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
January 1, 2007 to March 31, 2007

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Superconductivity Program
Quarterly Progress Report

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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 measurements 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

ORNL HTS research articles featured in the 2006 *Superconductor Science and Technology* special highlights collection.

Two Oak Ridge National Laboratory (ORNL) articles, "A perspective on conducting oxide buffers for Cu-based YBCO-coated conductors" by K.-H. Kim et al. and "Strong flux-pinning in epitaxial $NdBa_2Cu_3O_{7-\delta}$ films with columnar defects comprised of self-assembled nanodots of $BaZrO_3$" by S.-H. Wee et al., are featured in the 2006 Special Collection by the journal *Superconductor Science and Technology* (SUST). Comprising 32 papers, articles in the Collection were selected for their "presentation of outstanding new research, as valuable reviews of the field, and for receiving the highest praise from the SUST international referees." In addition, the article by Kim et al. and also "'Irradiation-free, columnar defects comprised of self-assembled nanodots and nanorods resulting in strongly enhanced flux-pinning in $YBa_2Cu_3O_{7-x}$ films" by A. Goyal et al. published in 2005 are among the most highly downloaded articles in the entire SUST journal during 2006. This is the second consecutive year that ORNL HTS research wholly funded by OE has received this distinction. These achievements reflect the high caliber and cutting-edge nature of HTS research at ORNL.
SUST 2006 Collection: http://herald.iop.org/susthighlights/m90/rsm/133375/link/562

Book on HTS co-edited by ORNL scientist slated for publication.

ORNL HTS researcher M.P. Paranthaman has co-edited a new book on HTS with V. Selvamanickam of SuperPower, Inc. Entitled "Flux Pinning and AC loss Studies on YBCO Coated Conductors," the book is scheduled to be published by Nova Science Publishers Inc. in 2007. Written by leading international HTS researchers including M.P. Paranthaman, R.C. Duckworth, A. Goyal, S. Kang, J. Li, T. Aytug, and D.K. Christen from ORNL, this book addresses the issues related to flux pinning, ac losses and thick YBCO film growth. It presents a comprehensive review of the status, issues and fundamental materials science studies necessary for the continuing improvement of YBCO coated conductors.
https://www.novapublishers.com/catalog/product_info.php?products_id=5675

ORNL HTS researcher promoted to a Distinguished Scientist.

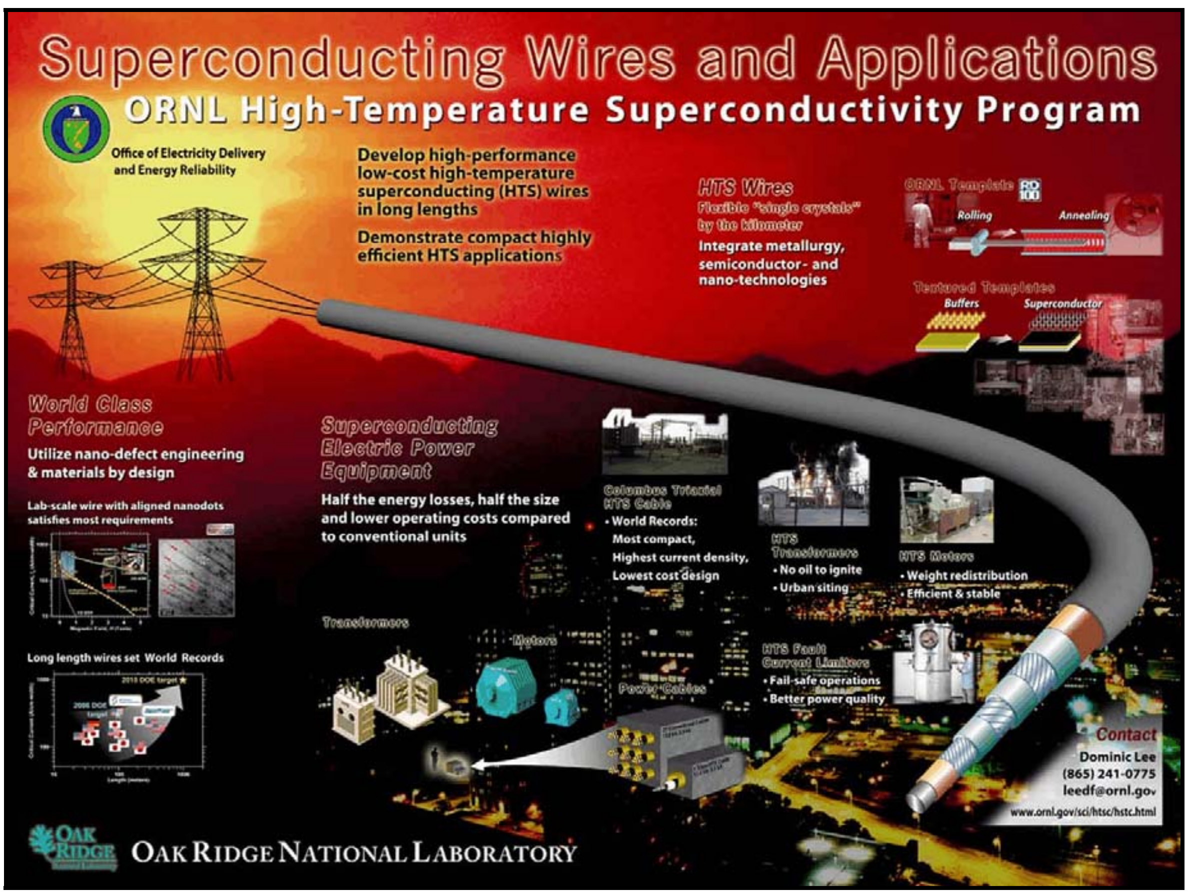
Parans Paranthaman of the ORNL Chemical Sciences Division (CSD) has been promoted to a Distinguished Scientist level. He is also the acting group leader for the Materials Chemistry Group in CSD. The combination of a strong record of scientific accomplishment and recognition in HTS, a strong work ethic, excellent teamwork, and a strong desire to be successful has made Parans a leader at ORNL.

ORNL HTS scientist invited to join *NanoTech Briefs* editorial advisory board.

Amit Goyal of the Materials Science and Technology Division (MSTD) has been invited to join the *NanoTech Briefs* Editorial Advisory Board. *NanoTech Briefs* reports on government, industry, and university nanotech innovations with real-world applications in areas such as electronics, materials, sensors, manufacturing, biomedical, optics/photonics, and aerospace/defense. Each issue of *Nanotech Briefs* also includes a special report on an industry or topic of timely importance to the nanotech field, an "in person" interview with a recognized leader in the nanotechnology field, a perspective from a nano business executive, and a look inside a state-of-the-art nano research facility.

ORNL HTS poster wins award.

An ORNL HTS outreach poster entitled "Superconducting Wires and Applications" has been named a winner of the 2007 American Inhouse Design Awards. Given by the editors of Graphic Design USA, the awards recognize graphic designs for their creativity as well as effectiveness in conveying the messages. The poster will be reproduced in a special 2007 issue of Awards Design Annual by Graphic Design USA.



HTS program members participated in DOE Wire Development and Applications Workshop.

Staff members contributed prominently, both as organizers and presenters, at the workshop held January 16-17 in Panama City, Florida. This annual workshop is sponsored by the Office of Electricity Delivery and Energy Reliability's Superconductivity Program for Electric Power Systems. The workshop, attended by about 75 participants, served as a forum to discuss the current status of the second-generation wires, electric power prototype demonstrations and possible second generation conductor engineering designs that could meet power application requirements. ORNL staff members David Christen, Michael Gouge, and Parans Paranthaman, along with five other DOE laboratory and industry representatives, served to organize the meeting and co-chair sessions. ORNL technical presentations were made by Michael Gouge, Amit Goyal, Dominic Lee, Parans Paranthaman, and Enis Tuncer. The meeting agenda and technical presentations can be accessed at http://www.energetics.com/wire07/agenda.html.

ORNL HTS Program is partner in four industry-led proposals to the DOE Superconducting Power Equipment Solicitation.

ORNL is supporting as the R&D partner four independent proposals for the DOE OE Superconducting Power Equipment (SPE) solicitation that were submitted by the industry-leads shown below in February 2007:

HTS Cable - Southwire Company.
HTS Transformer - Waukesha Electric Systems
HTS Fault Current Limiter - SuperPower, Inc.
HTS Generator – Siemens Power Generation, Inc.

Section 1.1: Wire Development

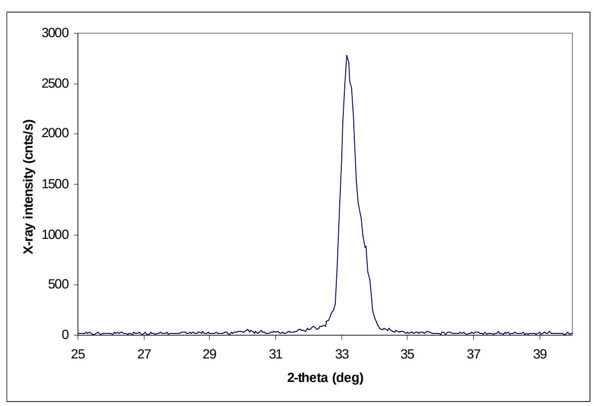
Focuses on materials processing and manufacturing issues that directly impact the cost, performance, application characteristics and scale-up of commercial 2G wires.

