U.S. Department of Energy
Office of Electricity Delivery & Energy Reliability
Superconductivity Program

Superconductivity for Electric Systems

Superconductivity Program Quarterly Progress Report

For the Period
April 1, 2007, to June 30, 2007

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Superconductivity Program
Quarterly Progress Report

For the Period
April 1, 2007, to June 30, 2007

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For:
Department of Energy
Office of Electricity Delivery and
Energy Reliability –
Superconductivity for Electric Systems

Control Milestones and Status

Control Milestone	Due Date	Status
Section 1.1: Wire Development.		
• Short sample RABiTS using slot-die MOD CeO_2 cap-layer with I_c of 300 A/cm.	April 30, 2007	Met Feb. 15, 2007
• Operational MOCVD system providing J_c greater than 2 MA/cm^2.	June 30, 2007	Met March 14, 2007
Section 1.2: Conductor Research.		
• Improve in-field performance flux-pinning factor to less than $\alpha = 0.2$.	May 31, 2007	Met Feb. 6, 2007
• Deposit multi-functional epitaxial buffer that can replace at least 2 standard buffers with J_c of 2 MA/cm^2.	July 31, 2007	Met Jan. 10, 2007
Section 1.3: Innovative and Enabling Technologies.		
• Commissioning of enhanced ac loss testing capability.	March 31, 2007	Met March 28, 2007
• Obtain nano-dielectic materials with enhanced electrical and physical properties.	July 31, 2007	On track
Section 1.4: Applied Superconductivity.		
• Develop overcurrent model for 2G wire (DC).	July 31, 2007	On track
• Complete 30-in test dewar and carry out HV tests.	July 31, 2007	Met Feb. 23, 2007
Section 1.5: Research and Technical Support.		
• Short sample 2G wire with I_c of 750 A/cm (SuperPower)	July 31, 2007	On track
• Complete delamination-strength measure-ments at 76 K on a total of 30 slit 2G wire samples with new geometries, fabricated by AMSC and SuperPower (NIST-Boulder).	July 31, 2007	On track

Significant awards, recognitions and events

SuperPower-ORNL HTS technology wins 2007 R&D 100 Award,
A technology entitled “High-Performance LMO-Enabled, High Temperature Superconducting Wires” by SuperPower, Inc., of Schenectady, NY, and Oak Ridge National Laboratory (ORNL) is named a winner of the 2007 R&D 100 Award. Based on an ORNL patented LMO buffer technology that was wholly funded by DOE Office of Electricity Delivery and Energy Reliability (OE), this work transitioned the technology from laboratory discovery to commercial manufacturing. By fully integrating the LMO buffer technology and other innovations into its manufacturing process, SuperPower has produced second-generation (2G) high temperature superconducting (HTS) wire that is nearly 600-m long with world record long-length performance. This result makes the SuperPower 2G HTS wire “one of the 100 most technologically significant products introduced into the marketplace over the past year.” OE provided funding to ORNL (full) and SuperPower (partial) for this work as part of its strategy to accelerate the development of 2G HTS wire through partnerships with industry. In addition to the R&D 100 Award, this project also won the 2006 ORNL Excellence in Technology Transfer Award, and has been nominated for the 2007 Southeast FLC Excellence in Technology Transfer Award.

ORNL HTS researcher receives the President’s Call to Service Award.
On April 30, 2007, ORNL HTS research staff member Patrick M. Martin received the President’s Call to Service Award – the highest level of recognition in the President’s Volunteer Service Award Program. His is one of only 15 Call to Service Awards given to the entire DOE national laboratory system and site offices this year. In 2003, President Bush created the President's Council on Service and Civic Participation, which initiated the President's Volunteer Service Award Program as a way to thank and honor Americans who, by their demonstrated commitment and example, inspire others to engage in volunteer service. This particular award level recognizes individuals, families, and groups that have volunteered 4,000+ hours of services over the course of their lifetime. Over the past 15 years, Mr. Martin has been working with and mentoring one or more students and teachers in the science and technology of HTS during the summers. In addition, he has participated in numerous laboratory-sponsored outreach activities to promote HTS technology and the pursuit of an education in the sciences. In addition to these professional activities, Mr. Martin is an ORNL division representative to the Knoxville Area Rescue Ministries, the provider of musical accompaniment at his church, an instructor in the East Tennessee Whitewater Club, a co-organizer of the Paddle/Discovery Festival, and has participated in many other community activities. Mr. Martin is also a full-time foster parent of three young children.

ORNL HTS researcher is elected Fellow of the American Ceramic Society.

Amit Goyal, ORNL Distinguished Scientist and Battelle Distinguished Inventor, has been elected Fellow of the American Ceramic Society. This recognition is based on Goyal's achievements in HTS R&D, which is wholly sponsored by the DOE OE. Goyal is also a Fellow of the American Society of Metals, the American Association for Advancement of Science, the Institute of Physics (UK), and the World Innovation Foundation (UK). His work on developing the science and technology for long-length high-performance low-cost uniform HTS wire has received other recognitions including a R&D 100 award, a Nano50 Award, and an Energy 100 Award. Goyal will be formally recognized during the American Ceramic Society's 109th annual meeting at Detroit in mid-September.

ORNL a partner in two winning "Superconducting Power Equipment" projects.
In a June 27, 2007, DOE announcement, two HTS projects with ORNL as partner were named winners in the Superconducting Power Equipment solicitation. These research demonstration projects will advance the development and application of HTS, which have the potential to alleviate congestion on an electricity grid that is experiencing increased demand from consumers. "Modernizing our congested and constrained electric grid - through the development of advanced, new technologies – is vital to delivering reliable and affordable power to the American people," Secretary Bodman said. "As demand for electricity continues to grow, we must take steps now to identify potential problems, identify solutions, and deploy new technologies to provide a secure and steady energy supply…:"

ORNL will be involved in two of the five winning projects. The two projects are:

1) *Southwire Company HTS Cable Project:* Southwire Company (Carrollton, GA) will use a 13.8-kilovolt HTS cable to connect two existing substation sites and solve a real-world electrical load problem near downtown New Orleans. The substations are owned by Entergy Corporation of New Orleans, LA, a member of Southwire's project team. The team also includes: DOE's Oak Ridge National Laboratory and nkt cables of Germany.
2) *SuperPower, Inc., HTS Fault Current Limiter Project:* SuperPower, Inc. (Schenectady, NY), will design, test, and demonstrate on the American Electric Power grid a 138-kilovolt HTS fault current limiter. The team also includes: Sumitomo Electric Industries, Ltd. (Osaka, Japan); Nissan Electric Company, Ltd. (Kyoto, Japan); The BOC Group, Inc. (Murray Hill, NJ); American Electric Power (Gahanna, OH); and DOE's Oak Ridge National Laboratory.

ORNL HTS Program is partner in 3 SBIR/STTR Phase I awards.

ORNL HTS staff members are involved in 3 of the 5 SBIR/STTR Phase I awards announced on April 27, 2007. These projects are:

1) American Superconductor Corporation: Low AC Loss YBCO Coated Conductor Geometry by Direct Inkjet Printing.
2) Composite Technology Development: Nanocomposite Insulation for 2G Superducting Wires.
3) Directed Vapor Technologies: High Rate Deposition of Epitaxial Films for Use in Superconducting Coated Conductors.

Of particular interest is the new collaboration with Composite Technology Development, Inc. (CTD), of Colorado. CTD is a small business that has been involved in cryogenic dielectrics development for the high energy physics community, as well as in innovative nano-composite dielectric materials.

Section 1.1: Wire Development

Focuses on materials processing and manufacturing issues that directly impact the cost, performance, application characteristics and scale-up of commercial 2G wires.

Subtask 1.1.1: ORNL – American Superconductor CRADA to develop RABiTS/MOD based 2G wire.

A. Goyal, F. A. List, M. P. Paranthaman, P. M. Martin, S. Sathyamurthy, S. Cook

Objectives:

This subtask is focused on the development of the $REBa_2Cu_3O_x$ (REBCO) RABiTS-based coated conductor technology that is in the pre-commercial development stage and requires further studies. The goal of the project is to establish a low-cost, high-performance, high throughput, high yield manufacturing process for the commercial manufacturing of RABiTS-based 2G wire. To achieve this, various tasks are focused on the improved understanding of the material science related to fabrication of RABiTS templates, metal organic deposition (MOD)-based REBCO layers, and detailed characterization and correlation of 2G wire properties with the process stability. The subtask is closely coupled to AMSC's 2G scale-up program and assists AMSC in developing and implementing a robust manufacturing process.

Highlights:

Texture improvement in Y_2O_3 seed layers on NiW substrates understood. New understanding used to fabricate substrates with sharpest texture and with highest self-field I_c to date.

Typically some texture improvement is observed in Y_2O_3 deposited on NiW substrates by reactive sputtering at AMSC. This texture improvement is critical to obtain the high performance YBCO films that AMSC has been fabricating. However, until now this texture improvement was not understood. Moreover, in the recent past, AMSC was finding that the sharpness of texture in this layer was varying even though the texture of the NiW was constant. Solving this problem was deemed critical to scale-up activities at AMSC. Based on recent understanding, significant progress has been made in fabrication of films with improved textures. Transport characterization of 0.8-μm MOD YBCO film gave the highest J_c obtained by AMSC so far – a J_c of 4.8-5 MA/cm^2 at 77K, self-field or an I_c corresponding to 380-400 A/cm at 77K, self-field!

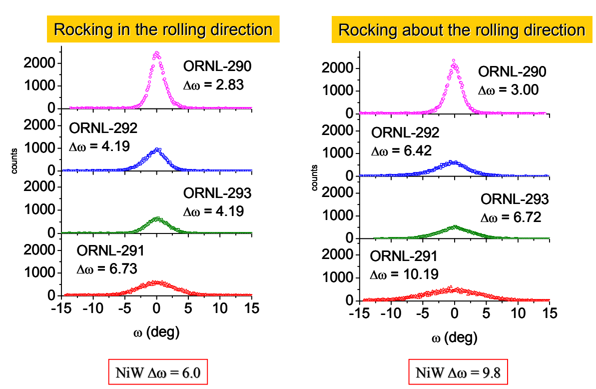


Fig.1. Out-of-plane textures for rocking the sample in or about the rolling direction for four Y_2O_3 films grown epitaxially on NiW substrates of constant texture. Clearly a big variation in the textures of the films can be observed.

A series of films with different textural sharpness of Y_2O_3 layers on NiW were examined at ORNL by X-ray diffraction and TEM. Figure 1 shows that the out-of-plane textures of four films made under different deposition conditions. Clearly a significant difference in the full-width-half-maximum (FWHM) of the out-of-plane texture of epitaxial Y_2O_3 layers is seen on NiW of the same texture. The difference in the FWHM can vary by as much as 7 degrees! Figure 2 shows the FWHM of the out-of-plane texture plotted as a function of the tetragonal distortion. The tetragonal distortion is defined as = c/a – 1. The figure shows that the film with the broadest FWHM of the out-of-plane texture is in tension as it has a negative tetragonal distortion. The other three films are all in compression and the film with the sharpest texture is the most in compression. Prior work on epitaxial CeO_2 layers at ORNL has shown that variation of oxygen stoichiometry in the films puts the films in tension. The variation in the sharpness of texture in the epitaxial Y_2O_3 films on NiW was also attributed to variation in the oxygen stoichiometry. This information was provided back to AMSC and they devised a method to better control the oxygen stoichiometry during the deposition of Y_2O_3 films and constantly obtain sharp textures in the Y_2O_3 film.

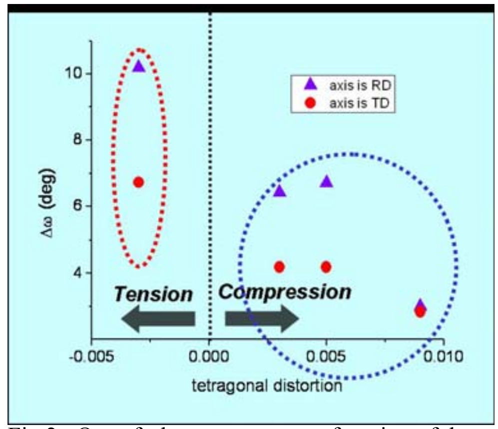


Fig.2: Out-of-plane textures as a function of the tetragonal distortion for four Y_2O_3 films grown epitaxially on NiW substrates of constant texture. The film with the broadest texture is in compression and the film with the sharpest texture has the most compressive stress.

YBCO (0.8 μm)	Δω=2.6°,2.5; Δϕ=5.1°
CeO_2 (75 nm)	Δω=2.5°,2.6°; Δϕ=5.3°
YSZ (75 nm)	Δω=2.6°,2.7°; Δϕ=5.3°
Y_2O_3 (75 nm)	Δω=2.8°,2.9°; Δϕ=4.9°
NiW 75 μm	Δω=5.6°,5.2°; Δϕ=6.6°

Fig.3: In-plane (Δω) and out-of-plane (Δϕ) textures through the stack. The very sharp texture in the Y_2O_3 seed layer is transmitted to the YBCO layer. The texture in the YBCO layer is the sharpest out-of-plane and in-plane texture obtained to date.

In keeping this summary short, details about the mechanisms of texture improvement are not being included here. However, based on theoretical analysis and cross-section TEM analysis, a large lattice mismatch between NiW and Y_2O_3 as well as incoherent growth of Y_2O_3 on NiW contributes to the sharpening with a tendency for the c-axis of the Y_2O_3 to shift towards the surface normal of the NiW substrate for films which have adequate oxygen content. Finally, based on this understanding, significant progress has been made in fabrication of films with improved textures. Y_2O_3 films with the sharpest texture to date were fabricated under appropriate conditions. Figure 3 shows the texture of various layers in a stack of NiW/ Y_2O_3/YSZ/CeO_2/YBCO. Transport characterization of this 0.8-μm-thick MOD YBCO film gave the highest J_c obtained by AMSC so far – a J_c of 4.8-5 MA/cm^2 at 77 K, self-field or an I_c corresponding to 380-400 A/cm at 77 K, self-field!

Technical progress:

Significant progress is also being made in the areas of strengthened substrate fabrication. Here the focus is on fabrication of composite substrates with a surface cube-texture. Very significant strides forward have been made with high-speed slot-die coating of $La_2Zr_2O_7$ solution-based buffer layers. Detailed progress report on these two topics will be provided in a subsequent report.

