated Conductors. So far the elements Nd, Er, Dy and Ho are being considered.

**Task 2**: Using LMO/IBAD- MgO tape from LANL, we first investigated different methods of establishing thermal contact with the heater block. Finally after considerable effort a technique using silver paint now results in visually seeing no difference in the color of the tape compared with the block, whose temperature is monitored by a thermal couple. A FTIR has successfully measured the temperatures and reflectance on growing YBCO on LAO, and we expect this will be possible soon on tape. Deposition on tapes are being done at various temperatures of the block, from 940$^{o}$C to 880$^{o}$C, so far. The R vs. T curves have shown improvement as the temperature is lowered, indicating chemical diffusion and reaction at the higher temperatures. Collaboration with LANL on the source of the elements in the diffusion into the YBCO are underway.

The high temperature demanded by the liquid in our process so far has been a challenge to processing on tapes. Our best performance on LAO has been with the temperature (block) of 940$^{o}$C down to about 900$^{o}$C, however recently the FTIR shows the temperature is 20 to 30$^{o}$C lower than the block temperature on growing YBCO on LAO. This suggests that we need to take the block with tape to lower temperatures, say 20 to 30$^{o}$C lower than that optimum for LAO.

If there is still signs of reaction two paths are possible: 1. Improve the diffusion barrier on the tapes. 2. Lower the melting temperature of the BaCuO liquid, allowing a lower process temperature. As we have shown, the liquid is needed for the high quality growth at the high rates, 10 nm/s to 20 nm/s, being explored. Our AFOSR program is exploring the basic materials science of the liquid phase stability region in T and O*, and will explore reported additives that lower the melting temperature. This information will provide immediate and direct information on the program here to lower the process temperature on metal tapes. Tapes so produced will be tested at Stanford and at LANL.

**Research Integration:** The Stanford DOE program is charged with supporting the effort at LANL to scale up the high rate process, and there is close collaboration. We informally exchange information with the group of Judith Driscoll and Jan Evetts at Cambridge University.