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, and 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:
1) HTS Program CPS Control Milestone Met - Short sample RABiTS using slot-die MOD CeO_2 cap layer with I_c of 300 A/cm.
A slot-die MOD CeO_2 cap layer in a RABiTS architecture (MOD-CeO_2/sputtered-YSZ/ sputtered-Y_2O_3/Ni5%W) supported high critical current, in a 0.8-µm YBCO film, resulting in an I_c/width of over 350 A/cm-width (77 K, self-field). All layers in this stack were deposited by AMSC. The challenge is to reproducibly grow MOD CeO_2 cap layer that can support high performance YBCO films. ORNL-AMSC CRADA is focused on establishing the optimum processing temperatures and gas environments for the formation of the CeO_2 films. The best CeO_2 MOD precursor will be selected for scale-up based on the processing temperature, texture, surface morphology, and film density.

2) Meters-long textured solution LZO buffer deposited on 4-cm-wide templates by slot-die coater.
Several meters of 4-cm-wide, slot-die coated LZO and subsequently annealed tape were fabricated. The LZO was coated on a Y_2O_3 buffered Ni-5at%W substrate from AMSC. The texture of the fully converted tape was measured continuously via X-ray line-scans at the center of the 4-cm-wide tape as well as at the edge of the tape. It was found that the (200) intensity tracked the substrate intensity at all points on the tape. A typical texture found on the LZO buffer is shown.



Technical progress:

1) Solution LZO buffer by slot die coating.

Work is ongoing to make 10-m-long, 4-cm-wide substrates with a 100-nm-thick coating of biaxially textured, slot-die coated and converted LZO. AMSC will deposit CeO_2 and YBCO on these tapes to evaluate the performance of the slot-die coated LZO layer.

2) Processing-properties-microstructure relationship.

Work is ongoing in the CRADA to optimize the pinning characteristics of 4-cm-wide YBCO conductors made by AMSC. Transport properties at 77 K and 65 K are being correlated with microstructural characteristics revealed by TEM as well as structural information obtained by X-ray diffraction. All of this information is then related to processing conditions in an effort to arrive at the optimal conditions for fabrication of long lengths of high performance conductors at AMSC.

3) Template development.

Work is also ongoing in the CRADA to fabricate stronger substrates with reduced magnetism. Significant progress continues to be made especially with composite substrates wherein the substrate comprises of either 2 or 3 layers of different compositions.

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 15, 2007.**
- Fabricate MOD LZO barrier buffer with homogeneous texture and a variation in mosaic of 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:

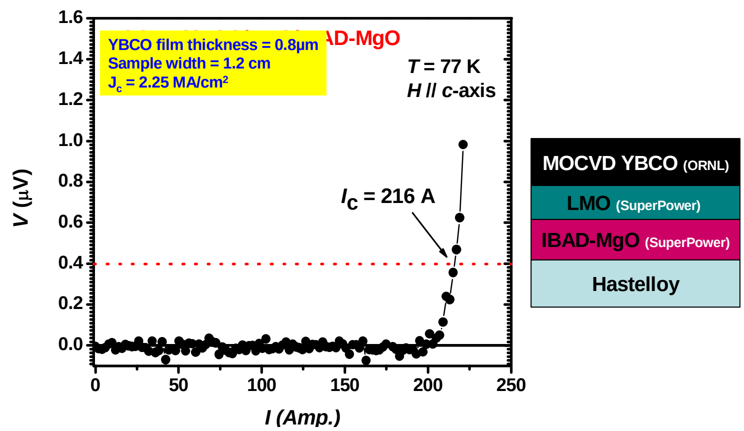
Interactions with AMSC included regular progress and planning teleconferences, as well as numerous and frequent sample exchanges with follow-up discussions on results. An on-site CRADA meeting was held at AMSC in March 2007. In attendance at the meeting were A. Goyal, M. Paranthaman, and D. F. Lee. Technical progress was discussed and plans were made for future work.

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:
HTS Program CPS Control Milestone Met - Operational MOCVD system providing J_c greater than 2 MA/cm^2.

One of the important critical needs that came out of the DOE's coated conductor workshop was 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 Metalorganic Chemical Vapor Deposition (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 needs 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. In March 2007, we have demonstrated the growth of YBCO films carrying a critical current, I_c of 216 A at 77 K. This translates to a critical current density, J_c of 2.25 MA/cm^2 for a film thickness of 0.8 µm. The current-voltage (I-V) curve for the same film is shown in the figure. Work is under way for in-field J_c enhancement through composition adjustments and doping.

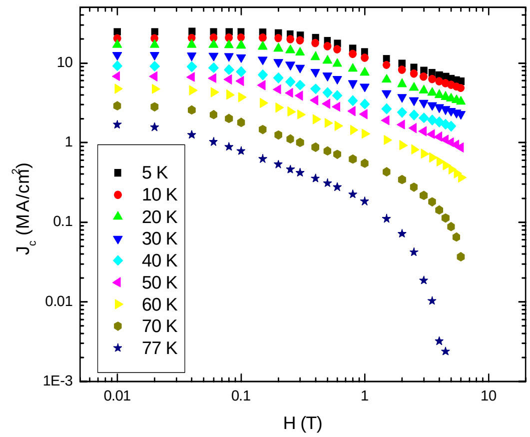


I-V curve of a 0.8-µm MOCVD YBCO film with an I_c of 216 A (2.25 MA/cm^2).

Technical progress:

Work has begun on determining wide-range temperature and field properties of SuperPower high-I_c coated conductors.

We have begun a systematic study of the magnetic field and temperature dependence of the loss-free electric currents in a series of high-current coated conductors produced in collaboration with SuperPower, Inc. Initial work is on a mixed rare-earth cuprate. In the study, both transport- and magnetically-determined critical currents will be compared, and assessments made of the detailed effects of flux creep and voltage criteria on the suitability for different applications.



Magnetization-derived J_c over a wide temperature and field range in a 2.1-μm SuperPower sample.

For the present sample, 2.1-μm thick, the measured self-field critical current at 77 K was nearly 450 A/cm-width by transport. The magnetization-derived critical current densities J_c over a wide temperature and field range are shown in the figure. For example, the values at 50 K (in principle attainable by single-stage cryocoolers) are over 1 MA/cm^2 in a field of 3 Tesla, corresponding to over 250A/cm-width - in the range required for practical high-field devices. Moreover, having been measured magnetically, the effective voltage criterion defining J_c is at the levels needed to assure sufficiently low energy dissipation. These and other practical issues will be elaborated as the studies continue.

Status of milestones:

- Operational MOCVD system providing J_c greater than 2 MA/cm^2. (June 30, 2007): **Met March 14, 2007**.
- Assist SuperPower in developing highly textured and uniform 1,000 meter-class IBAD-MgO/LMO substrate. (Sept. 30, 2007): On track.
- Assist SuperPower in obtaining high I_c thick films of 750 A/cm. (Sept. 30, 2007): On Track.

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.

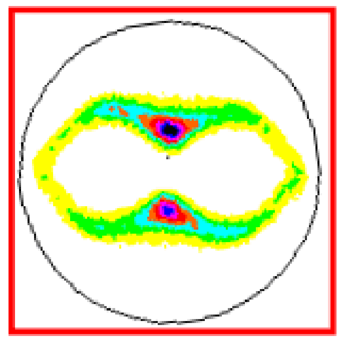
Section 1.2: Conductor Research

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 non-magnetic 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:
Predominantly cube texture obtained in strengthened nonmagnetic Ni-9.3%W template.
We have successfully formed a Cu-type rolling texture and a predominantly cube texture upon subsequent annealing for a completely nonmagnetic, Ni-9.3 at%W substrate. The figure shows a (111) pole figure of the substrate after rolling.



Cu-type rolling texture.

Upon annealing, the substrate showed a predominant cube texture. The in-plane full-width-half-maximum (FHWM) was 7.3˚. The out-of-plane FWHM in and about the rolling direction was 5.5˚ and 10˚ respectively. These cube-textured, Ni-9.3at%W substrate are of interest not only because they are completely nonmagnetic, but also because they are significantly stronger than pure Ni with a yield strength along the [100] direction being greater than 270 MPa.

Technical progress:
Work is ongoing to improve the rolling and annealing conditions of the Ni-9.3 at%W alloy. Work is also ongoing to form single-grain substrates of the same dimensional parameters as the present RABiTS substrates.

Status of milestones:
Fabricate a meter-long, strengthened, Ni-alloy-based substrate with reduced magnetism using a process which can be extended to long lengths. (Sept. 30, 2007): Behind schedule.

Interactions:
Both 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, and M. S. Bhuiyan

Objectives:
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. U.S. HTS wire manufacturers 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.

Highlights:
Improvement of texture and surface morphology of doped ceria seed layers.
Ceria buffer plays the key role as a cap and/or seed layer in YBCO 2G wire technology. The concerning issue 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. However, the typical MOD solution ceria layer has roughness in the order of 3-4 nm that exaggerates the reactivity between HTS and ceria, and it does not improve texture from that of the metal template. Therefore, reducing the surface roughness and improving the texture can result in better aligned HTS and lower the reactivity and thus better performance. We have employed various dopants to study the surface morphology and texture. Initial results show that appropriate dopant and processing can result in texture and roughness enhancement of solution seed layers.