Status of milestones:

- Short sample RABiTS using slot-die MOD CeO_2 cap-layer with I_c of 300 A/cm. (April 30, 2007): **Met February 2007.**

- Fabricate MOD LZO barrier buffer with homogeneous texture and a mosaic less than 2 degrees using a slot-die coating system on 4-cm-wide RABiTS. (July 31, 2007): **On track.**
- Demonstrate an I_c greater than 800 A/cm on 4-cm-wide continuously processed RABiTS with a solution LZO buffer. (August 31, 2007): **On track.**

Interactions:

Interactions with AMSC included regular progress and planning teleconferences, as well as numerous and frequent sample exchanges with follow-up discussions on results. Also, on-site visits were held as events warranted.

Subtask 1.1.2: ORNL – SuperPower CRADA to develop IBAD/MOCVD-based 2G wire.
M. P. Paranthaman, T. Aytug, R. C. Duckworth, A. Goyal, P. M. Martin, D. K. Christen

Objectives:
A critical need that was identified in the DOE Coated Conductor Roadmap is the development of a high throughput and economic deposition process for REBCO. SuperPower has demonstrated that REBCO films can be deposited by metal-organic chemical vapor deposition (MOCVD) at relatively high throughputs with world record performance. In addition to high critical current density with increased film thickness, flux pinning properties of REBCO films needs to be improved to meet the requirements for various commercial electric-power equipments. Various tasks in this project are focused on an improved understanding of the material science related to the fabrication of IBAD-MgO template, MOCVD deposition of REBCO films, and the detailed characterization and correlation of the 2G wire properties with the process stability. Another focus of this project is to investigate HTS conductor design optimization with emphasis on stability and protection issues, and ac loss measurements for SuperPower REBCO coated conductors.

Highlights:
Significant progress demonstrated in 2G wire and substrate using the enabling LMO technology.
ORNL-developed, LMO buffer technology is now fully integrated into SuperPower's Pilot 2G wire manufacturing operation. This enabled SuperPower to deliver nearly 10,000 m of 2G wire for the Albany Cable project. Optimization of LMO process has led to much higher throughput. This enabled SuperPower to produce world-record 2G substrates with piece length of 1,350 meters, breaking the 1 kilometer substrate threshold for the first time. In recognition of the importance of the ORNL LMO technology, an R&D100 award was won jointly by SuperPower and ORNL in 2007 for the product titled "High-performance LMO-based HTS wire."

Technical Progress:
Systematic studies of ORNL's MOCVD process conditions conducted to explore YBCO formation
One of the important critical needs for 2G wire is to develop a high throughput and economic deposition process for YBCO. SuperPower has demonstrated that high critical current (Y,Sm)BCO films can be deposited by MOCVD at rates of 45 meters/h (135 meters/h effective speed for 4-mm-wide tapes) with world record performance. In addition to enhancing high critical current density with increased film thickness, flux pinning properties need to be improved to meet the DOE requirements for various electric-power applications. ORNL is tasked to assist SuperPower in improving thick film I_c and flux pinning using SuperPower's research MOCVD reactor, now located at ORNL.

We are carrying out systematic studies of the growth of YBCO films by optimizing deposition temperature and oxygen flow rate. In order for this study to be transparent to SuperPower operation we have kept our deposition rates similar to the scaled up version of SuperPower process rates. SuperPower's state of the art LMO/IBAD-MgO tapes were used for this study. We also initiated a new collaboration through Vic Maroni of Argonne National Laboratory (ANL) for Raman microprobe analysis. Heater temperature profile is given below. YBCO growth characteristics are affected by both temperature and oxygen flow rate (number of moles of oxygen per unit time). For instance, x-ray diffraction (XRD) data along the tape length for various samples are shown below. Notice that the amount of unwanted *a*-axis grains are reduced by increasing the processing temperature as well as decreasing the oxygen flow rate. Following the XRD work at ORNL, tapes were sent to ANL for Raman microprobe analysis. The comparison of Raman spectra for two YBCO tapes processed at different oxygen flow rates are shown below. The sample processed at a higher oxygen flow rate shows more cation/oxygen disorder and more pronounced secondary phases compared to the lower oxygen flow rate processed sample. Raman analysis gives further information as to growth characteristics of the MOCVD films and well corroborates with the XRD observations. Similar work will be extended to RE modified YBCO compositions.

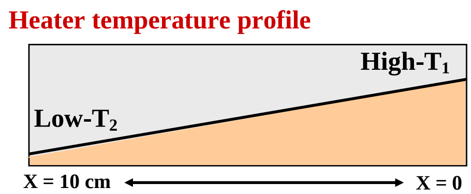


Fig. 1. Heater temperature profile of ORNL's MOCVD system

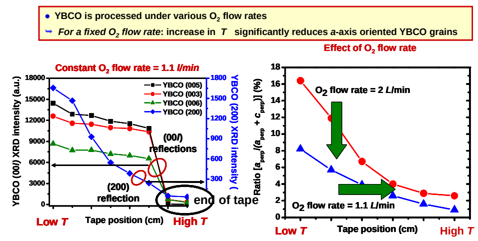


Fig. 2. XRD data of YBCO films processed at different temperatures and oxygen flow rates

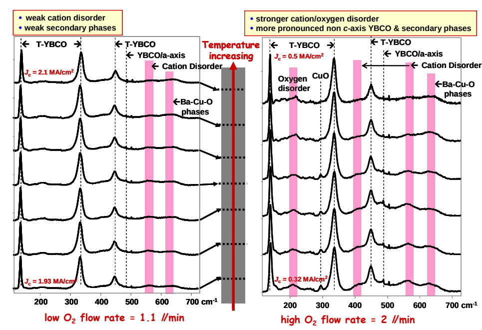


Fig. 3. Raman microprobe spectra taken on YBCO films processed at different temperatures and oxygen flow rates (Data provided by Vic Maroni, ANL)

Status of milestones:

- Operational MOCVD system providing J_c greater than 2 MA/cm^2. (June 30, 2007): **Met March 2007**.
- Assist SuperPower in developing highly textured and uniform 1,000-meter-class IBAD-MgO/LMO substrate. (Sept. 30, 2007): **Met June 2007**.
- Assist SuperPower in obtaining high I_c thick films of 750 A/cm. (Sept. 30, 2007): **Ahead of schedule.**

Interactions:

Interactions with SuperPower included regular progress and planning teleconferences, as well as numerous and frequent sample exchanges with follow-up discussions on results. Also, face-to-face meetings were held as events warranted. Initiated a new collaboration with ANL scientists for Raman microprobe analysis.

Subtask 1.1.3: ORNL – MetOx CRADA to characterize All-MOCVD 2G wires.
D. K. Christen, P. M. Martin, Y. Zhang, L. Heatherly

Objectives:
This work is focused on the development of RABiTS-based coated conductor technology that is in the pre-commercial development stage. MetOx is a Houston-based small business that is interested in developing and manufacturing 2G wire using an all-MOCVD process, including buffer(s) and HTS. If successful, there is a real potential that low-cost 2G wire can be produced due to the inherently high deposition rate of the MOCVD technique. It will also expand the number of domestic HTS wire suppliers to ensure a steady supply of the core component needed for HTS devices.

Technical progress:
1) Superconducting properties have been measured on a series of YBCO coatings produced by MetOx.
It is important to obtain superconducting properties of MetOx HTS coatings that have been deposited on either MetOx buffered RABiTS or on ORNL RABiTS for comparative evaluation and identification of processing issues. A series of five coated conductor samples were deposited by MetOx on both types of templates. ORNL conducted electrical transport measurements to determine critical current density J_c as a function of magnetic field at 77 K for fields parallel to the c axis. In addition, the effect on J_c of magnetic field orientation was established in a 1 Tesla field. Magnetic susceptibility measurements documented the super-conducting transition temperatures T_c. The data are being assessed by MetOx and ORNL to determine refinements in the processing protocols.

2) A 3-meter length of ORNL textured NiW tape was supplied to MetOx for continued evaluation of their MOCVD HTS coatings.
MetOx will continue to make depositions of both buffers and HTS coatings on textured templates for incremental evaluation and process development. ORNL textured tape helps enable the MetOx developmental approach.

- In addition, MetOx plans to provide ORNL with their buffered tape for ORNL to make qualifying HTS depositions. The ORNL HTS coatings should offer insight into areas of focus for MetOx processing adjustments.

Status of milestones:
- Deliver 10m+ textured template/RABiTS to MetOx for MOCVD buffer/HTS deposition.(Sept. 30, 2007): **Met May 2007.**
- Characterize diffusion behavior of MetOx MOCVD buffer.(Sept. 30, 2007): **On track**.
- Characterize MetOx MOCVD HTS in magnetic fields (Sept. 30, 2007): **Ahead of schedule**.

Interactions:
Interactions with MetOx have included the measurement and analysis of MetOx HTS coatings for the dependence of superconducting properties on magnetic field strength and orientation. ORNL has supplied MetOx with textured NiW alloy for the development of MetOx MOCVD buffers and HTS coatings.

Section 1.2: Conductor Research

Provides underlying knowledge base needed to address the relationships between substrate and HTS performance, processing and microstructure development, and how various factors can affect current flow over long lengths. Pertinent findings to be integrated into Wire Development research.

Subtask 1.2.1: Textured substrates with improved characteristics. A. Goyal, L. Heatherly

Objectives:

While textured metallic templates such as Ni-5%W have sufficient mechanical integrity for practical applications, enhancement in yield strength is preferred for handling during wire fabrication. This increased strength will enable higher manufacturing speed and therefore lower cost. Also, a low or nonmagnetic substrate will reduce the ac losses of the conductor. This project seeks to investigate innovative approaches to develop the materials science and solutions to the above stated issues.

Highlights:

Warm rolling key to obtaining cube texture in Ni-9.3% strengthened non-magnetic alloy.

Addition of high W contents to Ni reduces the magnetism of Ni and increases the strength dramatically. For Ni-9.3at%W composition, the substrate is completely nonmagnetic at all temperatures and has a yield strength of ~300 MPa at room temperature. Unfortunately, for W contents greater than 5at%W in Ni, a texture transition occurs upon conventional rolling. We have discovered that warm rolling will circumvent this transition, resulting in cube textured substrates using Ni-9.3%W.

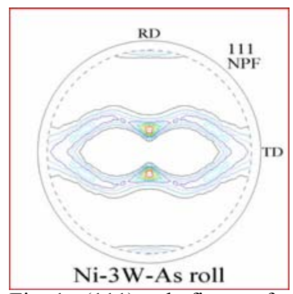


Fig. 1. (111) pole figure of 99% deformed Ni-3at%W substrate in an as-rolled condition. A typical Cu-type rolling texture is obtained.

For W contents less than 5at%, a “Cu-type or pure metal-type” rolling texture is obtained. Figure 1 shows a typical (111) pole figure for a Cu-type rolling texture in Ni-3at%W. This rolling texture is a necessary precursor for formation of the desired cube annealing texture corresponding to {100}<100>. Beyond 5at%W a texture transition occurs and a “brass-type or an alloy-type texture” is obtained. Figure 2 shows the typical (111) pole figure for a brass-type rolling texture. This does not give the cube texture upon annealing and results innumerous high-angle boundaries and is not suitable as a substrate for growth of epitaxial HTS.

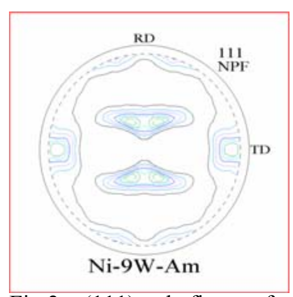


Fig 2. (111) pole figure of 99% deformed Ni-9at%W substrate in an as-rolled condition. A typical brass-type rolling texture is obtained.

In order to enable formation of cube texture in Ni-9.3at%W a processing breakthrough was necessary to reverse the texture transition mentioned above. In order to achieve this, the role of stacking fault energies was examined. It was found that the texture transition referred to above comes about because of a change in stacking fault energy upon addition of higher W amounts. Since a reverse effect in stacking fault energy is obtained as one increases the temperature of deformation, Ni-9.3at%W substrate were warm-rolled at elevated temperatures as opposed to rolling at room temperature. Figure 3 shows that upon doing so, one can reverse the texture transition from brass-type to Cu-type. The above is quite significant and upon annealing under appropriate conditions, a cube texture should form. Details about the annealing conditions and the textures obtained will be the focus of a following report.

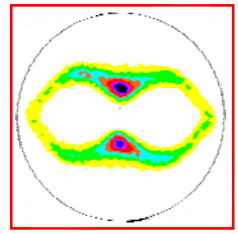


Fig. 3. (111) pole figure of 99% hot-rolled Ni-9.3at%W substrate in an as-rolled condition. A typical Cu-type rolling texture is obtained.

Technical progress:

Significant progress on the formation of cube texture on high W containing Ni alloys is being made. Details will be provided in a subsequent report.

Status of milestones:

- Fabricate a highly strengthened, Ni-alloy based substrate with reduced magnetism using a process which can be extended to long lengths. (Sept. 30, 2007) Revised: **Met June 2007.**

Interactions:

Tasks in this base program project involve close consultations and discussions with AMSC. In addition, sample from AMSC will be included in the UHMFP process.

Subtask 1.2.2: Solution buffer development for low cost conductors.
M. P. Paranthaman, S. Sathyamurthy, M. S. Bhuiyan

Objectives:
The objective of this research is to develop strategic low-cost solution based buffers for coated conductors. Buffer layers play a key role in REBCO 2G wire technology. The purpose of the buffer layers is to provide a continuous, smooth and chemically inert surface for the growth of the HTS film, while transferring the biaxial texture from the substrate to the HTS layer. HTS wire manufacturers in the U.S. are now in a position to produce reasonable quality coated conductors in "pilot-scale" mode. Cost of substrate manufacturing, however, remains high because of the relative inefficiency of physical vapor deposition (PVD) method. Solution buffer approach is an inherently low cost method that combines fast deposition rate, rapid crystallizing potential and inexpensive equipment. Indeed, an all-solution approach to buffer and REBCO processing has been projected as the cheapest route to produce 2G wires. The goal of this project is to develop the materials science and technique that can result in high quality solution buffer(s) that can sustain large critical currents comparable to its PVD counterparts.

Technical progress:
Progress continues on the development of La_3TaO_7 (LTO), La_3NbO_7 (LNO), doped CeO^2 and LZO solution buffers directly on textured metal templates in terms of out-of-plane texture improvement, thickness, roughness, density, and process refinement.

Status of milestones:
- Develop solution precursor and processing method for epitaxial solution buffer that can replace at least two standard buffers with J_c of 2 MA/cm^2 (Sept. 30, 2007): **On track.**

Interactions:
This base program research involves substantial interaction with AMSC on buffer evaluation using commercial HTS deposition process. There is also interaction with the Applied Superconductivity Center at the University of Wisconsin-Madison on buffer material development.

Subtask 1.2.3: HTS processing for critical current and pinning enhancement.
S.-H. Wee, T. Aytug, K.-H. Kim, R. Feenstra, P. M. Martin, Y. Zuev, M. Paranthaman, L. Heatherly, A. Goyal, D. K Christen

Objectives:
U.S. HTS wire manufacturers are now producing 2G wires with reasonable properties in relatively long lengths. To meet the performance requirements of practical commercial applications, however, it is necessary to further improve the HTS transport properties. For example, operation of high-field equipment (motors, generators, air-core transformers) requires performance levels of J_e of 15-30kA/cm^2 at 55-65K, 2-5 T. Performance optimization will require both sustained high current density with increased film thickness and improved flux pinning. Improvements in the properties of the YBCO coating require a thorough understanding of the pinning mechanisms, as well as control of a possible combination of nanostructures through extrinsic means. This work seeks to establish the limits of performance that are attainable via incorporation of controlled nanostructure defects within the HTS films and provide guidance or pathways to the ongoing work in CRADA's with U.S. HTS wire manufacturers to further improve the HTS superconducting properties.

Highlights:
1) Superconducting properties of state-of-the-art SuperPower prototype conductors were measured over a wide range of temperature and magnetic and electric fields.

We have combined three experimental techniques to explore the voltage-current relations of the materials over a wide parameter range. This is important because the criterion used to define critical current density, J_c, by electrical transport corresponds to excessive heat generation for use in most real applications. The detailed behavior at the low dissipation levels was provided by the extended measurements using transport, magnetization field-sweep, and current decay (flux creep) techniques to map the current vs voltage over many orders of magnitude.

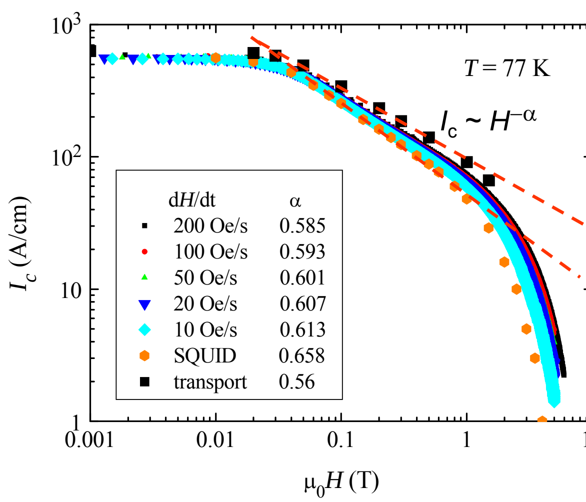


Fig. 1. Magnetic field dependence of J_c measured at different electric field levels. The power-law decay exponent shows field dependence, and is larger at the low E-fields needed for applications.

One relevant finding was a dependence on electric field level of the parameter, α, that characterizes the decay of J_c with magnetic field (i.e., the fall-off of J_c found from transport measurements may differ from that at actual operating conditions). Additional analyses of related results show potential for feasible operation of the developing materials, for example, in superconducting solenoids cooled by single-stage cryocoolers.

2) An improved scientific basis for understanding flux-pinning by self-assembled nanodot columns was provided by systematic "flux creep" studies.

High-performance HTS coatings are needed for efficient and cost-effective 2G wires. Flux pinning by controlled defect structures can provide improved properties for applications in magnetic fields. Several features related to vortex pinning have been investigated for Nd-Ba-Cu-O-based coated conductors, either undoped or doped with $BaZrO_3$ particles to form self assembled columnar defect structures.

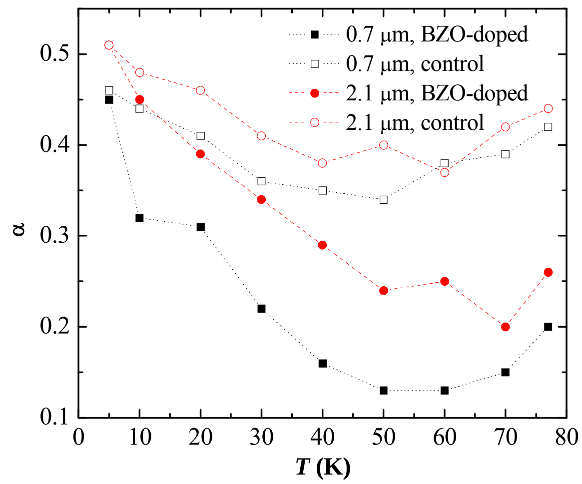


Fig. 2. The power-law exponent a describing the field-induced falloff of J_c, for several samples of undoped and BZO-doped NdBCO coatings on IBAD substrates.

Relatively thin (0.7 μm) and thicker (2.1 μm) materials on IBAD substrates were studied, and the dependence of the critical current density J_c on temperature (5 K – T_c) and on the magnitude of magnetic field (0 – 6.5 T, applied || c-axis) was investigated. Doping with BZO reduces substantially the fall-off of current density with applied magnetic field (lower α values) over the entire temperature range, with the effect most pronounced near 50-77 K. Studies of the decay with time of the current density J revealed features similar to those generated in single crystals by irradiation with heavy ions. Effective vortex pinning energies were successfully modeled with an inverse power law dependence of the form $U_{eff}(J) \sim U_0 (J_0/J)^{\mu}$, with the most notable differences between the sets of materials being the scale of current density J_0. These results help to understand the pinning of vortices and current conduction in materials with engineered defect structures, at low dissipation levels suitable for many applications

Technical progress:

Work is ongoing and proceeding well to provide an understanding of the mechanisms for self-assembly of the second-phase precipitates into stacked columns that provide strong flux pinning. The wide-range properties measurements are being further analyzed to provide guidance for applications operating parameters.

Status of milestones:

- Improve in-field performance flux-pinning factor to less than α = 0.2. (July 31, 2007): **Met Feb. 2007** (in conjunction with subtask 1.2.4).
- Understand formation mechanism of columns of self-assembled nanodots. (Sept. 30, 2007): **Ahead of schedule.**

Interactions:

The research was performed in close coordination with SuperPower, Inc. who provided the research samples for the wide-range characterizations and substrates for the BZO-doping studies. The results will assist SuperPower in a more quantitative assessment of their materials for potential applications.

Subtask 1.2.4: High performance rare-earth HTS.

S.-H. Wee, K.-H. Kim, Y. Zhang, R. Feenstra, T. Aytug, P. M. Martin, Y. Zuev, A. Goyal, H. M. Christen, M. P. Paranthaman, D. K. Christen

Objectives:

While performance and pinning enhancements are concentrated on YBCO, (mixed) rare-earth HTS have so far been neglected. The main reason for the emphasis on YBCO is because it is the most studied HTS 1-2-3 compound and ample results are available for comparison. Other rare-earth and mixed rare-earth HTS, however, have been shown to exhibit substantially different T_c, in-field performance, pinning behavior, etc., when compared to YBCO. The main goal of this project is to establish the material science base of (mixed) rare-earth growth under various deposition/conversion conditions that are suitable for 2G wire processing. Detailed characterization of their performance and understanding of various pinning mechanisms will open up new avenues for commercial 2G wire production tailored to specific applications and needs.

Highlights:

Initial studies have been conducted on a series of Sm-substituted YBCO films deposited by PLD.

We have initiated a systematic study of the effects of partial Sm substitution for Y, in order to assess the possible benefits of rare-earth replacement for performance enhancement. In this quarter, we have characterized the superconducting properties of these materials, deposited using the new deposition chamber and a series of ORNL-synthesized PLD targets of the compositions, $Sm_xY_{1-x}Ba_2Cu_3O_y$, for x= 0, 2.5%, 5%, and 7.5%. For the 7.5% substitution, the critical current density J_c is comparable to the optimized unsubstituted material. Here, all films depositions were conducted using parameters determined for the x=0 case, leading to the likelihood that further improvements can be achieved by optimizing deposition conditions specific to the 7.5% material.

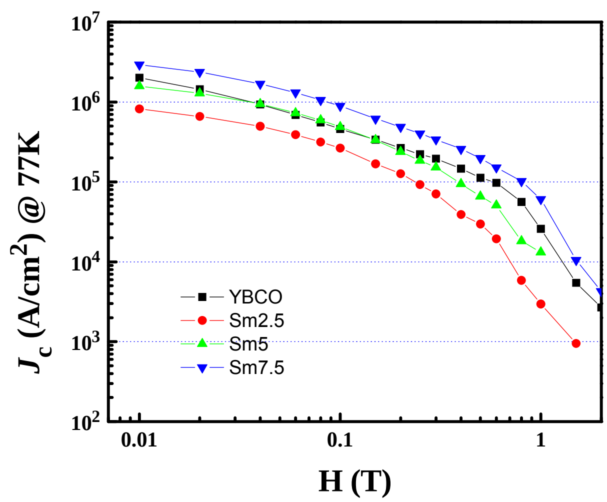


Fig. 1. Critical current density J_c measured at a low electric field criterion of 10^{-3} – 10^{-4} μV/cm, for different levels of Sm substitution in $Sm_xY_{1-x}Ba_2Cu_3O_{7-\delta}$ thin films.

Technical progress:

Work is in progress to optimize deposition conditions for the 7.5% Sm-substitutions, and evaluate the properties for thick coatings.

Status of milestones:

- Establish the (compositions) type of effective (mixed) rare earth combinations for HTS films. (July 31, 2007): **On track.**
- Improve in-field performance flux-pinning factor to less than α = 0.2. (May 31, 2007): **Met Feb. 2007** (in conjunction with subtask 1.2.3).

Interactions:
Interactions include extensive collaboration with University of Tennessee (UT) on transport and magnetic characterization and pinning analysis. Results are communicated to our industry partners to assist them in process development and planning activities.

Subtask 1.2.5: Substrate simplification to reduce cost.

M. P. Paranthaman, M. S. Bhuiyan, A. Goyal, L. Heatherly, K. Kim, T. Aytug, S. H. Wee, F. A. List, S. W. Cook, R. Feenstra

Objectives:

Buffer layers play a key role in REBCO 2G wire technology. Important buffer layer characteristics are to prevent metal diffusion from the substrate into the superconductor, as well as to act as oxygen diffusion barriers. Presently, up to 7 buffer layers are used in the standard architecture of 2G wires. To reduce cost and complexity as well as associated mechanical and reliability concerns, it is highly desirable to reduce the number of buffer layers. This may be accomplished by utilizing multi-functional materials that can combine the tasks of various buffers into one. This project seeks to develop the materials science foundation of various candidate buffer materials suitable for a simplified substrate architecture, as well as understanding and method to improve the mechanical integrity of these substrates.

Technical progress:

Research suggests that single solution buffer RABiTS architecture may be feasible.

The current RABiTS architecture consists of a starting template of biaxially textured Ni-W (5 at.%) with a seed layer of 75-nm Y_2O_3, a barrier layer of 75-nm YSZ, and a cap layer of 75-nm CeO_2 all deposited by physical vapor deposition (PVD) techniques. Further cost savings via buffer thickness reduction and simplified buffer architecture, however, will require novel buffer materials with multi-functional properties. We have successfully deposited solution based La_3NbO_7 (LNO) buffers directly on textured Ni-3W substrates. The powder XRD pattern for solution LNO buffers (5 coats) on Ni-W substrate is shown here. About 0.8-µm-thick YBCO films with an I_c of 64.7 A/cm (J_c of 0.8 MA/cm^2) at 77 K and self-field was demonstrated on newly developed single solution based LNO buffers. While this performance is rather low, it shows some initial promise that thick YBCO films can be deposited on simplified buffers. Efforts are being made to study the diffusion properties of similar solution based buffers.

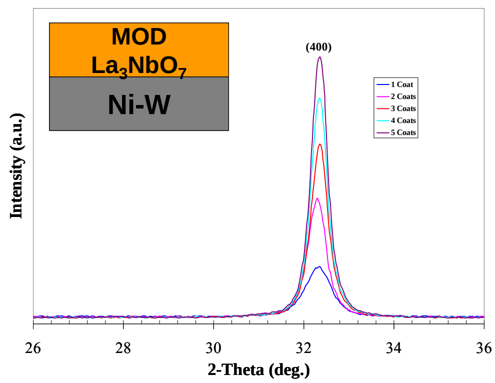


Fig. 1. Powder XRD pattern of solution LNO on Ni-3W substrate

Status of milestones:

- Deposit multi-functional epitaxial buffer that can replace at least two standard buffers with J_c of 2 MA/cm^2. (July 31, 2007) **Met Jan. 2007**.

Interactions:

Interactions include collaboration with UT on materials development. Results are communicated to our industry partners to assist them in process development and planning activities.

Subtask 1.2.6. Wire Development Group: Ex situ RBCO coatings with enhanced performance and flux pinning properties. R. Feenstra, F. A. List

Objectives:

The Wire Development Group (WDG) represents a multi-institution collaboration led by American Superconductor Corporation (AMSC). The primary goal is to establish a materials science basis for continued transport properties enhancement in RABiTS-2G wires featuring low-cost, ex situ $RBa_2Cu_3O_7$ coatings (RBCO; R is a rare earth or Y). Although the emphasis is on MOD-BaF_2 (TFA) processing for the RBCO layer, complimentary ex situ techniques such as PVD-BaF_2 and fluorine-free processes are also studied by the WDG. The multi-year vision presented at the 2006 Peer Review includes the reproducible achievement of wire operating at 1000 A/cm-width at 77 K, I_c > 500 A/cm in magnetic fields of 3 T parallel to (a,b) and 1.5 T parallel to the c-axis at temperatures ≥64 K, and pinning forces exceeding 20 GN/m^3 at 77 K. The WDG brings together the strengths and expertise of the collaborating institutions (LANL, ORNL, ANL, FSU, UH) to provide a framework for the necessary research and development.