Table 1. Texture data for doped ceria seeds grown directly on Ni-3W substrates.

Texture Comparison Data for Ceria and Doped Ceria						
	Ceria/Doped Ceria			Substrate		
Materials	Out of Plane Texture		In Plane Texture	Out of Plane Texture		In Plane Texture
	(deg.)		(deg.)	(deg.)		(deg.)
	phi-0	phi-90		phi-0	phi-90	
CeO_2	8.84	5.12	6.34	8.07	5.2	6.22
$Ce_{1-x}A_xO_2$	6.12	4.25	6.16	8.07	5.2	6.22
$Ce_{1-x}B_xO_2$	8.4	5.8	7.3	8.07	5.2	6.22
$Ce_{1-x}C_xO_2$	9.8	6.3	9.3	8.07	5.2	6.22

We have successfully demonstrated the effect of dopants in Ceria seeds on texture and surface morphology. The dopants used are identified as A, B, and C. Initial analysis from XRD and texture measurement (Table I) suggests that dopant "A" has the potential of yielding the desired properties. Therefore a comprehensive study was performed for "A" under various processing temperatures. It can be concluded that there is an increase in surface roughness with increase in process temperature. On the other hand very low temperature results in broader texture. The present study (Table II) suggests that processing the ceria film with dopant "A" at 900°C to 950°C can yield the desired characteristics of surface smoothness with improved texture.

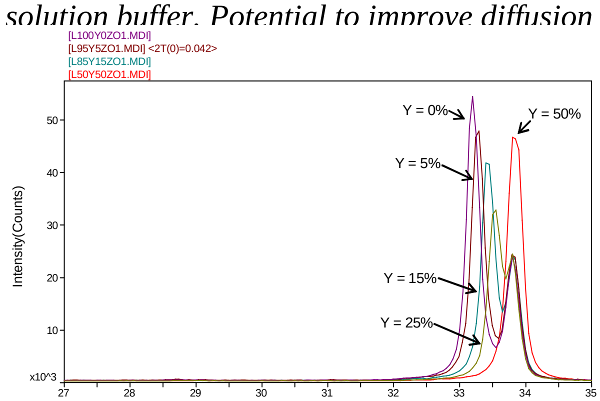
Table 2. Texture comparison data for A-doped ceria.

	Doped Ceria			Substrate		
Temperature	Out of Plane Texture		In Plane Texture	Out of Plane Texture		In Plane Texture
(° C)	(deg.)		(deg.)	(deg.)		(deg.)
	phi-0	phi-90		phi-0	phi-90	
900	4.5	4.36	6.56	9.6	5.72	6.68
950	3.94	3.83	6.26	9.6	5.72	6.68
1000	4.25	4.1	6.35	9.6	5.72	6.68
1050	4.36	4.25	6.63	9.6	5.72	6.68

Technical progress:

Cube texture obtained in doped-$La_2Zr_2O_7$ (LZO) solution buffer. Potential to improve diffusion barrier properties.

High I_c of 336 A/cm has previously been obtained on RABiTS with LZO solution barrier buffer layer, which exceeded the performance of its physical vapor deposited YSZ counterpart. Earlier SIMS studies have shown that there is some amount of Ni diffusion through the LZO and a film >80 nm is required for effective barrier. Also, Yttrium seed layer is found to diffuse into LZO. Hence, we are studying the effect of Y-doping on the barrier properties of LZO films. Using Y_2O_3 seeded textured substrates, we have optimized the processing conditions for a variety of doping levels (0-50%) and highly textured Y-doped LZO films have been synthesized. The Ni diffusion barrier properties of these films will be compared to that of pure LZO and a correlation of the barrier properties with dopant levels will be developed in the near future.



X-ray diffraction patterns of Y-doped LZO films on Y_2O_3/Ni-W substrates.

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:

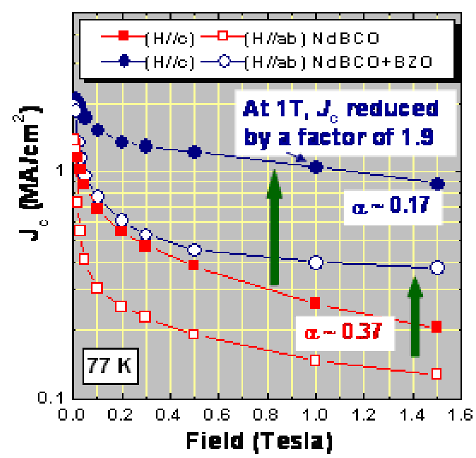
This base program research involves substantial interaction with AMSC on buffer evaluation using commercial HTS deposition process. There is also interaction with the University of Wisconsin-Madison on buffer material development.

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, and D. K Christen

Objectives:
U.S. HTS wire manufacturers are now producing 2G wires with reasonable properties in restively 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 Tesla. 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:
HTS Program CPS Control Milestone met - Improve in-field performance flux-pinning factor to less than a = 0.2.

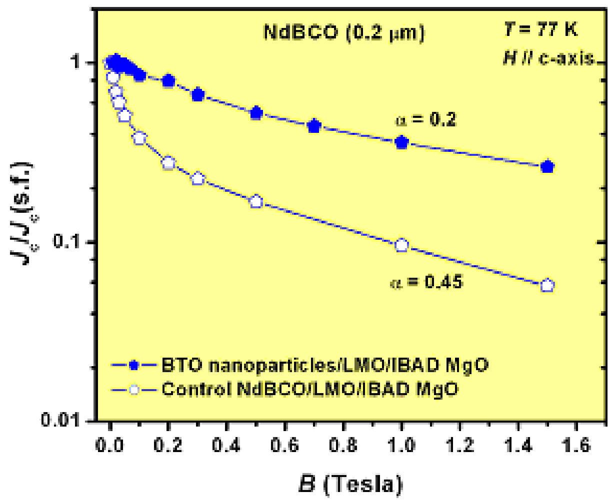
1) Incorporation of self-assembled nanodot columns lowers a of 0.7 mm NdBCO film to 0.17.
3-D self-assembled stacks of $BaZrO_3$ (BZO) nanodots oriented parallel to the c-axis of the film were formed in 0.7-µm-thick, epitaxial $NdBa_2Cu_3O_{7-\delta}$ (NdBCO) films, deposited on IBAD-MgO templates via pulsed laser deposition. The aligned nanodot columns provide excellent pinning and lower the a to 0.17. Work is under way to develop means by which this defect micro-structure may be incorporated into films deposited by commercially-selected processes.



J_c's of 0.7 µm NdBCO and NdBCO+BZO films on IBAD-MgO for H//a-b and H//c directions.

The figure shows the field dependent J_c versus applied magnetic field for 0.7-µm-thick NdBCO and NdBCO+BZO films at 77 K with both field directions, the field applied perpendicular (H//ab) and parallel (H//c) to the c-axis of the film. The self-field J_c for BZO-doped films is ~2.0 MA/cm^2, ~40% larger than J_c ~1.4 MA/cm^2 for the undoped film. For H//c, a remarkable improvement in the in-field J_c is achieved for the NdBCO+BZO film. This can be ascribed to the c-axis oriented, columnar defects comprised of self-assembled stacks of BZO nanodots. Additional defects and strain that is formed around the interfaces between BZO nanodots and the matrix, are a possible reason for the concomitant augmentation in J_c at H//ab for NdBCO+BZO films. At a magnetic field of 1.5 T, the J_c at H//c for BZO-doped sample reduced only by a factor of 2.3 and is still over 1 MA/cm^2, more than a factor of 4 over the performance of the sample without the BZO additions. The exponent, α, in the power-law of $J_c \sim H^{-\alpha}$ was calculated by linear regression of the in-field J_c data at H//c in the power-law regime of 0.2-1.5 T. A remarkably smaller α of ~0.17 is achieved from NdBCO+BZO film, compared to α ~0.37 for pure NdBCO film.

<u>*2) Low α of 0.2 obtained in NdBCO film deposited on surface decorated IBAD-MgO.*</u>
High performance is one of the most important requirements of a practical 2G HTS wire. In addition to self-field J_c at 77 K, high current carrying capability in the presence of a magnetic field is also essential. This is particularly true for applications such as transformers and motors. In February 2007, we demonstrated in a model-system using PLD that very good pinning can be obtained in NdBCO with nano-particle surface decoration. <u>An α value of 0.2 was obtained.</u> Work is under way to develop means by which the defect structures may be introduced into HTS films deposited by commercially-selected processes.



J_c dependencies on magnetic field for surface modified IBAD-MgO/LMO substrate and control sample.