Highlights:

Amelioration of interlayer formation in multi-coat MOD-BaF_2 precursors

To achieve large critical currents I_c in RBCO coated conductors by an MOD-BaF_2 process, AMSC has developed a multi-coat deposition process to produce precursor films of suitable total thickness. By design, the process features sub-layers which are relatively thick (0.6-1 μm), so as to minimize the number of deposition and intermediate annealing processing steps. An undesirable side effect, however, is the formation of compositional gradients though the thickness of each sub-layer. These gradients (most notably for Cu) express a dense "interlayer" of secondary phases at the interface between two stacked MOD sub-coatings during processing, affecting adversely the RBCO nucleation and growth. The severity of these effects increases with the sub-layer thickness. Building on characterization results obtained at ANL for RBCO double-coat films partially processed and quenched at AMSC, an alternative processing route ameliorating the interlayer effect was developed at ORNL.

Double-coat MOD precursors were supplied by AMSC and processed in the low-pressure conversion system. Using information provided by the real-time XRD capability as well as post-characterization of quenched films, it was recognized that previously optimized conversion conditions induce formation of Cu_2O at the interlayer position. FIB-SEM imaging of such films (performed in close collaboration with D. J. Miller of ANL) revealed that the Cu_2O segregates into a band of nearly contiguous grains, apparently without engaging the other precursor components. By contrast, following insertion of an oxidizing processing step, the Cu can be made to oxidize to CuO, which was found to chemically react with R_2O_3 to form $R_2Cu_2O_5$. The latter oxide comprises a favorable intermediary phase in the reaction path towards RBCO.

Double-coat precursors converted using this modified process appeared structurally dense and more homogenous than counterparts converted in the presence of a Cu_2O interlayer. Magnetization measurements indicate a conservative I_c underlimit of 250 A/cm at 77 K and self-field. Although further process optimization is required to match previously reported record I_c values, the alternative process is evidently robust. This holds promise for a reproducible route towards high-I_c values in long lengths of double-coated tape. As is customary for all work performed by the WDG, details of the processing have been transferred to AMSC who will evaluate similar approaches in their pilot production system.

Technical Progress:

Processing of AMSC MOD-BaF_2 precursors

One of the strengths of the WDG is the ability to incorporate out-of-the-box approaches to highlighted scientific and technological problems by synergy between the participants. As the only Laboratory participant with a hands-on thick film ex situ BaF_2 program, ORNL has taken on the task of applying their expertise in the processing of thick e-beam deposited (PVD) BaF_2 precursors towards similarly thick, multi-coat MOD precursors. Although fully processed films from PVD and MOD precursors exhibit major similarities in grain structure, grain-boundary meandering, and I_c performance, subtle differences in the precursor microstructure and fluorine chemistry mandate that subtle differences in the optimization schemes be applied. The knowledge base to simply transition between PVD and MOD precursors is presently lacking. In addition to building this knowledge base, a practical goal of MOD processing studies at ORNL is to supply an "out-of-the-box" approach to the conversion of MOD films, complementing rather than duplicating AMSC's process development.

Two furnace systems for the ex situ processing of BaF_2-type precursors are being used for this WDG research. The first is a conventional flowing gas system (at atmospheric total pressure). High-J_c films with thickness between 0.03 and 3 μm were produced consistently with this system for films on metallic substrates converted from PVD-BaF_2 precursors. The second system is unique to ORNL and features a vacuum chamber for low-pressure conversions, resistive sample heating for fast and accurate temperature control, and real-time (in situ) XRD. This system too has been used extensively for PVD precursor processing, as well as exploratory work on MOD precursors.

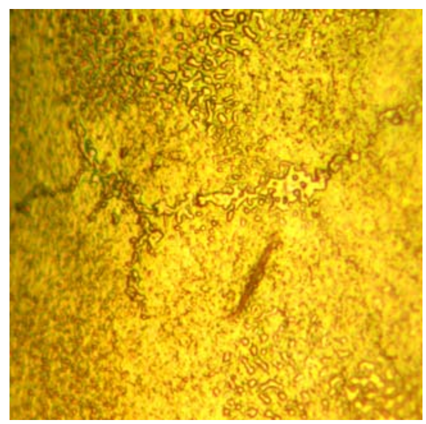


Fig. 1a.

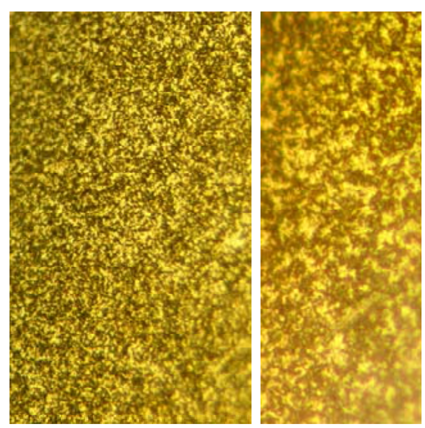


Fig. 1b

A question of some debate is the existence and possible role of transient liquid phase(s) in the conversion BaF_2-type precursors. Although strong indications for such liquids exist, it has been difficult to prove their effect. Early experimentation with the AMSC MOD precursors in both the atmospheric and low-pressure conversion systems revealed the expulsion of large amounts of liquid to the film surface. The liquid(s) appeared in the form of droplets, puddles, as well as "eruptions." EDX analysis of the latter showed the solidified phase to be a barium-cuprate. This is consistent with the existence of low-melting phases in the Ba-Cu-O phase system. Figure 1a shows an example of a puddle formed by coalescence of various droplets. Films with such large amounts of liquid-phase formation exhibited poor transport properties, indicating the need for better control. This control may be achieved by variations in the processing conditions, most notably the ramp rate to the conversion temperature, the temperature itself, and the water partial pressure (H_2O vapor initiates the BaF_2 conversion reaction). An example of a double-coat film in which excess liquid-phase formation was successfully suppressed is shown in Fig. 1b. I_c(77 K, sf) measured by SQUID magnetometry for this film was ~240 A/cm-w. The tendency for excess liquid-phase formation was found to increase with the film thickness (i.e., number of sub-layer coatings). The direction of continuing research is to develop reproducible means to control and abate excess liquid-phase formation in the multi-coat MOD-BaF_2 films.

Status of milestones:

- Initiate conversion of MOD HTS precursor and demonstrate an initial Ic of greater than 200 A/cm. (July 31, 2007) **Met June 2007.**

Interactions:

Interactions include frequent discussions and sample exchanges with WDG members including AMSC, ANL, LANL, FSU and UH.

Section 1.3: Innovative and Enabling Technologies

High-impact innovative R&D that can drastically affect the performance, cost or characteristics of HTS wires. Also R&D activities in enabling technologies that are necessary for commercial applications of HTS.

Subtask 1.3.1 : HTS filamentization to reduce ac loss.
F. A. List, R. C. Duckworth, S. W. Cook

Objectives:
As they stand presently, as-manufactured 2G wires are approaching the performance current carrying metrics. However, these wires produce high ac losses in applied ac fields (>1 W/m) that slow their immediate implementation into HTS applications. Creating filaments within the HTS structure presents one interesting solution that can reduce the ac loss, but further work is needed to understand and optimize filamentized 2G wires. These include filament width and geometry and filament width distribution, as well as J_c distribution across the surface of the template. This project seeks to examine and develop cost-effect means to produce filamentized 2G wire, and to understand the effects of various filament factors and geometries on ac losses.

Highlights:
1) Reduction of ac loss observed in YBCO filamentized samples with continuous silver stabilizer
While the reduction of ac loss in YBCO coated conductors has focused primarily on the filamentization of both YBCO and its stabilizer (copper and/or silver), a method to reduce ac loss for a continuous silver stabilizing layer has been investigated here. The use of a continuous stabilizing layer has advantages with respect to stability because current can be shared between filaments in the event of a hot-spot or filament break. However the use of a continuous stabilizer between filaments can increase the coupling losses when ac fields are applied. Through manipulation of oxygen annealing after silver is deposited on YBCO, a method to introduce barrier resistance between filaments has successfully reduced the coupling loss contribution by a factor of three in silver-coated YBCO filamentized samples.

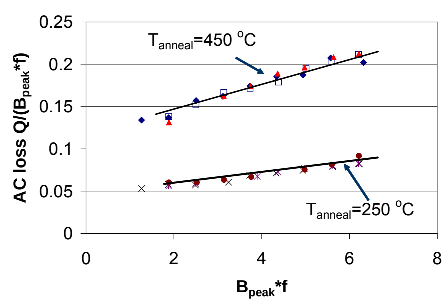


Fig. 1. Comparison of ac losses as a function of the product of the peak field and its frequency for YBCO filament samples with continuous silver stabilization that have been oxygen annealed at 250°C and 450°C for one hour.

Starting with filamentized YBCO, the YBCO surface was exposed to air for one day and then a 3 μm layer of silver was deposited onto the entire film. Once the silver deposition was completed, the samples were oxygen annealed at different temperatures for one hour, which has been shown by Ekin (1993) to impact the interface resistance between silver and YBCO. Figure 1 shows the ac loss as a function of product of the peak applied magnetic field and its frequency. For the data shown in Fig. 1, the slope of the line indicates the level of coupling loss in the filaments; the higher the slope, the higher the coupling loss. From Fig. 1, the coupling losses decreased as the oxygen annealing temperature was dropped from 450°C to 250°C, which should coincide with an increase in interfacial resistance between the silver and YBCO. This shows that it is possible to reduce the coupling component of ac loss while maintaining on continuous stabilizing layer. Future work will focus on quantifying the contact resistance/current transfer length in this configuration and determining its impact on conductor stability.

2) Reduction of ac loss by a factor of 10 in filamentized HTS conductors achieved
To establish a baseline for the work on coupling losses in continuous silver stabilized YBCO filament samples described in the highlight above, the reduction in hysteretic ac loss and elimination of coupling losses between filaments needed to be established in laser etched YBCO samples. By subjecting filamentized sample to oxygen annealing to remove HTS to substrate coupling, a factor of 10 ac loss reduction was achieved.

Starting with continuous, 0.8-μm thick YBCO samples prepared in a research MOCVD SuperPower system at ORNL, a series of 1.2-cm-wide, 6-cm-long samples were sent out for laser scribing. The power of the laser was adjusted to remove the YBCO and buffer layers but keep the underlying substrate intact. After the samples were laser scribed, one sample was oxygen annealed at 500°C to oxidize the electrical connection between the filaments. In previous work on laser-scribed samples, it has been shown that coupling between the substrate and the filaments was possible in laser-scribed filaments, but oxygen annealing the sample at 500°C for 2-3 hours removes the coupling. Figure 2 shows the removal of the coupling losses for the MOCVD samples when a sample experiences a post-oxygen anneal. From the ac loss analysis for the post-oxygen annealed film, the critical current of the sample was estimated to be 181 A. When the losses in the measured sample are compared to those predicted for a continuous 1.2-cm wide YBCO sample with the same critical current (Fig. 3), a loss reduction of a factor of 10 was achieved in the filamentized YBCO sample.

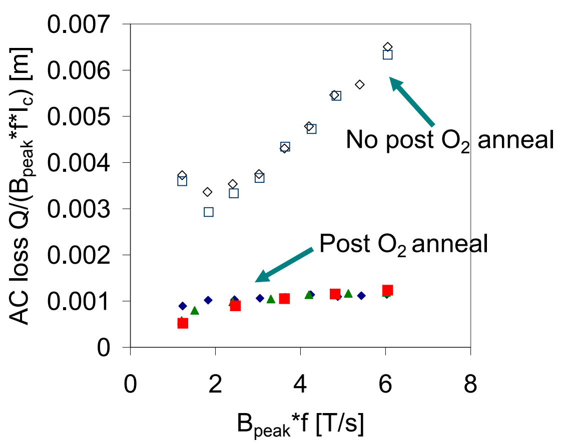


Fig. 2. Comparison of ac losses at 77 K as a function of the product of the peak perpendicular field and the frequency for a pair of laser-scribed YBCO samples--one oxygen annealed at 500°C and the other not.

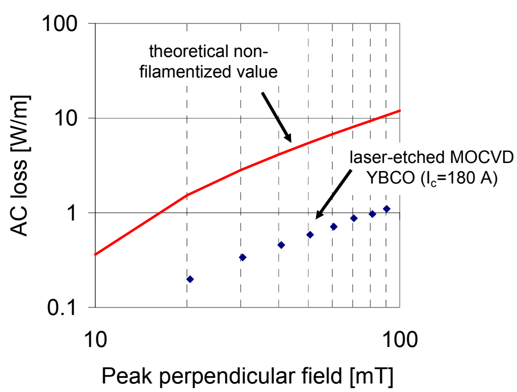


Fig. 3. Comparison of ac losses at 77 K and 60 Hz as a function of peak perpendicular field between a laser-scribed YBCO sample after oxygen anneal and theoretical ac loss for a nonfilamentized YBCO sample with same critical current.

Status of milestones:

- Benchmark stability code for transient and steady state currents. (Aug. 31, 2007): **On track.**

- Reduce ac loss by 10 times with filamentized HTS conductor. (July 31, 2007): **Met June 2007.**

Interactions:

- The inkjet filamentization work is performed in close coordination with AMSC to assist in their process evaluation and planning activities
- YBCO samples produced by a research SuperPower MOCVD system at ORNL were utilized. Samples were sent to Florida State University for MO imaging that will provide a better understanding of coupling losses in filamentary samples

Subtask 1.3.2: Conductor design and engineering for practical HTS applications.
R. C. Duckworth, J. A. Demko, M. J. Gouge, C. M. Rey

Objectives:
As long lengths of REBCO coated conductor become available from U.S. 2G wire manufacturers, the ability to study quench and stability and ac loss in superconducting cables and coils is possible. With the emphasis of using REBCO in the SPE solicitation by DOE, quantifying these and other issues on a short sample basis and in prototype devices will be necessary to assure and accelerate the successful implementation of 2G wires into these grid applications. The goal of this project is to establish the scientific foundation to understand the behaviors of 2G wires and prototypes in the areas of ac losses, quench and stability, responses of splices, etc. Yet another purpose of this research is to develop means by which these application specific characteristics can be enhanced.

Highlights:
Experimental ac loss measurements completed in YBCO prototype cables.
To help with the successful implementation of YBCO coated conductors in future superconducting cable projects, two single-phase, 1.25-m-long YBCO cables were successfully designed, fabricated, and tested. These high temperature superconducting cables were constructed to determine differences, if any, in YBCO cable construction and performance when compared to BSCCO-based superconducting cables. In addition, these YBCO cables allowed for the investigation of YBCO coated conductors from both AMSC and SuperPower, which could give us some insight into how the different tape architectures affect cable performance. While these tapes have widths of approximately 4 mm, the method of copper stabilization affects the tape stiffness and thickness and could impact the installation and performance of a YBCO cable. We have found that normalized ac losses of the two cables converge at higher I_{peak}/I_c ratios, indicating that increasing the I_c is an effective way to reduce transport losses.

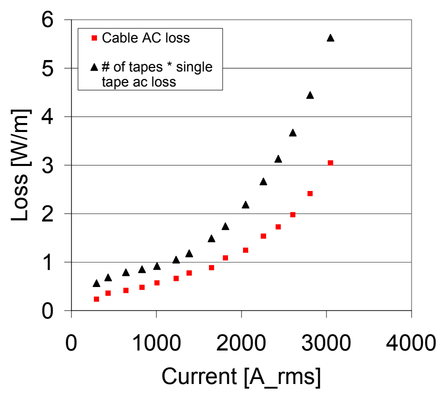


Fig. 1. AC loss at 77 K for AMSC cable as a function of ac current. The single tape result shown above is the ac transport loss on an individual AMSC YBCO tape multiplied by the number of tapes in the cable.

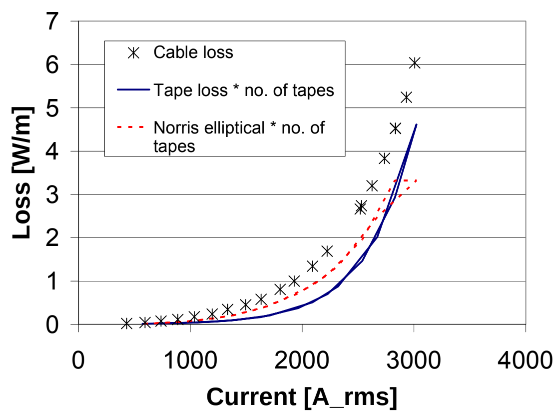


Fig. 2. AC loss at 77 K for SP cable as a function of ac current. The single tape result shown above is the ac transport loss on an individual AMSC YBCO tape multiplied by the number of tapes in the cable.

Each cable consisted of two layers of YBCO tapes wound on an insulated 1.5-in. former. These tapes were wound at opposing +/- 20 angles which allowed the current distribution to be similar as current distribution in long length cables. Based on the single tape specifications that were provided by AMSC and SuperPower, the critical current of both cables at 77 K was greater than 95% of the single tape values. The critical current in the AMSC cable was 5380 A and 4300 A for the SP cable; both values are almost twice the critical current in other YBCO cables that have been reported publicly. Figures 1 and 2 show the ac loss as a function of current for both cables and each cable was compared to the single tape ac transport loss multiplied by the number of tapes. While the functional dependence for the ac loss in the AMSC cable was similar to the single tape values, this was not the case in the SP cable. Despite this difference, there is some common functionality between the two when the critical current is taken into account as is done in Fig. 3. While the ferromagnetic substrate of AMSC causes a divergence at low currents, the convergence of the ac loss of the two cables indicate that increasing the cable critical current is an effective means of reducing ac loss in YBCO cables. Additional modeling is under way to better understand the source of the ac loss in the cable, which will meet the HTS milestone for minimization of ac loss in cable by the end of September.

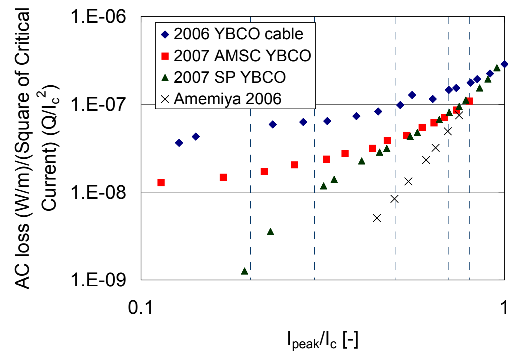


Fig. 3. AC losses in AMSC and SP prototype YBCO cables divided by the square of the critical current as a function of the ratio of the peak current to the critical current.

<u>Technical progress:</u>

<u>1) New test facility used to study ac loss in spliced YBCO coated conductor geometries</u>

Building on the successful commissioning of our new ac loss test facility, the reduction of ac loss was examined in assembled geometries using as-manufactured YBCO coated conductors. The use of as-manufactured YBCO is being considered as an alternative in the event that the cost increase that is associated with the filamentization of YBCO is significantly higher than the project tape cost.

During the last year, it was observed that spliced stacks of YBCO coated conductors reduced ac loss when compared to the nonspliced stacks of YBCO coated conductors as shown in Fig. 4. A spliced stack of YBCO, shown in Fig. 5, consists of two 2-mm-wide YBCO coated conductors, which are soldered together, and a break is added to a single tape to create a low resistance joint. On a longer sample, the two 2-mm-wide YBCO conductors would have periodic breaks in opposing layers to introduce low resistance joints along the length. However based on the previous result, it was not clear whether the break was the source of the ac loss reduction or the second superconducting tape.

By expanding the available sample area exposed to a given field in the new test facility, a new set of samples was made where just a simple copper splice was placed in the center of a 4-mm-wide YBCO and compared to a continuous 4-mm-wide YBCO tape with approximately the same critical current. From Fig. 6, there is a reduction observed for the copper spliced YBCO sample, but it was not of the same order as was seen previously in Fig. 5. While the resistive break may have helped, its influence on ac loss reduction may be secondary to the presence of the second YBCO tape. Further testing of 2-mm and 4-mm-wide YBCO samples will confirm this possibility.

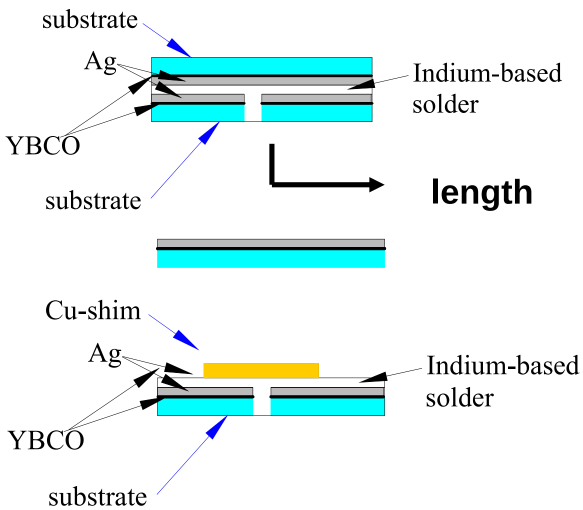


Fig. 4. Schematic of splice stack of 2-mm-wide YBCO tapes (top) and of single YBCO tape with copper splice (bottom).

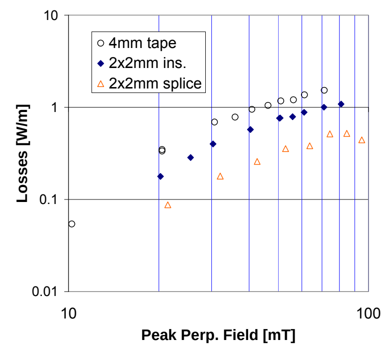


Fig. 5. AC loss at 77 K and 60 Hz as a function of peak perpendicular field for a 4-mm-wide YBCO (Ic=60 A), an insulated 2x2-mm-wide YBCO tape stack, and a spliced 2x2-mm-wide YBCO tape stack.

2) *__Splice measurements on YBCO coated conductors show orientation dependence, solder material secondary__*

Splices are an essential part of the construction of all superconducting devices. If the splice resistance is too high in a given device such as a transformer, motor, or cable, then additional heating could limit the operational limits of the device. Building on previous results of splices with BSCCO, a series of splices were made with 344-superconductor from AMSC and copper-surround stabilized YBCO from SuperPower to determine best practices for splices with a focus on solder material, splice length, and sample orientation. Sample orientation refers to whether the copper closest to the YBCO in the first sample is soldered to the copper closest to the YBCO in the second sample (H-H) or soldered to the copper closest to the substrate (H-S).

For each sample run, seven different splices are made for a given splice length, material, and orientation. The voltages are measured as a function of current for each splice as well as a control section of the YBCO tape, which makes sure the voltage that is measured, is below the critical current of the sample. A schematic of the sample and sample test setup is shown in Fig. 7.

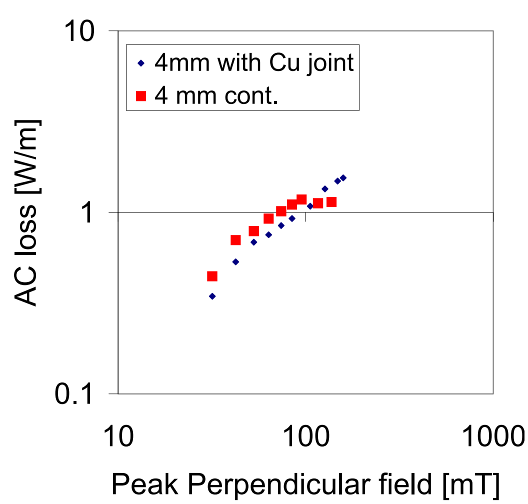


Fig. 6. Comparison of the ac loss at 77 K and 60 Hz for a copper spliced 4-mm-wide YBCO coated conductor and a nonspliced 4-mm-wide YBCO coated conductor.

Fig. 8 shows the splice resistance as a function of splice length for both AMSC and SP tapes for different solder materials and orientations. For similar solders, there was no real difference between AMSC and SP tapes and the splice resistance. However for similar tapes and solders, the splice resistance increased by an order of magnitude. While the resistance is still below 1 μohm, the orientation may become an issue as the operating current increases for a given application.

Fig. 7. Experimental setup for splice measurement of YBCO coated conductors and schematic of series of splice joints that was wound on the anodized aluminum mandrel.

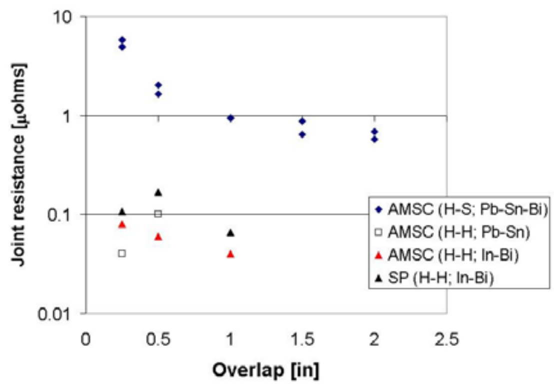


Fig. 8. Splice resistance as a function of splice length for different YBCO tapes, orientation, and solder materials

<u>Status of milestones</u>:

- Commissioning of enhanced ac loss testing capability. (March 31, 2007): **Met March 2007**.
- Establish the level of stability in spliced YBCO samples. (Sept. 30, 2007): **On track.**
- Develop theoretical methodology for ac loss minimization in YBCO cables. (Sept. 30, 2007): **On track.**
- Characterize ac loss and stability of YBCO coils as a function of cooling conditions and coil geometry. (Sept. 30, 2007): **On track.**

<u>Interactions:</u>

- AC loss measurements were conducted on YBCO as-manufactured 4-mm and 2-mm-wide YBCO tapes from SuperPower.
- Representative YBCO splices with three different candidate solders on AMSC YBCO 344 superconductor were fabricated and sent to NIST-Boulder for electrical and mechanical characterization

Subtask 1.3.3: Novel tailor-made cryogenic nano-dielectric materials.

E. Tuncer, I. Sauers, D. R. James, A. R. Ellis, M. P. Paranthaman, K. More and A. Goyal

Objectives:

In general, dielectric materials currently used in HTS grid applications (cable, transformers, fault current limiters) are essentially "off the shelf" and have not been developed specifically for cryogenic applications. Nano composite dielectrics represent a new class of materials with the potential for tailoring to the application by using base materials that operate well at low temperatures and adding nano-particles that improve specific targeted physical properties such as thermal conductivity, mechanical strength, thermal compatibility (i.e., contraction) and permittivity. Objectives of this project are to develop scientific understanding of novel cryogenic dielectric materials, identify materials and their processing to affect targeted properties while maintaining or improving the cryogenic dielectric characteristics, and correlate modeling with experimental data to facilitate the discovery of effective materials.

Highlights:

1) Measurement setup to determine thermal properties of cryogenic dielectrics has been completed and tested.

A new experimental setup was constructed using the existing cryo-refrigerator chamber. A measuring program was written to record the transient time response of materials to an applied constant-heat-input. The setup will be employed to characterize the thermal properties of both commercial and developed dielectric materials. Thermal conductivity of materials is needed in cryogenic system design.

2) ORNL obtained nanodielectric composite with enhanced thermal property without electrical degradation.

Solid dielectric materials are needed for low temperature application as spacers between high and low voltage nodes in an apparatus. Unfilled resins do not have desired mechanical properties for cryogenic applications due to cracking in a temperature cycle. Therefore they are mainly loaded with particles or fibers to enhance the mechanical integrity of the material. Although desired mechanical strength can be obtained with micron size particulate fillers, the electrical properties of the matrix degrade. It has been shown previously that nanometer size fillers do not degrade the breakdown strength of matrix resin. Unfilled and 10wt% barium titanate filled resin samples were prepared using the centrifugal mixer, and no difference in dielectric strength of the unfilled and filled samples was observed. Thermal property measurement performed with the new experimental setup indicated that the filled samples have better thermal conduction compared to unfilled ones. Resin-nanoparticle composites can be implemented in HTS grid applications when materials for mechanical support as well as for cryogen-free designs are of importance.

Technical Progress:

1) Selected candidate polymeric materials for cryogenic application have been characterized.

Performance of dielectric materials and their compatibility determine the size of electrical insulation systems. Electrical properties of polymeric materials are needed for cryogenic applications. Several polymeric materials, polyvinyl alcohol, poly(methyl methacrylate) and polyvinyl butyral resin were selected and characterized using the dielectric spectroscopy technique. The permittivity of polymers are between 3-4 at cryogenic temperatures. Their 63% breakdown values are between 100-300 kV/mm. These materials are potential candidates to be implemented in nanodielectric composites as matrix media in equipment and apparatus designed for HTS grid applications. The properties of these materials can be further improved with addition of nanometer size inclusions.