We have been engaging in research efforts to enhance in-field J_c through flux pinning defect engineering. A potential way to improve wire performance is by decorating substrate surfaces using preformed nanoparticles. This approach is attractive because both the formation of nanoparticles and the deposition of these particles onto substrate surfaces can be accomplished by low-cost solution techniques. In addition, different subsequent HTS deposition methods may be applicable and different type of technical substrates may be used. In this quarter, we have succeeded in applying preformed $BaTiO_3$ (BTO) nanoparticles to biaxially textured metal substrate surfaces using solution-based deposition technique. NdBCO films were then grown on these and on control substrates with untreated surfaces. Ability of HTS to withstand the effect of magnetic fields can generally be examined through the pinning exponent α (equation $J_c \sim B^{-a}$). The lower the a, the better the pinning and in-field J_c. Transport electrical properties measure-ments of these samples showed substantial enhancement of flux pinning for the nanoparticle decorated sample as evidenced by the significant enhancement of in-field J_c performance, where an α-value of 0.2 is obtained. This result demonstrates the effectiveness of growth-induced defects for flux pinning in HTS films that can be produced by a relatively simple technique of nanoscale substrate surface modification.

<u>Technical progress:</u>
Work is ongoing to understand how the 3D self-assembly of nanodots of BZO occurs inside the HTS film. Both a theoretical and an experimental investigation is under way.

Status of milestones:

- Improve in-field performance flux-pinning factor to less than $\alpha = 0.2$. (May 31, 2007): **Met Feb. 6, 2007** - *in conjunction with subtask 1.2.4.*
- Understand formation mechanism of columns of self-assembled nanodots. (Sept. 30, 2007): On schedule.

Interactions:

The ex-situ HTS research is performed in close coordination with the Wire Development Group to compliment and expand on the corporate research at AMSC. Interactions include extensive collaboration with University of Tennessee on transport characterization and pinning analysis. Results are communicated to our industry partners to assist them in process development and planning activities.

Subtask 1.2.4: High performance rare-earth HTS.

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

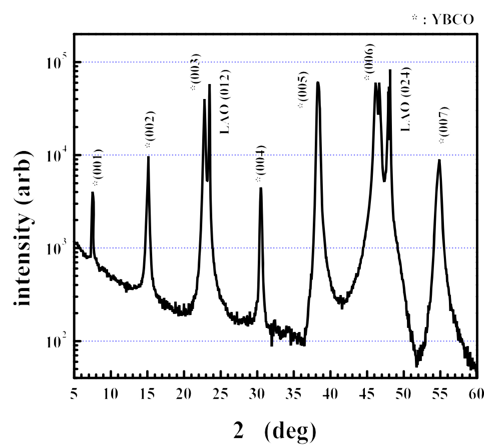
New PLD chamber qualified for HTS film deposition.

Superconducting properties have been measured on YBCO films made in the new, dedicated PLD chamber described below. These samples serve as qualification prototypes to demonstrate near-optimized deposition parameters. These samples, 0.2-µm-thick, yield magnetically-determined critical current density values J_c = 3 MA/cm^2 at 77 K and 70 MA/cm^2 at at 5 K, establishing viable conditions for systematic studies of rare-earth doped cuprates in this system.

Technical progress:

New capabilities established for deposition of rare-earth substituted HTS coatings.

We have deployed a new deposition chamber for the formation of HTS coatings by pulsed laser ablation. The new system adds a third chamber to be served by the single Compex excimer laser. This chamber will be dedicated to the deposition of rare-earth substituted 123 coatings, with the aim of discovering HTS coatings with optimized properties, since previous empirical observations have indicated intrinsic, beneficial effects from rare-earth additions/substitutions.



The system has undergone substrate heater upgrades to accommodate fixed sample temperatures of up to ~900°C in oxygen. In initial testing, samples were ablated from a YBCO target onto $LaAlO_3$ single crystal substrates at temperatures of 760 and 780°C, in background oxygen pressures of 200 and 100 mTorr, respectively. The crystal structure was characterized by X-ray diffraction, and indicated that fully epitaxial YBCO films were formed, as illustrated in the figure.

Status of milestones:

- Improve in-field performance flux-pinning factor to less than α = 0.2. (May 31, 2007): **Met Feb. 6, 2007** - *in conjunction with sub-task 1.2.3.*
- Establish the (compositions)-type of effective (mixed)-rare earth combinations for HTS films. (July 31, 2007): On track

Interactions:

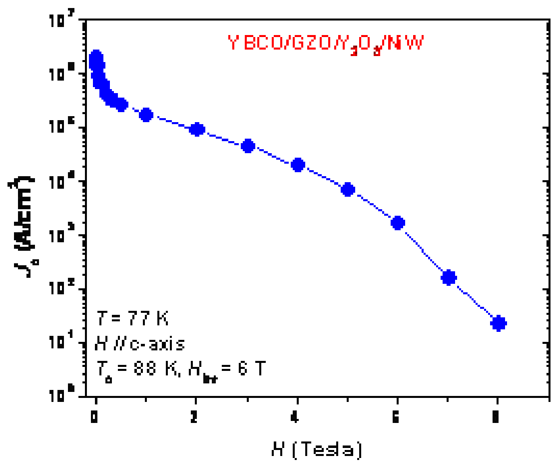
We are working in collaboration with NIST Gaithersburg to arrive at a suitable composition for mixed rare-earth HTS films based on phase-diagram considerations. Films of the selected compositions will be deposited at ORNL via PLD on RABiTS and IBAD substrates. ORNL expects to receive PLD targets in a month or so and will then begin optimizing the deposition conditions for the films.

The ex-situ HTS research is performed in close coordination with the Wire Development Group to compliment and expand on the corporate research at AMSC. Interactions include extensive collaboration with University of Tennessee on magnetic and transport 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.
T. Aytug, S.-H. Wee, M. P. Paranthaman, A. Goyal, L. Heatherly, F. A. List, S. W. Cook, and 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.

Highlights:
HTS Program CPS Control Milestone met - Deposit multi-functional epitaxial buffer that can replace at least 2 standard buffers with J_c of 2 MA/cm^2.
Buffer layers play a key role in YBCO 2G wire technology. The purpose of the buffer layers is to provide a continuous, smooth and chemically inert surface for the growth of the YBCO film, while transferring the biaxial texture from the substrate to the HTS layer. Important buffer layer characteristics are to prevent metal diffusion from the substrate into the superconductor, as well as, to act as oxygen diffusion barriers. In January 2007, we demonstrated in a model-system using PLD that a single $Gd_2Zr_2O_7$ layer may replace both the YSZ-barrier and CeO_2 -cap layers with J_c of 2.4 MA/cm^2. Work is under way to determine whether this high J_c can be sustained in thicker films, and whether this and other potential simplified substrate architectures are feasible for HTS deposited by commercially-selected processes.



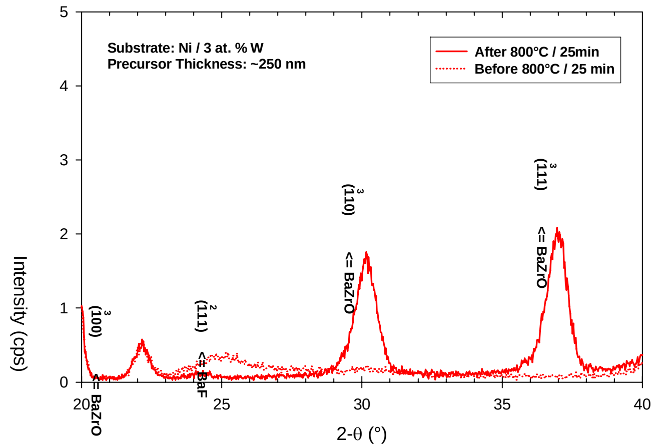
Magnetic field-dependency of J_c for a 0.2-µm-thick PLD-YBCO film on GZO/Y_2O_3-buffered Ni-W substrate.

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. To achieve high throughput (increase deposition rate), both major U.S. wire manufacturers have chosen reactive sputtering as the preferred method. 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 epitaxial films of $Gd_2Zr_2O_7$ (GZO) on thin (10 and 75 nm) Y_2O_3 buffered Ni-W substrates. YBCO films with a J_c of 2.4 MA/cm^2 at 77 K and self-field was demonstrated on newly developed reactively sputtered GZO films using pulsed laser deposition. Field-dependence J_c for 0.2-µm-thick PLD-YBCO films on GZO/Y_2O_3-buffered Ni-W substrate is shown in the figure.

Technical progress:

An E-beam precursor approach to RABiTS buffers.

Deposition of multi-component oxide buffer layers on textured metal substrates for HTS RABiTS applications typically involves sputtering at rates between 1 and 10 Å/sec. Significantly higher rates of deposition (~100 Å.sec) of these buffer layers are achievable using e-beam evaporation. Using a three-source e-beam evaporation system, zirconium metal and barium fluoride have been co-deposited at room temperature on bare textured Ni/3 at. % W and Y_2O_3 buffered Ni/5 at.% W. The resulting precursor has been processed in 200 mTorr water vapor at 700-800°C to form crystalline $BaZrO_3$. Preliminary results have shown the $BaZrO_3$ to be randomly oriented for both substrates (see figure). Efforts are under way to develop suitable processing for the growth of epitaxial $BaZrO_3$.



In-situ x-ray diffraction results (q – 2q) before and after precursor processing showing the formation of randomly oriented $BaZrO_3$ on (100) texture Ni/3 at. % W.

Status of milestones:

- 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**.