2) Selected commercially available insulating films have been characterized.
To utilize commercial electrical insulation films, which are employed in room temperature applications, in cryogenic power applications, it is needed to know the dielectric behavior of such films at low temperatures. In addition acquiring dielectric properties of such films draw a baseline for material development efforts in our laboratory such that scientists look for improvement by comparison. In addition, equipment designers can select the appropriate novel materials over these already existing films. Three dielectric films, porous high density polyethylene (Tyvek®), polypropylene laminated paper (PPLP®) and polyimide (Kapton®), were selected and characterized. It was observed that all three materials have different dielectric breakdown strength behavior. Polyimide has the highest breakdown strength of all with 63% failure probability of 300kV/mm. PPLP and Tyvek have their 63% failure probability at 113kV/mm 44kV/mm respectively. Tyvek has very low dielectric permittivity that is close to liquid nitrogen. A database is needed for cryogenic physical properties of commercially available materials for cryogenic power apparatus designers. A web-based database is in progress.

Status of milestones:

- Develop nano-dielectic materials with enhanced electrical and physical properties.(Aug. 31, 2007): **On track.**
- Build and test an apparatus for measuring thermal conductivity as a function of temperature in the range 20-300K. (Aug. 31, 2007): **Met June 2007**

Interactions:

Results are communicated to the appropriate industry partners. Also, a possible dielectrics partner has been identified and potential areas of collaboration are being discussed.

Section 1.4: HTS Applications

Work with industry to perform generic R&D on issues related to the practical application of HTS. Also work in the design, operation, reliability and efficiency of prototype HTS demonstrations.

Subtask 1.4.1: HTS Cable System R&D.
J. Demko, M. J. Gouge, C. Rey, R. C. Duckworth.

Objectives:
HTS cable systems have been demonstrated which can carry several times the current (2-5x), and hence several times the power, of conventional cable systems of the same physical size. In order for HTS cables to be commercial, however, many issues remain to be solved. Objective of this project is to perform generic research on remaining issues that are critical to the development of HTS cables systems of arbitrary lengths that will lead to the successful commercialization of HTS cables. These include the development of system components associated with high voltages, cryogenic systems for long cables, and analytical models to simulate the behaviors of wires and cables during operation.

Highlights:
The AEP Columbus HTS Cable continues to provide power to customers.
The cable continues to operate and provides power to 8,600+ residential, commercial, and light industrial customers. Thus far, the cable system has experienced four power-down events – three unplanned events and one planned maintenance – all without damage to the cable system. In addition, the cable has withstood a number of fault current events, again without damage to the cable system. The operation experience and gathered data are very valuable to the industry.

Technical progress:
Work begins on the evaluation of thermal-hydraulic effects in long cable cryostats.
ORNL began working with Southwire staff (Mark Roden) on a test to evaluate thermal-hydraulic effects in long cables/cryostats. An existing 50-m vacuum-jacketed cryostat that was used for an earlier Bixby cable prototype will be used for a pressure drop test in the field. It was decided to drop the surrogate fluid test and test only with liquid nitrogen. One major concern is that the SPE cable is proposing to use a counterflow configuration. This has been shown to be limited in length to maybe a few hundred meters for most practical sizes (see J. A. Demko, et. al., "Practical AC Loss and Thermal Considerations for HTS Power Transmission Cable Systems," IEEE

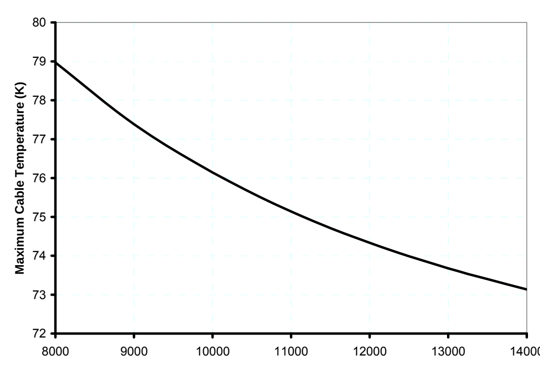


Fig. 1. Preliminary calculations of a 1700-meter long counterflow cable similar to the proposed SPE configuration.

Transactions on Applied Superconductivity, Volume: 11 Issue: 1 Part: 2 , March 2001, page(s): 1789 –1792).

Preliminary analysis results given in Fig. 1 show that for a 1700-m-long cable using the same dimensions as the existing triaxial HTS cable design require very high flow rates (~10000 g/s to limit the maximum temperature to 76 K in the cable) compared to other installations such as AEP Bixby substation (~300 to 500 g/s). The higher flows are attributed to axial and inter-stream thermal conductance effects which become exacerbated in very long length cable systems. The pressure drop scales approximately with the mass flow squared, so the system pressure drop could increase by 500 times the existing cable system. Methods to reduce these flow requirements through modifications to the triax cable design are being investigated.

An accurate thermal-hydraulic model for the proposed longer SPE cable can be developed but a cryogenic test loop is required to validate the calculations. This is proposed to be designed and installed next year depending on funding, to provide additional data needed to calibrate analysis of long length cables. The thermal effects are due to heat in-leak and ac losses which change the properties of the liquid nitrogen along the cable length. ORNL completed preliminary calculations for determining flow required to cool the long cable. The model in conjunction with the test loop results will be used to optimize the cable former diameter and the cryostat inner diameter.

Status of milestones:

- Develop overcurrent model for 2G wire (DC). (July 31, 2007): **On track.**
- Qualify new Cryoflex dielectric insulation in 15 kV and 35 kV class model cables with appropriate high voltage testing for each class. (Sept. 30, 2007): **On track**.
- Evaluation of HTS cable system architectures for long length systems. (Sept. 30, 2007): **On track.**

Interactions:

Work involves close and regular collaboration with Ultera (Southwire & nkt cables).

Subtask 1.4.3: Baldor Reliance Electric CRADA: HTS Industrial Motor.
C. Rey, R. C. Duckworth

Objectives:
HTS motors offer prospects for improved efficiency, smaller size and weight, and better overload tolerance in comparison with conventional motors. HTS motors will have half the losses of conventional motors of the same rating. Applications will be for motors above 1000 horsepower for utility and industrial customers. A 5000 hp HTS motor could save a single customer $50,000 in energy costs per year. About 1/3 of U. S. electrical energy generated is used to power motors of this rating and above. Potential energy savings for the U. S. alone, if HTS motors fully penetrate the marketplace, could be as high as $1B per year. Objective of this collaborative work with Reliance Electric is to develop HTS motors and address issues such as the use of 2G wire in rotor field coil winding, quench characterization and detection, and stable cryogenic operation.

Highlights:
Apparatus to test HTS wires at low temperatures, high currents, and high magnetic fields at various angles has been constructed and tested.
A simple but elegant test apparatus was designed and fabricated in order to study the critical current (I_c) behavior of 2G YBCO tape. The test apparatus was designed to probe the following parameter space of the 2G YBCO tape:

- High Currents (0 → >300 A) → upgrade to 580 A
- B-field dependence (0-5 T)
- Temperature dependence (30 K → 85 K)
- Angular dependence (0˚ → 90˚)
- Reasonable length scales (0 - 10 cm)
- Statistical significant sampling
- Splice characterization

Shown in Fig. 1 is a full view of the test apparatus used to test the 2G YBCO tape. The measurement portion of the test rig was attached to a Cryomech AL-330 cryocooler, which was used to cool the 2G YBCO tapes. The test apparatus was designed to measure the I_c of five discrete segments of YBCO tape originally cut from one continuous piece length. A close-up (end view) of the test apparatus is shown in Fig. 2. Each of the five separate 2G YBCO tapes was mounted on five separate measurement platforms. The five measurement platforms were oriented at the following angles with respect to the external applied magnetic field (B-field): 0˚, 30˚, 45˚, 60˚, and 90˚. During operation, the test apparatus (shown in Figs. 1 and 2) was lowered into a vacuum cryostat which was surrounded by a NbTi solenoid magnet capable of reaching magnetic fields up to 5 T.


Fig. 1. Front-view of test apparatus used to measure I_c of 2 G YBCO tapes vs. magnetic field and orientation angle (θ).

Initial tests were performed at 83 K in order to study the I_c vs. B and θ at a temperature close to T_c and in the low current carrying capacity regime of the 2G YBCO tape. Initial measurements were performed on 4-mm-wide, copper-stabilized YBCO tape fabricated by SuperPower. Test results shown in Fig. 3 are a plot of the critical current (I_c) vs. B-field for five different field orientations at 83 K. Results show that at 83 K, the YBCO tape has an anisotropic I_c in which the I_c for B-fields parallel to the axis of the tape are ~3-4 times larger than the I_c with a B-field perpendicular to the axis of the tape. For the remaining angles in between 0˚ and 90˚, the I_c shows a weak dependence on B-field orientation, in which a slight decrease in I_c is observed as the external applied B-field has a smaller parallel component (i.e., a more perpendicular component).

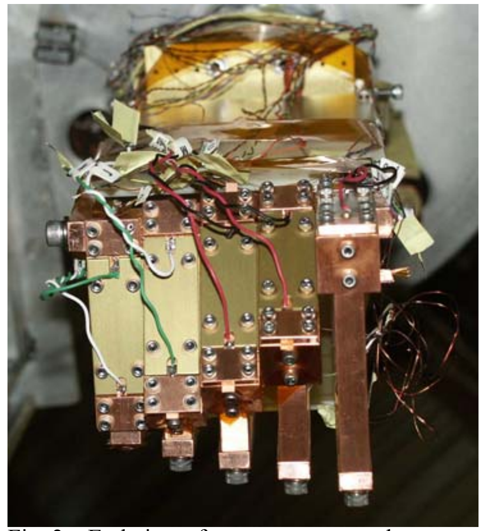


Fig. 2. End view of test apparatus used to measure I_c of 2 G YBCO tapes vs. magnetic field and orientation angle (θ).

Future plans for work performed from July through the close of the SPI effort in September 2007 include: a) presentation of results at the annual DOE Peer Review in August 2007, b) testing more samples from multiple vendors, c) investigate splice configurations vs. B, T, and θ, d) lower temperatures, and e) coordinate testing w/NIST for mechanical behavior.

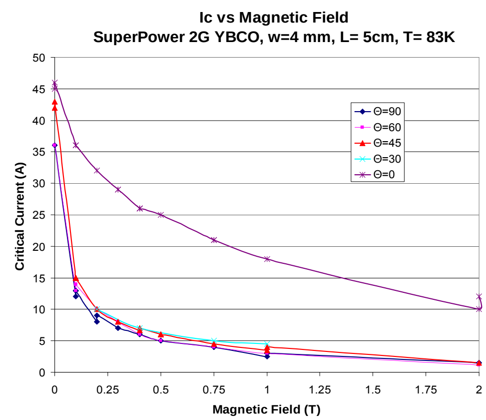


Fig. 3. I_c vs. B-field for five (5) separate field orientations at T=83 K.

Status of milestones:

- Conduct research to characterize DC loss (voltage drop vs. current, temperature, magnetic field, and magnetic field direction) in 2-G HTS tapes. (Sept 30, 2007): **Met June 2007.**

Interactions:

Work includes close collaboration with Baldor Reliance Electric. Results are communicated to Rockwell to assist in their motor development and planning activities.

Subtask 1.4.4: Fault current limiter CRADA with SuperPower.

D. R. James, A. R. Ellis, I. Sauers, E. Tuncer

Objectives:

ORNL has teamed with SuperPower, Inc., on the development of a superconducting fault current limiter (FCL). This is an enabling device that can significantly mitigate fault currents and prevent costly equipment damages. It promises to positively impact electric power transmission/ distribution reliability and security by introducing a new element in the grid that provides lower cost solutions for grid protection. Purposes of the project are to assist in the development of FCL by performing high voltage (HV) R&D on specified FCL internal components and providing technical design support.

Highlights:

Performed high voltage test of 138-kV bushing fro FCL.

A high voltage bushing which is planned to be used on the SuperPower HTS fault current limiter, has been tested at ORNL in both ambient air and in open bath liquid nitrogen. Tests included AC withstand, partial discharge, and impulse (BIL) withstand. The bushing successfully passed multiple testing.

The bushing was furnished by SuperPower and shipped to ORNL. Previous calculations and impulse testing in air by ORNL determined the gaps and spacing needed to withstand lightning impulse voltages of 650 kV of both polarities. This is the first time this laboratory has performed testing at this voltage level. Based on this information, a nonconducting stand was designed and built of wood to hold the bushing in a vertical orientation which allowed a 60-in. (1.52 m) sphere to earthed-plane gap to be set. A lifting beam was purchased which allowed the bushing to be hoisted with a large 50-cm corona ring on the top lead. For the lower termination in air, two 22-in. (55.9 cm) diameter aluminum hemispheres were obtained and welded to form a sphere (Fig. 1). The stand was also designed with a lower position that allowed the bottom part of the bushing to be immersed in an open bath of LN_2 (Fig. 2). In this case a 6-in. (152.4 mm) diameter stainless steel sphere was used with a 6-in. gap to a grounded plane at the bottom of the dewar. Much smaller gaps can be used in LN_2 since the dielectric strength of LN_2 is much higher than that of air.

Drew Hazelton and Wayne Ordon of SuperPower came to ORNL to participate in the tests which were done from April 16 – 20. The testing order followed was the same as the manufacturer. The bushing passed 5 successive negative lightning impulse voltages at 654 kV which verified the manufacturer's factory tests. Partial discharge was tested up to 100 kVrms which was the limit of the equipment and found to be 1.1 pC at 99.9 kVrms. The bushing then passed a 60 sec withstand test at 200 kVrms which was the maximum voltage of the power supply. Partial discharge tests were successfully repeated completing the air tests.

The open dewar was installed and bushing repositioned at the lower gap. A thermocouple was mounted on the bushing to monitor cooldown. Slow continuous addition of LN_2 to the dewar allowed the bushing to cool down slowly and fill the bath after several hours.