Interactions:

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

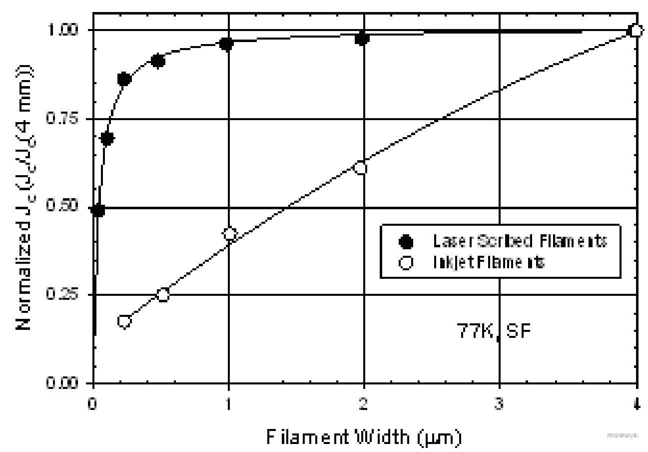
Section 1.3: Innovative and Enabling Technologies

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, and 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 fields (>1 W/m) that slow their immediate implementation into ac 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, 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.

Technical progress:
I_c decreases with filament width in filamentized conductor produced by inkjet. Inkjet printing is being evaluated at ORNL as a potentially low-cost, high-rate method to fabricate filamentary HTS coated conductor. The use of filamentary coated conductor in HTS applications such as motors, generators, and transformers can lead to substantial reductions in AC losses. Crack-free, HTS inkjet filaments have been successfully prepared on RABiTS substrates with a variety of filament widths ranging from ~100 μm to 1 cm. The J_c, for these inkjet filaments is found to decrease significantly and nearly linearly with decreasing filament width (see figure). In contrast, the J_c for filaments prepared by laser scribing of similar HTS coated conductor is much less sensitive to filament width, especially for filament widths greater than 250 μm. The behavior of J_c with filament width for inkjet filaments is believed to be process-related and the collective result of a) a broad distribution of thickness across individual inkjet filaments and b) a strongly thickness dependent, narrow processing window for maximum J_c. Strategies to overcome these processing-related challenges are being developed and explored.



Variations in I_c with filament width in conductors produced by inkjet and laser scribing.

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): On track.

Interactions:

The inkjet filamentization work is performed in close coordination with AMSC to assist in their process evaluation and planning activities

Subtask 1.3.2: Conductor design and engineering for practical HTS applications.
R. C. Duckworth, J. A. Demko, M. J. Gouge, and 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 device s 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 I_c variation with magnetic field and temperature, ac losses, quench and stability, splice performance, etc. Yet another purpose of this research is to develop means by which these application specific characteristics can be enhanced.

Highlights:
HTS Program CPS Control Milestone met - Commissioning of enhanced ac loss testing capability.
In order to better understand ac loss in HTS coated conductors, a new test facility was commissioned and successfully brought on line in March 2007. The first operation and sample measurements were completed in the new ac loss test facility on commercially available super-conducting materials. The test facility shown in Fig. 1 below is a double racetrack resistive copper magnet immersed in liquid nitrogen that provides an ac background field up to 170 mT. This field is 70% higher than previous ac background coils used at ORNL. Additionally, the sample length and field orientation allow for the angle dependence characterization of longer superconducting samples. This hardware provides a valuable diagnostic tool that will address the best methods to reduce ac loss in advanced conductor geometries without having to remove the sample to adjust the field angle.

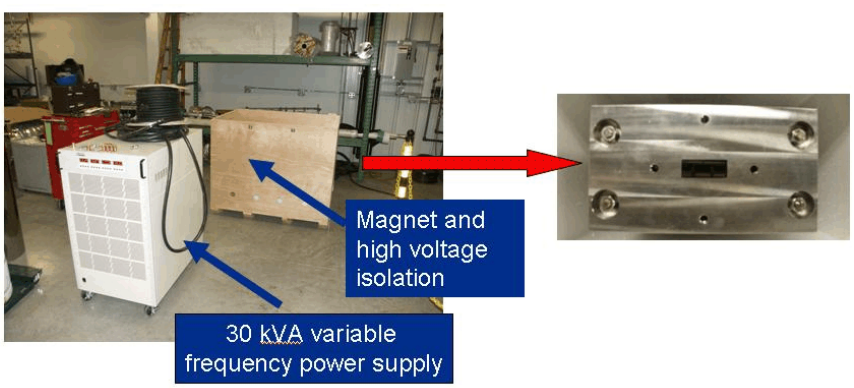


Fig. 1. AC loss test facility with 30-kVA, variable frequency ac power supply. Close-up of double-racetrack, resistive coil is shown to the right.

The first sample measurements were conducted on an as-manufactured YBCO coated conductor from AMSC. The superconductor was a 344 superconductor with a critical current of 150 A at

77 K. This superconductor has a 4-mm-wide, 75-µm-thick Ni-5at%W buffered substrate with a ~1-µm-thick YBCO superconducting layer that is laminated between two 4.4-mm-wide, 50-µm-thick copper stabilizing layers. The sample was outfitted with a heater and thermometer to calibrate the thermal response of the sample to a known heat input so that when the external ac field was applied, the change in temperature was used to measure the generated ac loss. Figure 2 shows the ac losses for this sample as a function of applied ac field when the field was perpendicular (higher losses) and parallel to the tape face. An angle dependent scan of the ac loss is shown in Fig. 3. While the experimental ac losses as a function of field was in agreement with the Brandt theory for perpendicular field, there was a discrepancy between the experiment and theory for the parallel fields. This discrepancy is consistent with the influence of the ferromagnetic Ni-5at%W substrate on the ac loss that has been reported elsewhere.

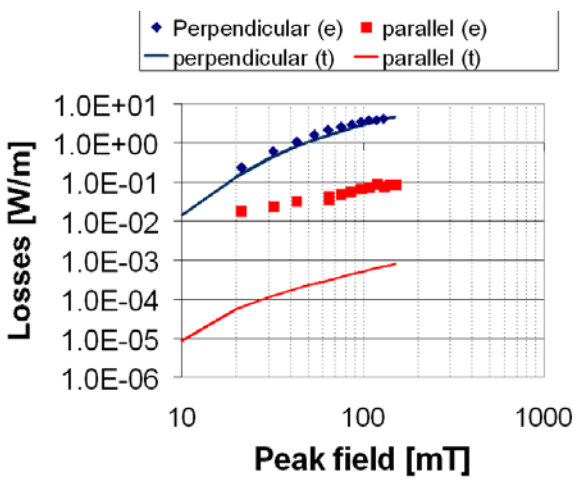


Fig. 2. AC loss at 77 K and 60 Hz in applied ac fields for an AMSC 344 superconductor with a critical current of 150 A with applied ac field perpendicular and parallel to the tape face. The Brandt model for hysteretic loss in the superconductor is shown by solid lines.

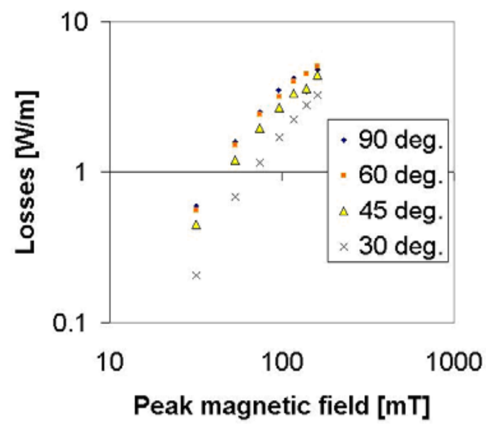


Fig. 3. AC loss at 77 K and 60 Hz in applied ac field as a function of angle for an AMSC 344 superconductor with a critical current of 150 A.

Technical progress:

1) Experiment initiated to characterize the current distribution in YBCO tapes.

With YBCO having a preferred orientation for splices, it should follow that in the presence of resistive zones or faults, the copper stabilization nearest to the substrate should carry less current than the copper stabilization nearest to the YBCO. For superconducting coils, this means that this part of the stabilization decreases the engineering current density with only a possibly modest impact on conductor stability. The copper would still function as either a thermal stabilizer or a means to electrically connect the substrate to the YBCO layer. Initial results, however, suggest that stability of 2G conductors may not be orientation dependent.

To examine the stability effect, two current leads were attached to both sides of conductor as shown in Fig. 1. The copper that was soldered to each side of the conductor was identical in length and thickness and the area of solder joint was the same to prevent the resistance of the current leads from impacting the measurement. Voltage taps were attached to each current lead to measure the voltage drop across each lead. After the sample measurement was completed, the sample was removed and the current leads were calibrated through the measurement of the voltage drop as a function of current. The only common point of electrical contact during sample characterization was where the dc power source connected to the current leads. The sample and leads were held in place on a G10 sample holder and the YBCO sample was insulated with dielectric tape to isolate it in the open liquid nitrogen bath.

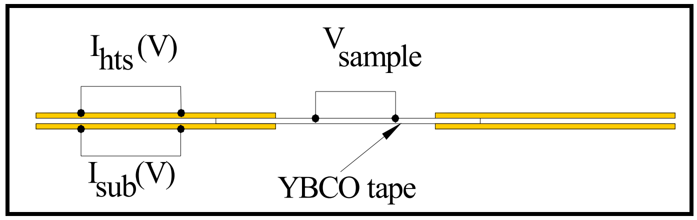


Fig. 1. Schematic of dual current lead setup.

Samples that were examined were as-manufactured YBCO coated conductors from AMSC and SuperPower. From AMSC, the YBCO coated conductor was a 344-superconductor with a total width of 4.4-mm and thickness of 0.15 mm. Two 50-µm-thick layers of copper were laminated with solder to the 4.0-mm wide YBCO tape, which had a critical current of 104 A and an n-value of 15 at 77 K. The YBCO coated conductor from SP was 4.0-mm wide and had copper surround stabilizer thickness of 38 µm on each side. Its critical current was 68 A and the n-value was 22. The current distribution was measured during conductor characterization (V-I curves) and for short duration, dc current impulse measurements. Figures 2 and 3 showed that during V-I measurements, the percentage of current flowing to the copper in contact with the YBCO (*Ihts%*) and the copper in contact with the substrate (*Isub%*) divided evenly as the current increased. This nearly equal distribution was also present during the impulse measurements as pictured in Figs. 4 and 5. These results would suggest that the stability of the conductor is not orientation dependent, but further measurements of the current transfer is needed to determine whether these results are sensitive to current lead length or other factors that may artificially influence the results.

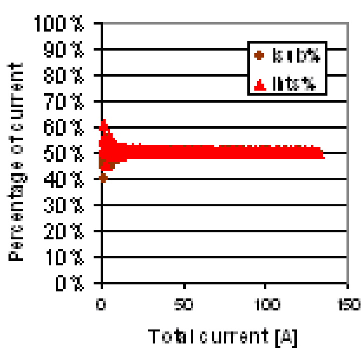


Fig.. 2. Current distribution during V-I measurement of AMSC 344-superconductor at 77 K with a critical current of 104 A.

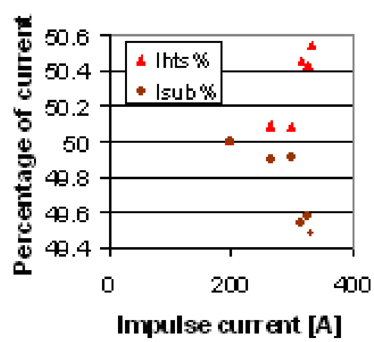


Fig. 3. Current distribution during V-I measurement of SP YBCO coated conductor with 38 µm of surround stabilizer and a critical current of 104 A at 77 K.

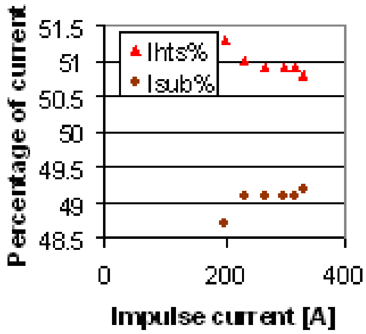


Fig. 4. Current distribution in AMSC 344 superconductor as a function of dc impulse currents.

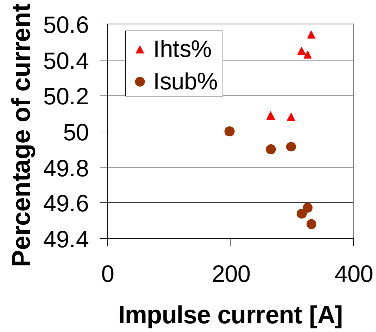


Fig. 5. Current distribution in SP YBCO coated conductor as a function of dc impulse currents.

2) *Initial analyses suggest that n-value strongly influences the modeling of thermal runaway in YBCO coated conductors.*

The finite difference model that was used to understand the role of critical current uniformity on conductor runway was utilized to analyze previous measurements of SuperPower YBCO tapes with different amounts of copper stabilization. Initial analyses suggest that the n-value strongly affects the modeling.

Figure 1 shows the experimental thermal runaway time as a function of current (normalized to I_c) for a set of YBCO tapes with different amounts of copper stabilization. Utilizing the thermal and electrical properties of the conductor and assuming a uniform critical current and n-value over the conductor length, Fig. 2 shows that the model prediction underestimated the thermal runaway time for the copper-stabilized YBCO coated conductors, while it overestimated the thermal runaway time for the YBCO coated conductor with only silver stabilization.

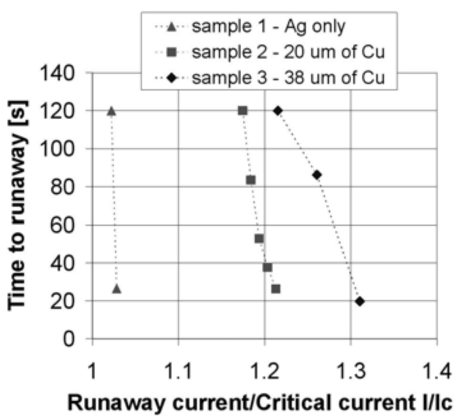


Fig. 1. Time to runaway as a function of the ratio of the runaway current to end-to-end critical current. The amount of copper-surround stabilizer is indicated for each sample. Lines shown are meant as visual guides and not trends in the experimental results.

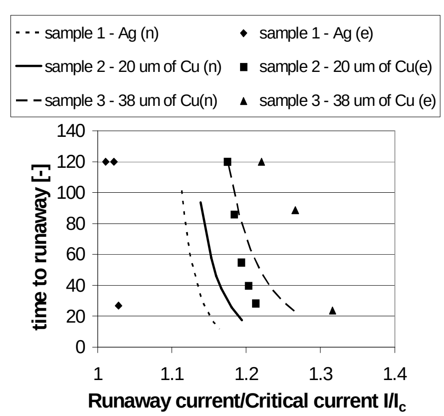


Fig. 2. Comparison between numerical (n) and experimental (e) results for the time to thermal runaway as a function of the ratio of current to critical current for samples 1, 2, and 3.

The differences in Fig. 2 are strongly influenced by the n-value of each conductor. The numerical simulation results that are shown in Fig. 3 for samples 2 and 3 (20 μm and 38 μm of surround copper stabilizer respectively) indicate the jump in thermal runaway has more to do with n-value than the amount of copper stabilization. Since the thermal runaway is a balance between resistance of the superconductor and the resistance of the metal layers, the YBCO coated conductor with only silver stabilization may have had a region of localized high n-value, which could explain the difference in numerical and experimental results for the sample with only silver stabilization.

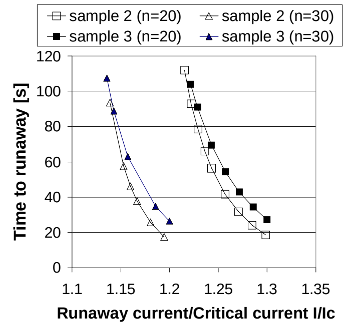


Fig. 3. Numerical prediction of time to runaway as a function of current for samples 2 and 3 with selected n-values.

<u>Status of milestones</u>:

- Commissioning of enhanced ac loss testing capability. (March 31, 2007): **Met March 28, 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>

Measurements were performed primarily on 2G wires provided by AMSC and SuperPower. Results are communicated to the appropriate industry partners to assist them in process development and planning activities.

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

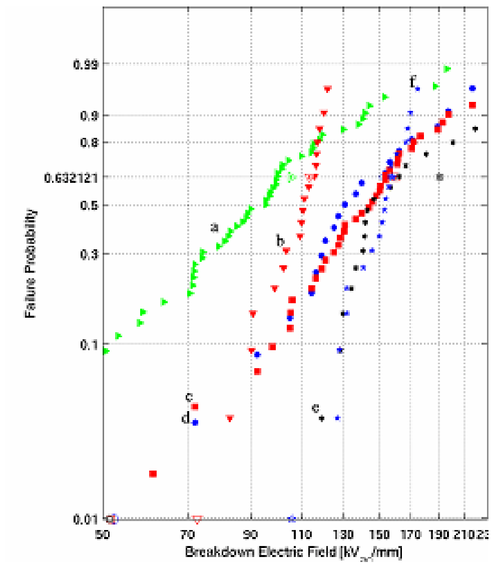
Objectives:

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:

Dielectric breakdown strength affected by PMMA solvents. Preparation of polymeric materials plays an important role in their electrical properties. To investigate this we have prepared PMMA with three different solvents, acetone, toluene and acetic acid. The acetone dissolves the PMMA quickly, but it is very volatile and did not form nice smooth PMMA films. The other two on the other hand form excellent PMMA films. Breakdown strength is found to be affected by the solvents. PMMA mixed with acetic acid is found to exhibit very high dielectric strength.

The breakdown tests performed on these samples are shown here. The values are compared to other materials tested. The labels denote different materials as follows, a:PVA, b:PPLP, c & d: PMMA toluene, e: PMMA acetic acid and f:Cryoflex. PMMA prepared with acetic acid has very high dielectric strength at 77 K.



Weibull probability plot of breakdown in various polymers/mixtures: a) PVA, b) PPLP, c-d) PMMA toluene, e) PMMA acetic acid, and f) Cryoflex.

Technical progress:

1) PMMA filled with magnetic nano-particles show effect on dielectric properties.

Magnetic nano-particles obtained from Adam Rondinone (CNMS and CSD) were dispersed in PMMA. Both the PMMA and particles were diluted in toluene solutions. Dielectric measurements show that properties are affected by the magnetic nano-particles in various ways.