The bushing again passed 5 consecutive negative lightning impulse shots at 653 kV in LN2. The partial discharge tests were repeated again to 100 kVrms where the level was less than 5 pC and hence passed the test. An open circuit test of the partial discharge system without the bushing indicated that most of the partial discharge detected was coming from the detector system and not the bushing. The 200 kVrms withstand test for 60 seconds was again passed as was a repeat of the partial discharge test. The tan delta and capacitance measurements were performed before and after each series of voltage measurements and found to be consistent. Impulse tests were again repeated in LN_2 the next day with 5 consecutive negative withstands at 655 kV. The polarity was switched to positive and 5 consecutive withstands were obtained at 655 kV. Partial discharge was also successfully repeated. Hence overnight immersion in LN_2 did not adversely affect performance.

Fig. 1. Wayne Ordon of SuperPower inspects a 22-in. (55.9 cm) diameter aluminum sphere used as a bushing termination for air withstand tests. A large air gap of 60 in. (1.52 m) was required to prevent flashover when qualifying at 650 kV impulse voltages.

The bushing was allowed to warm up slowly over 48 hours and the high voltage tests were repeated in air at room temperature. The bushing successfully passed five negative impulses at 664 kV peak. The partial discharge test was passed at less than 1.7 picocoulomb at 100.6 kVrms. The bushing then passed a 60 second withstand test at 200.4 kVrms ac followed by a second partial discharge test which passed at 2.6 picocoulomb at 100.3 kVrms. Based on these tests, we do not believe the bushing was degraded by immersion in LN_2 and is a viable candidate for use.

Fig. 2. Left to right, Drew Hazelton and Wayne Ordon of SuperPower and Alvin Ellis of ORNL examine the lower end of the bushing immersed in LN_2. Ice formation occurs on the sheds just above the surface of the LN_2.

These successful tests also demonstrated the ability to test large 138 kV class bushings to the 650 kV BIL level in the ORNL high voltage facility.

Status of milestones:

- Participate in DOE Readiness Review to develop 2G matrix elements. (Feb. 28, 2007): **Met Dec 2006.**
- Complete HV testing of SFCL matrix sub-assemblies at ORNL. (Sept 30, 2007): **On track.**

Interactions:

ORNL has been working closely with SuperPower on the design of SFCL. There were frequent discussions and exchanges in preparation for the HV bushing test. SuperPower staff came to ORNL to participate in the above HV bushing tests in open bath liquid nitrogen.

Subtask 1.4.5: Cryogenic dielectric R&D and design rules.
I. Sauers, E. Tuncer, D. R. James, A. R. Ellis

Objectives:
Cryogenic dielectrics, like cryogenic cooling systems, is an enabling technology for HTS grid applications. Conventional dielectrics have grown with the grid over the last 120 years to higher voltage levels, now approaching 1 MV in some cases, and high component reliabilities with proven materials. Utilities expect comparable reliability for new technologies and this puts a high expectation on the performance of HTS devices. To meet the expectation, there is an increasing need for cryogenic dielectric data on liquid nitrogen and other materials, such as fiberglass reinforced plastics (G10) at longer gaps where currently the data available in the literature is sparse. Partial discharge, surface flashover, ac and impulse breakdown data are needed with sufficient statistical information to design large scale systems with adequate safety factors. In this work we focus on characterizing generic cryogenic dielectric properties, including aging studies, on existing materials, as well as developing generic design rules that can be used by the high voltage engineer in designing HTS cables, transformers, fault current limiters, and terminations.

Technical progress:
AC breakdown in liquid nitrogen
Liquid nitrogen (LN_2) is commonly used both as a coolant and electrical insulation in HTS equipment for power applications. Hence it is necessary to know the electrical breakdown characteristics of LN_2 under a variety of practical conditions. Measurements on ac breakdown in liquid nitrogen were performed in a stainless steel dewar of 30-in. (762 mm) diameter which could be pressurized from 1 to 2 bar absolute (Fig. 1). The high voltage electrode was a 4-in. (101.6 mm) diameter stainless steel sphere to a grounded plane. The finish on the sphere was a typical industrial grade which might be used in practice. A sliding seal at the top of the bushing allows the high voltage lead to be moved up and down for changing the gap in place with the electrodes still immersed in LN_2 which greatly speeds up data acquisition. The breakdown voltage increased linearly with gap over the limited range studied which is expected for this electrode geometry since the electric field is approximately uniform for gaps small compared to the sphere radius. Larger gaps were not studied since the phase-to-ground voltage rating of the bushing could not be exceeded.

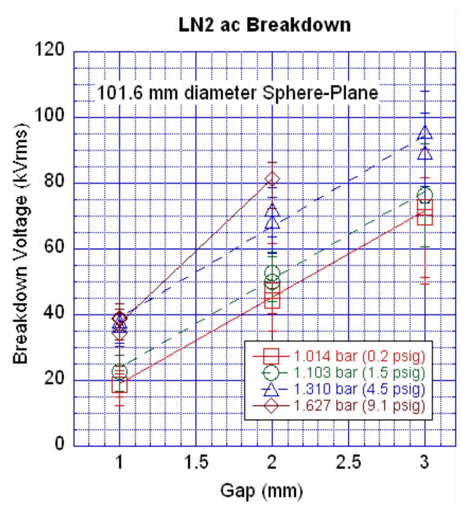


Fig. 1. AC breakdown data for liquid nitrogen as a function of gap for 101.6 mm (4 in.) sphere to plane electrode geometry. The symbols are the average value of at least 10 breakdowns and the error bars are the minimum and maximum breakdown values.

It is important to understand the statistics of the breakdown values since equipment must be designed such that the predicted failure probability is quite low, for example 1%. A Weibull distribution is frequently used as a model for the failure probability in breakdown measurements where the failure mechanism is thought to be due to a "weakest link" or defect.

This distribution is given as:

$$F(V) = 1 - \exp[-(V/V_{63.2})^b] \quad (1)$$

where $F(V)$ is the cumulative failure probability and $V_{63.2}$ is the breakdown voltage with probability of 63.2%. On a Weibull plot, *b* is the so-called shape parameter or slope of the straight line fit to the data. If the data fit a straight line well, then it can be assumed that the breakdown values follow a Weibull distribution. Figure 2 shows the liquid nitrogen ac breakdown values for the 101.6 mm (4 inch) sphere-to-plane gap for a pressure of 1.014 bar (0.2 psig) for gaps of 1, 2, and 3 mm. From such plots the breakdown voltage for a 1% failure probability can be estimated. This data can be used for design purposes in a number of applications. For example a 2 mm gap for this geometry and pressure should hold off about 26 kVrms with a 1% failure probability. Additional work is needed on the statistics of impulse breakdown in liquid nitrogen gaps, especially at higher voltages.

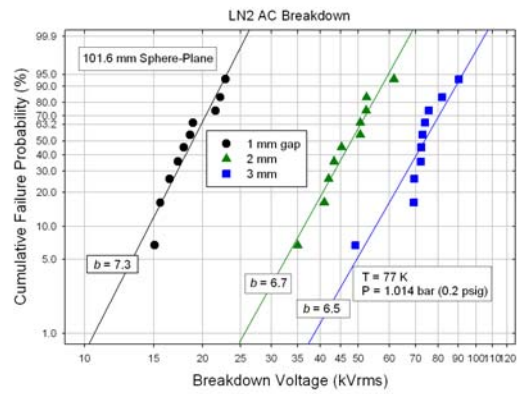


Fig. 2. Liquid nitrogen gap ac breakdown voltages plotted as a Weibull distribution of failure probability. The electrode geometry was 101.6 mm (4 inch) sphere-to-plane at a pressure of 1.014 bar (0.2 psig). The *b* values are the Weibull shape parameter and slope of the linear fit.

Status of milestones:

- Quantify ac and impulse breakdown in LN2 as function of gap and electric field profile. (Aug 31, 2007): **Met June 2007.**
- Quantify breakdown strength and partial discharge characteristics of solid G10 in cryogenic environment. (Sept 30, 2007): **On track,**

Interactions:

Results are communicated to the appropriate industry partners to assist in their development and planning activities.

Section 1.5: Technical R&D and Support (Subcontracts)

Laboratory-coordinated activities involving the R&D of 2G wires and technical support of the HTS program.

Subtask 1.5.1: American Superconductor Corporation 2G wire development subcontract.
M. W. Rupich (AMSC)

Objective:

AMSC is in the final stages of commissioning a manufacturing line for the production of 2G HTS wire based on the MOD-YBCO/RABiTS™ technology. AMSC's process is presently capable of producing 2G wire with a performance level nearing that required for initial commercial and military HTS wire-based applications. However, in order to meet the DOE and commercial cost/performance targets for broad market acceptance, it is necessary to further increase the critical current of the 2G wire, optimize the wire architecture and properties for specific applications and reduce the 2G wire manufacturing cost. The objective of this subcontract is to accelerate the development of a low-cost manufacturing process for 2G wire by (1) improving the process rates and yields of the continuous processing technologies, (2) enhancing the critical current of the YBCO layer, and (3) developing 2G wire architectures suitable for commercial and military applications.

Highlights:

- *AMSC's 2G scaleup on track for production capacity of 720 km/year in December 2007*
  - 100% of production scale equipment installed
  - 75% of processes qualified
- *1.4 μm YBCO films qualified for insertion into AMSC's baseline production*
  - 150 A (375 A/cm-w) achieved in 5-meter qualification runs of 344 superconductors.
  - 1.4 μm hybrid Y(Dy)BCO/YBCO process slated for standard production in CY2007.
- *Additional rate enhancements increase capacity of slowest steps in production process.*
  - Improvements in texture anneal and decomposition rates increase capacity to beyond 720 km/yr target for 344 superconductors.
- *AMSC's 344 superconductors used in successful cable test.*
  - Nexans fabricated and successfully tested a cable built with AMSC's 344 superconductors
  - Cable specifications include:
    - 138 kV – 1820 A @ 74 K, 30 meters, 2-layer conductor – 33 tapes 2G wire (1-layer screen 1G wire)

Technical progress:

- *Improved texture in RABiTS template leads to increased Jc in YBCO films*
  - Mechanism controlling texture enhancement in Y_2O_3 seed layer was identified. Standard (4-cm) RABiTS template produced in AMSC's pilot line with the enhanced texture supported J_c's of 5 MA/cm^2 in a 0.8-μm-thick Y(Dy)BCO film.
- *Process Improvements*
  - Improvements of texture anneal process increased processing capacity (344 superconductor equivalent) to ~2Mm/yr.
  - A modified decomposition process demonstrated in R&D equipment that increases process capacity (344 superconductor equivalent) to ~1M m/yr for 1.4-μm-thick HTS.

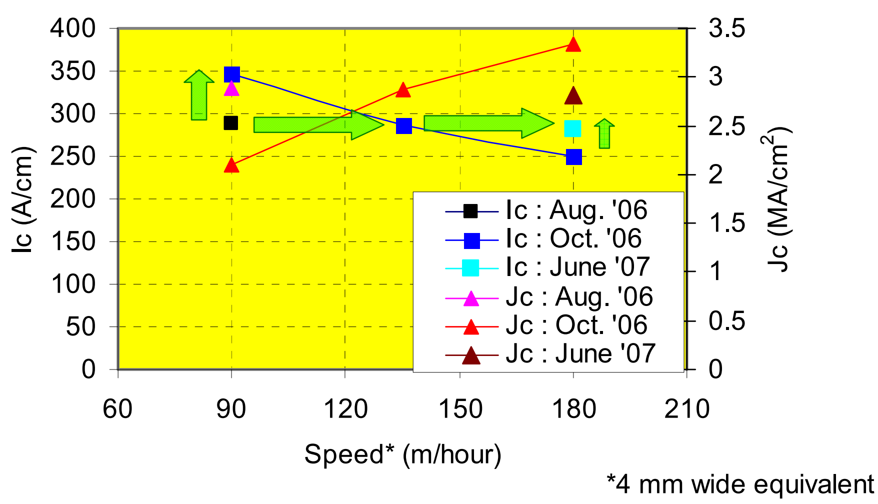
Status of milestones:

- ✓ 20–100 meter length of 344 superconductor wire with a critical current exceeding 100 A at 77 K, self-field (July 31, 2007).
  - **Achieved January 2007** - 117 A (77 K, self-field) over 70 m of 344 superconductor.
- 100 meter lengths of 344 superconductor with an Ic exceeding 120 A at 77 K, self-field.
  - **On track for December 2007**.
  - 150 A demonstrated in 5-meter qualification wires

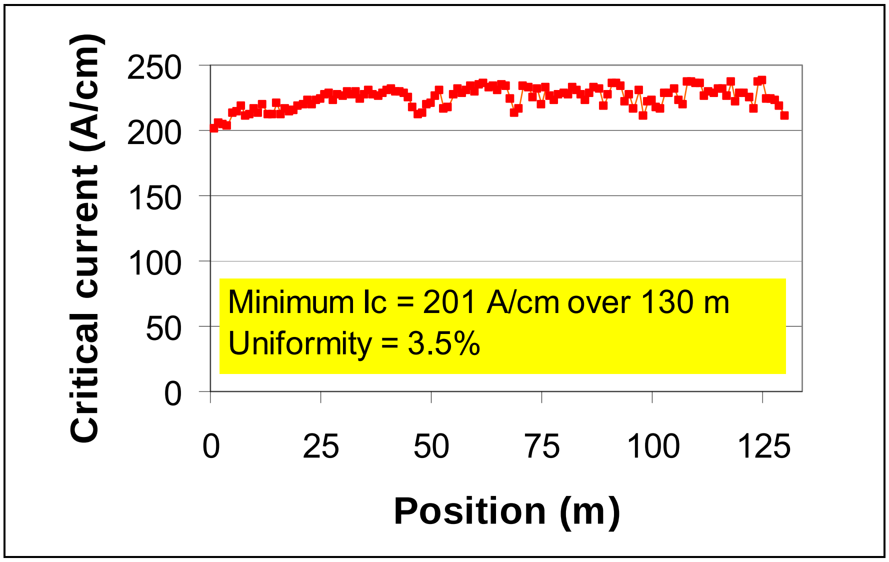
Subtask 1.5.2: SuperPower, Inc., 2G wire development subcontract.
V. Selvamanickam (SuperPower)

Objective:
SuperPower is now in a position to produce good quality 2G wire in "pilot-scale" mode with performance level that satisfies most HTS demonstration applications. To meet the DOE and practical commercial application cost/performance target, however, it is necessary to further improve the HTS transport properties. Further, it is important to refine the conductor structure and fabrication processes to reduce the conductor cost. The purpose of this project is to accelerate the development of commercial long-length high-performance IBAD/MOCVD 2G wire.