Dielectric measurements (Fig. 1) at room temperature were performed with impedance and polarization methods. It was observed that small amounts of particles added to the PMMA decreased the dielectric permittivity of the base polymer. However, the sample with the highest particle concentration had very similar dielectric permittivity to the base material at a broad

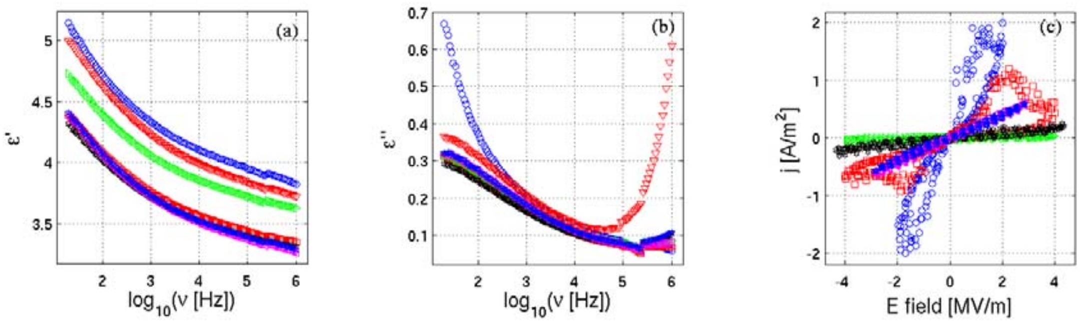


Fig. 1. (a) real and (b) imaginary parts of dielectric permittivity for unfilled and magnetic nano-particles filled PMMA. (c) Dielectric polarization in unfilled and filled samples. The unfilled PMMA is plotted by open circles.

frequency range. Addition of particles decreases the dielectric loss in the material as well. The polarization measurements revealed the actual physical mechanism that caused the decrease in the permittivity even with inclusion of metallic particles. Notice that the pure PMMA illustrated a hysteresis with high polarization and plausibly ionic conductivity. Samples with low amounts of nano-particles modified the electrical properties and decreased the polarization effects in the polymer, such that they restricted the polarizing units. The breakdown data (Fig. 2) of the samples did not show significant changes for unfilled and filled materials at 77 K. The filled samples had higher 63% breakdown values than the unfilled PMMA except for the sample with the highest nano-particle concentration. The data spread on a broad range. Breakdown values at 63% were between 140 and 160 kV/mm.

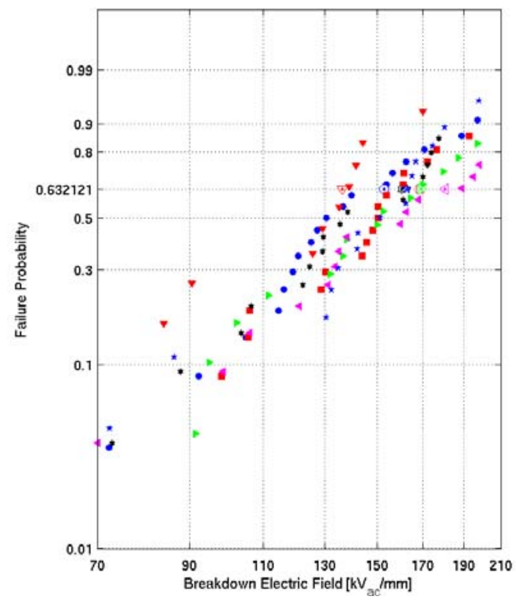


Fig. 2. Dielectric breakdown data at 77 K for unfilled and magnetic nano-particles filled PMMA.

2) New computer program developed for the dielectric characterization of materials.

A new measurement program in Labview was written for the dielectric characterization of materials. The program controls the Keithley 6517A and reads out the current with varied voltage inputs. The voltage is taken to be a saw tooth with a given low frequency period as shown in Fig. 1. To test the program and the measurement setup, a sample composed of polyvinyl alcohol which is filled with nanometer-size, ferroelectric, barium titanate particles was fabricated. The barium titanate concentration is 10 wt % in the sample. The nonlinear behavior of the composite was observed as a hysteresis in the current-voltage diagram as seen in Fig. 2. Similarly the behavior is also significant in the voltage and current versus time plots in Fig. 1. In the figures responses at the end of the measurement cycle are presented.

Nonlinear behavior of this composite can be used in field grading applications, where high electric regions in an insulation system can be covered with this material to distribute the electrical stress. Further investigations on the subject are needed. Samples with different wt % of barium titanate will be fabricated. The temperature dependence of the nonlinear behavior as well as the dielectric permittivity of the samples will be measured.

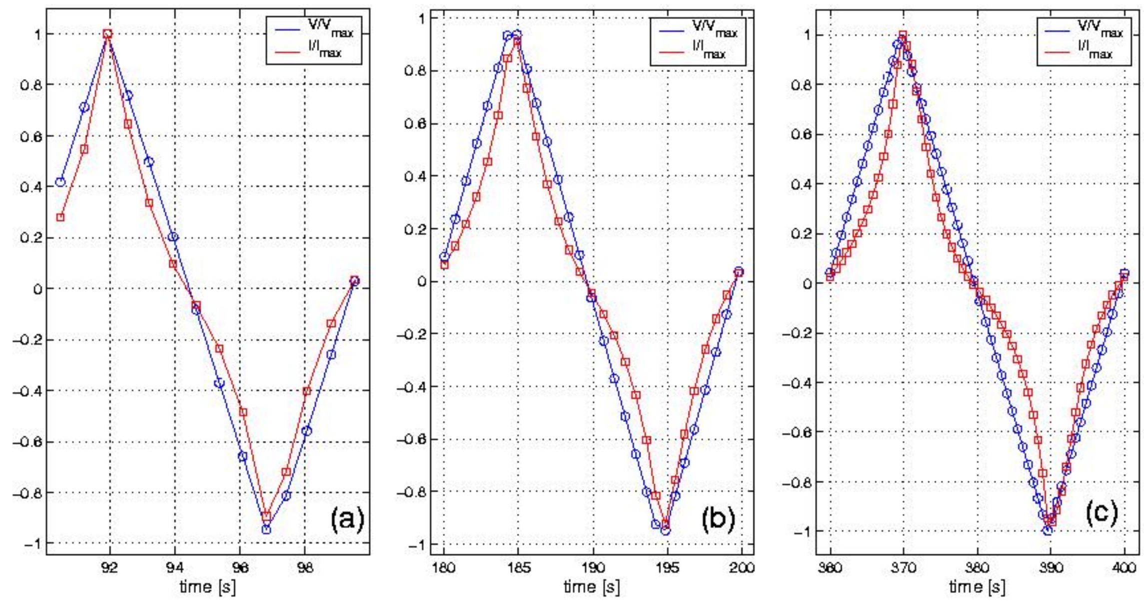


Fig. 2. Nonlinear behavior of barium titanate-filled polyvinyl alcohol. The period of the input voltage is varied (a) 10 a, (b) 20 s and (c) 40 s.

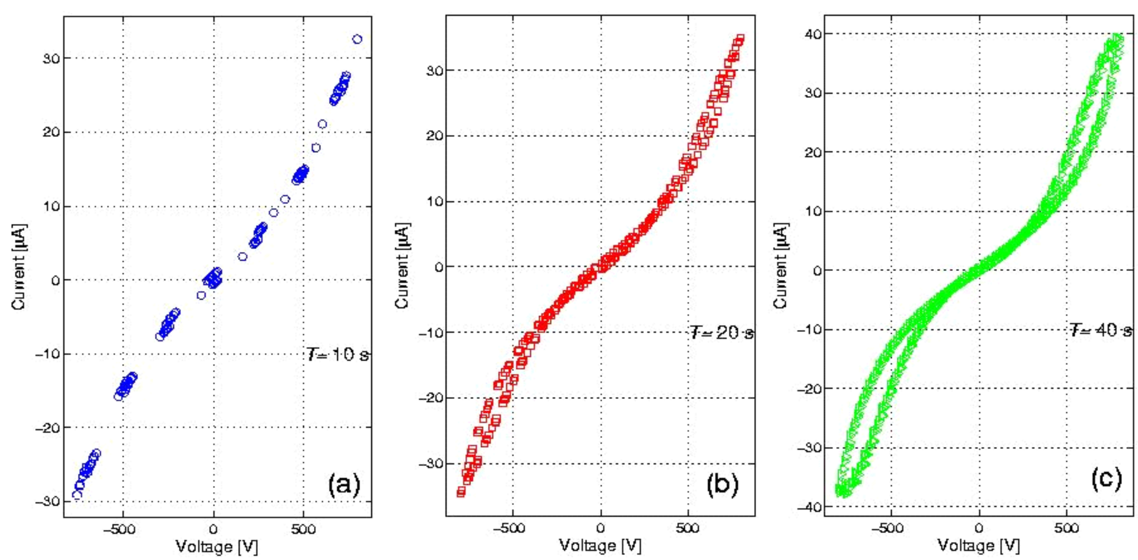


Fig. 2. Nonlinear behavior of barium titanate-filled polyvinyl alcohol. The period of the input voltage is varied (a) 10 a, (b) 20 s and (c) 40 s.

Status of milestones:

- Obtain nano-dielectric materials with enhanced electrical and physical properties.(July 31, 2007): On track.
- Built and test an apparatus for measuring thermal conductivity as a function of temperature in the range 20-300K. (Aug. 31, 2007): On track.