Highlights:
Significant enhancements in production rates.
SuperPower has invested significant amount of resources on the optimization and scale-up of its MOCVD-IBAD 2G wire, with particular emphases on wire performance, uniformity, length and throughput. As a result, substantial progress has been made with many record long-length performances achieved at high production rates. Last quarter, we reported several achievements of long-length 2G wire produced at high speeds, the slowest step (MOCVD) having a speed of 135 m/h of 4-mm-wide wire. This quarter, we increased the speed of the MOCVD process to 180 m/h of 4-mm-wide wire. At the same time, we maintained a high critical current level of 285 A/cm in a 1-µm-thick HTS film produced at this high rate. The figure on the next page shows the advancements made in the last year in increasing the speed of the MOCVD process. Next, we produced a 130-m-long 2G wire with all processes at high speeds (IBAD MgO at 360 m/h, homo-epi MgO at 345 m/h, LMO at 345 m/h, and MOCVD at 180 m/h, all values for 4-mm-wide wire). A minimum critical current of 201 A/cm was achieved over 130 m with a 3.5% uniformity in I_c (see next page). The speeds listed above correspond to annual production capacities of 1400 km/year for the IBAD, homo-epi MgO, and LMO processes and 720 km/year for MOCVD, even assuming that only 45% of time in a year is available for deposition.



Increase in production speed of MOCVD process while maintaining high Ic performance



Process	Month	IBAD MgO	Homo-epi MgO	LMO	MOCVD YBCO
Speed of 4 mm wide tape (m/h)	Oct. '06	360	240	240	135
	June '07	360	345	345	180
Production capacity (km/yr) (if 45% of time/year is available for deposition)		1,440	1,380	1,380	720

Long-length 2G wire with all processes at high production rates

Status of milestones:

- Short sample 2G wire with I_c of 750 A/cm. (July 31, 2007): **On track** – *reached 740 A/cm.*
- Short sample 2G wire with a J_e of 30 kA/cm^2 at 77 K, 1 T (without copper stabilizer) (July 31, 2007): *Presently at 20 kA/cm^2 level.*

Subtask 1.5.3: NIST-Boulder electromechanical studies for superconductor development subcontract.

N. Cheggour, Danko van der Laan (NIST-Boulder)

Objective:

Substantial advances have been achieved in the development and fabrication of 2G wires, particularly in the area of critical current performance. For these wires to be broadly employed in practical applications, however, both the electromechanical responses and the mechanical integrity of 2G wires under operational stresses in cryogenic environment must be determined and understood. In addition, these factors will vary with wire geometry and will therefore influence the conductor design and fabrication. Objective of this project is to perform the electromechanical research needed to develop 2G wires for electric power-grid and high magnetic-field applications. Critical performance feedback will be provided to companies and organizations developing the conductors and demonstration projects.

Highlights:

Initial results suggest substantial improvement in 2G wire delamination strength.

HTS/buffer delamination in 2G wires will result in catastrophic failure. This failure mode has been of particular concern in wires that have been slit. We have been collaborating with wire manufacturers to improve the delamination strength under transverse tension. Data feedback is critical to the present wire production scale-up process. Recent results have shown that an improved quality control during 2G wire production may significantly raise the delamination strength, even for slit conductors. More delamination testing is underway to verify this finding. In addition, conductors with new geometries to improve the delamination strength, conductors with a thick YBCO coating, and those with filamentized YBCO layer for low AC loss, will be tested shortly.

Technical progress:

1) New electromechanical test configurations for 2G wires.

We converted the experimental setup for the determination of longitudinal compressive and tensile strain effects on 2G wires. The setup has been automated and can be operated without requiring the use of a servo-hydraulic test system. This helped free up the servo-hydraulic setup for conductor delamination studies and studies on coated conductor splices. Progress has been made on the engineering/physics modeling of the intrinsic strain effect. The data is needed by the wire developers to set strain limits for engineering designs.

2) Commence modeling of "hard" bending on critical current.

We have been studying the critical current vs. hard-bending strain in order to obtain engineering design data for power cable bending limits. The database has been extended with results on YBCO coated conductor with thick YBCO layers. We have begun the modeling of the hard bending effect on critical current, to predict this effect from data obtained from tensile and compressive strain on critical current.

3) Stress-strain characterization of 2G wire joints.

Due to finite wire length, most practical HTS applications will contain solder joints. Failure at these critical nodes will render the device inoperable. Therefore, it is necessary to determine and understand the joint characteristics at room and cryogenic temperatures to avoid failure during winding, field-splicing, installation and operation. We have designed a new experiment to measure both the joint resistivity and the coated-conductor critical-current as a function of stress at 76 K. Various joints, made by ORNL using different types of solders, were tested at NIST. We measured differences in joint resistivity between samples before stress is applied. Depending on the joint preparation, a large increase in resistivity is measured at relatively low stress levels. Procedures for joints preparation are needed to ensure that the joint resistivity does not deteriorate with stress.

Status of milestones:

- Complete delamination-strength measurements at 76 K on a total of 30 slit 2G wire samples with new geometries, fabricated by AMSC and SuperPower. (July 31, 2007): **On track.**
- Complete measurements of critical-current vs. hard-bending strain at 76 K on a total of 6 2G wire samples, fabricated by AMSC and SuperPower. (Sept. 30, 2007): **On track.**

Interactions:

We maintain substantial interactions with industry and organizations by independent testing of their HTS wires. Results are communicated to the appropriate partners to assist in their development and designing activities.

Subtask 1.5.4: NIST-Gaithersburg subcontract to investigate HTS phase relationships.
W. Wong-Ng, L. P. Cook, I. Levin (NIST-Gaithersburg)

Objective:
In order to maximize the performance and provide for cost-effective means to fabricate 2G wires, accurate data on the phase equilibria of mixed lanthanide HTS compounds and their behavior as applied to thin films is required. The main objective of this work is to provide critical phase equilibrium data on the single-phase regions of mixed lanthanide HTS phases under conditions that match 2G wire processing. These phases fall in the systems Ba-R-R'-Cu-O, where R and R' are selected lanthanides and Y. The data will enable improvement of the superconducting properties of 2G wires through enhanced flux-pinning, leading to expeditious and cost-effective market entry. Another objective is to determine a parallel set of Ba-R-Cu-O phase diagrams as applied to films. Since phase assemblages in thin films could differ from those predicted by the bulk phase equilibria, availability of phase relations for Ba-R-Cu-O films will be critical for the further development of 2G wires.

Highlights:
By mixing the smaller lanthanides Y with the larger Sm in the $Ba_{2-x}(Sm_{1+x-y}Y_y)Cu_3O_{6+z}$ superconductor, both flux-pinning and melting properties can be tailored and optimized. Following the determination of the single-phase region of the solid solution $Ba_{2-x}(Sm_{1+x-y}Y_y)Cu_3O_{6+z}$ under various processing conditions so as to provide data for intrinsic flux pinning applications, we have succeeded determining the phase equilibria in the vicinity of the $Ba_{2-x}(Sm_{1+x-y}Y_y)Cu_3O_{6+z}$ phase. We found that this solid solution (in the BaO-poor region) is in equilibrium with CuO, $BaCuO_2$, $(Y,Sm)_2Cu_2O_5$, $(Sm,Y)_2CuO_4$, $Ba(Sm,Y)_2CuO_5$, and $BaCu_2O_2$ under 100 Pa p_{O2} at 810°C. This information also identifies possible phases for flux pinning application, an important area for coated conductor development.

A paper concerning the understanding of melting temperature of $Ba_2RCu_3O_7$ (R= Nd, Sm, Gd, Y, and Er) has been submitted. The conventional Debye temperature, customarily estimated using an isotropic approximation, fails to account for the trend of melting temperatures for the $Ba_2RCu_3O_7$ high T_c superconductors, as a function of the ionic radius of R^{3+}, or $r(R^{3+})$. We overcame this problem by calculating the 'improved' Debye temperatures using the mean sound velocity along the *c*-axis of $Ba_2RCu_3O_7$ that features an anisotropic layered structure.

Phase relationships of $Ba_2RCu_3O_{6+x}$ (where R=lanthanides or mixed lanthanides) on films provide guidelines for coated conductor processing. We have used the mixed lanthanide films in the system Ba-(Nd,Eu,Gd)-Cu-O to demonstrate the difference between phase relations in films and in bulk. We have also successfully prepared combinatorial films using the RABiTS substrate provided by AMSC and used these to construct the $BaCuO_2$-Y_2O_3-CuO diagram for films. We confirmed the absence of the green phase, BaY_2CuO_5, which leads to different phase relations around $Ba_2YCu_3O_{6+x}$ in films.

Technical progress:

1) *Phase equilibria of the Ba-Sm-Y-Cu-O system*

In addition to completing the single-phase region determination of the solid solution $Ba_{2-x}(Sm_{1+x-y}Y'_y)Cu_3O_{6+z}$ under different processing conditions so as to provide data for intrinsic flux pinning applications, we have succeeded investigating the phase diagram in the BaO-poor region of the complex Ba-Sm-Y-Cu-O system under 100 Pa p_{O2} at 810 °C. Phase relationships surrounding the $Ba_{2-x}(Sm_{1+x-y}Y'_{y})Cu_3O_{6+z}$ single phase in the complex multi-component $BaO-Sm_2O_3-Y_2O_3-CuO_z$ system, including solid solution studies of various related phases have been studied in detail. We found that this solid solution (in the BaO-poor region) is in equilibrium with CuO, $BaCuO_2$, $(Y,Sm)_2Cu_2O_5$, $(Sm,Y)_2CuO_4$, $Ba(Sm,Y)_2CuO_5$, and $BaCu_2O_2$.

Currently we are continuing to collaborate with ORNL and AFRL to use selected samples of this $Ba_{2-x}(Sm_{1+x-y}Y_y)Cu_3O_{6+z}$ region with Sm/Y ratio of 0.667/0.333 to correlate with superconducting properties. The targets have been prepared at NIST and have been delivered to AFRL for film deposition on single crystal substrates. Once they have succeeded the deposition process, the targets will be delivered to ORNL for film deposition on RABiTS.

2) *Phase Relationships Determination in the Ba-R-Cu-O System*

We successfully determined the phase relationships of the Ba-Y-Cu-O, Ba-(Nd,Eu,Gd)-Cu-O, Ba-Nd-Cu-O and Ba-Gd-Cu-O systems in film form. At 735 °C and 100 Pa p_{O2}, high-temperature x-ray diffraction experiments showed that while $BaNd_2CuO_5$ ('brown-phase' structure) can be prepared in film form using the trifluoroacetate solution methods on $SrTiO_3$ substrates, $BaGd_2CuO_5$ and $Ba(Nd_{1/3}Eu_{1/3}Gd_{1/3})_2CuO_5$ ('green-phase' structure) cannot. As a result of the absence of the 'green phase' in films, $Ba_2(Nd_{1/3}Eu_{1/3}Gd_{1/3})Cu_3O_{6+x}$ is in equilibrium with the 'brown phase,' and a compatibility line is found between $Ba_2GdCu_3O_{6+x}$ and Gd_2O_3 in the BaO-poor region of the Ba-Gd-Cu-O diagram, a configuration different from that of the bulk phase diagram.

We are continuing to advance our understanding of the phase relationships of the thin film Ba-Y-Cu-O system in the vicinity the high-temperature superconductor Y213 using the combinatorial thin film synthesis approach with oxides as targets and RABiTS as the substrate (provided by AMSC). Similar to the films prepared using the "BaF_2" process, we also confirmed the absence of the green phase BaY_2CuO_5. Because of this absence, phase relations around $Ba_2YCu_3O_{6+x}$ are different from the bulk for the combinatorial route as well. Possible reasons for different phase relationships in bulk and thin film materials include strain, texturing, and kinetics that are determined by the substrate, film thickness, and the processing conditions. We continue to study the cause of the differences with particular focus on the effect of fluorine and other differences in processing conditions.

Status of milestones:

- Complete initial determination of single-phase regions for selected mixed lanthanides (July 31, 2007): **On track.**
- Complete initial study on processing relationships among phases in selected Ba-R-Cu-O systems as applied to films (Sept. 30, 2007): **On track**

Interactions:

We continue to interact with ORNL and AFRL on phase equilibria and property studies of $Ba_{2-x}(R_{1+x-y}R'_y)Cu_3O_{6+z}$; with BNL on modeling of phase transitions and melting of $Ba_2RCu_3O_{6+z}$ phases; with ORNL and AMSC on phase relationships of Ba-Y-Cu-O and Ba-R-Cu-O films. (we have completed a Ba-Y-Cu-O diagram for films on RABiTS provided by AMSC); and with Superpower on the determination of the interaction of $Ba_2YCu_3O_{6+z}/LaMnO_3$, where $LaMnO_3$ is a potential buffer layer.

Subtask 1.5.5: University of Houston MOD processing and pinning subcontract.
K. Salama (Univ. Houston)
Status of milestones:

- Under negotiation.

Subtask 1.5.6: Energetics technical support subcontract.
B. Marchionini (Energetics)
Status of milestones:

- Compile and distribute to DOE the results from the Annual Peer Review Meeting: **On track.**

Subtask 1.5.7: TMS technical support subcontract.
P. Herz (Technology & Management Services, Inc)
Status of milestones:

- Complete remaining web-design tasks: **Met Feb. 2007.**

Subtask 1.5.8: Bob Lawrence & Associates outreach subcontract.
Bob Lawrence (Bob Lawrence & Associates)
Status of milestones:

- Publish periodic Superconductivity Update Newsletter for HTS outreach: **On track.**

Subtask 1.5.9: Navigant HTS Technology and market Assessment subcontract.
David Walls (Navigant)
Status of milestones:

- Complete HTS Market Assessment report. **On track.**

Planned ORNL Foreign Travel:

Name	Destination	Date	Purpose
Isidor Sauers	Vancouver, Canada	Oct. 13 – Oct. 18	Attend and host 2007 Conference on Electrical Insulation and Dielectric Phenomena (CEIDP).
Parans Paranthaman	Tsukuba, Japan	Nov. 2 - Nov.7	Attend 20th Int'l Symposium on Superconductivity (ISS07) and visit research centers.
Amit Goyal	Jeju Island, Korea	Nov. 6 – Nov. 12	Attend Int'l Workshop on Coated Conductors for Applications (CCA07) and visit research centers.