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. A. Demko, M. J. Gouge, C. Rey, and R. C. Duckworth.

Objectives:
HTS cable systems have been demonstrated that can carry several times the current (2-5x), and hence several time 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 operate within design specifications.
The cable operated through the Ohio winter season after some external bushing temperature sensor settings were reduced to be consistent with low ambient temperatures on the coldest winter evenings. While the HTS cable continues to provide power to more than 8,600 residential, commercial and light industrial customers, two events have occurred in this quarter. These events triggered programmed responses without damaging the cable, and demonstrate the value of real-world testing necessary for broad commercial adoption of the HTS technology.

On January 3, the unintentional loss of the station battery system while troubleshooting a ground caused a breaker to open which removed input power to the cable cryogenic system. As a result, the HTS cable was taken offline according to the control strategy. The cryogenic system and HTS cable were restored shortly after the initial incident was resolved. In addition, there was a brief cable system outage on February 15 due to some leaking sensor line isolation valves on the cryogenic skid that were replaced. These unplanned, real-world occurrences demonstrate the robust design margin of the HTS cable system, and provide valuable operational data.

Technical progress:
1) Work begins on the evaluation of thermal-hydraulic effects in long cable cryostats.
ORNL began working with Southwire (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. In parallel, efforts are ongoing to develop a model to simulate this test so the experimental results can be correlated with the model. Based on this, a realistic thermal-hydraulic model for the proposed longer SPE cable can be developed. 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 deter
to optimize the cable former diam

2) Feasibility of thermal ac loss measurement in superconducting cables demonstrated.

Based on discrepancy between the thermal and electrical ac loss measurements for a YBCO cable that was measured in July 2006 and in preparation for the measurement of two new YBCO cables, an investigation was carri
possible alternative method to me
V-I product for dc heating when t
in the cable. This method resulted
this known heat source was used to calibrate the platinum resistance temperature detector (RTDs) on the cable.

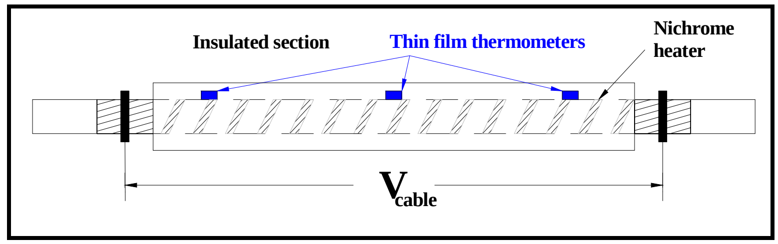


Fig. 1. Diagram of thermal ac loss measurement setup for the YBCO cable.

The HTS prototype cable that was measured was a two-layer, 1.25-m-long YBCO cable that was wound on a 25.4-mm-diameter G10 former with the 344-superconductor produced by AMSC. Each layer consisted of sixteen YBCO tapes that were wound at ± 20° pitch angles on the former and were attached to solid copper end plugs with a Sn-42 Bi-58 solder. This solder was chosen as a compromise between the recommended solder 52In 48Sn with a melting point of 118 C and the solder used in the copper lamination which has a melting point of 179 C. A set of thermometers and a nichrome heater were wound to the exterior of the cable and then covered with 16 layers of PPLP insulation. This insulation isolated the thermometers from the liquid nitrogen bath and allowed for measurement of the ac loss. While the use of the local heater has been previously used to estimate ac loss, the difference between the electrical and thermal ac loss measurements suggested that an alternative method was needed. The alternative method for measuring the ac loss thermally was found through adaptation of a successfully demonstrated method used for single HTS tapes. When the dc current exceeded the cable critical current, the product of the current and the voltage drop across the insulated section produced uniform heat generation along the length of the cable. This known heat load is used to calibrate the platinum thermometers that were positioned along the length of the cable as shown in Fig. 1. Then, the change in temperature is measured when ac

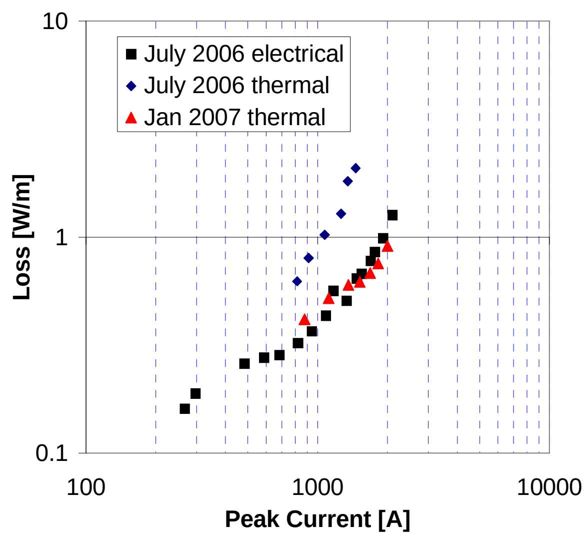


Fig. 2. Comparison of electrical and thermal ac loss measurements made in July 2006 to the thermal ac loss measurements in January 2007 on the same 25.4 mm diameter, 1.25-m long YBCO cable.

current is applied to the cable and the ac loss as a function of ac current is found. It appeared that the thermal method using the nichrome heater overestimated the change in temperature due to a known heat input. When the new thermal method was compared to the previous measurements shown in Fig. 2, the agreement between the thermal and electrical data has improved greatly.

3) Preliminary study being performed to evaluate the feasibility of HTS dc cables to power supercomputers and data centers.

The implementation of the next generation, peta-flop-scale supercomputer at ORNL is already under way. Consistent with that planning is the corresponding facility engineering to support these planned upgrades. One of the major problems with the planned upgrades in computer processing speeds is the corresponding need for increased electrical power and interior cooling for the facility. The electrical power for the next generation supercomputer i.e. the Cray –Baker and beyond (Cray-Marble and Cray-Granite), all will require a 48 V dc input to the processor board. At this relatively low voltage level, this translates to an ever increasing amount of feeder current to handle the enormous electrical power load. At these low dc voltage and high current levels, the corresponding conventional copper and/or aluminum electrical bus required to carry this enormous power is massive in size and weight. For facility planning purposes, the approximate electrical input power requirements that have been estimated for these next generation supercomputers are: a) 3 MW for the Cray-Jaguar, b) 7-10-mW for the Cray-Baker, and c) up to 30 MW for the Cray-Granite and Cray-Marble. In reviewing this proposal, it should be clarified that there is presently (February 2007) an existing ~7.3 MW of electrical power available to building 5600 supplied by three (3) separate electrical feeds rated at: 2 MW, 2 MW, and 3.3 MW, respectively. Therefore, to obtain the necessary 30 MW in the final installation, an additional 23.7 MW of electrical power will need to be added to the facility by year 2010. It is these additional 23.7 MW of electrical power that is addressed in this proposal. For the purposes of this proposal, we have rounded the required electrical power value to ~24 MW.

In this application, a superconducting electrical bus (cables) operating with a large dc current level has the potential to significantly reduce the size, weight, and energy consumption over a corresponding conventional copper/aluminum bus. The Applied Superconductivity Group (ASG) has been tasked with looking at various options of supplying large amounts of electrical power via a high-current, low voltage dc bus. An initial study was performed and four different options were identified. These four options are:

1) Conventional ac power baseline:	Option 1
2) DC power at 48 V and 500 kA:	Option 2
3) DC power at 1.2 kV and 20 kA with converter:	Option 3
4) DC power at 410 V at 58.5 kA without converter:	Option 4.

The advantages and disadvantages of the HTS dc cable to the conventional solution are listed below.

Advantages

- Interface to the supercomputer internal power supply at 410 V dc enhances efficiency by ~3% (for the 24 MW load only)→ 720 kW reduction in heat load to the facility

- Zero electrical ac bus losses resulting in a ~2% higher transmission efficiency →429 kW reduction in heat load (Option 4 cryogenic system)
- Significantly lighter weight
- Significantly smaller cross-sectional area of the HTS electrical bus
- Significantly smaller facility footprint
- Zero magnetic fringe field (co-axial design→ see Fig. 4)
- Transmission loss independent of length allowing remote placement of source power feed
- Reduced arc-flash hazard inside supercomputer facility

Disadvantages

- HTS wire presently is over 2-5-times more expensive→ selling for ~$50-150/kA-m compared to conventional copper for ~ $25-30/kA-m
- DC HTS cable needs to be cooled to an operating temperature of ~70-77 K and therefore requires a cryogenic cooling system. This adds additional capital cost and an electrical power penalty which must be factored into the overall annual operating costs

The constraints of the electrical power problem addressed is this study are:

- The study addressed the addition of 23.7 MW (~24 MW for calculation purposes) to Building 5600
- A 13.8 kV ac transformer located external to the ORNL supercomputer facility (Building 5600) will supply the electrical power from the new ORNL substation.
- The planned upgrade in electrical power will scale from ~7.3 MW in calendar year 2007 up to 30 MW by calendar year 2010 (see Figs. 1a and 1b).
- The electrical power feed to the processing boards of the Cray supercomputer requires a 48 V dc input at <3% ripple.
- The rectification of the 13.8 kV ac to dc feed is located approximately 100 m from the ORNL supercomputer facility.
- The cryogenic system necessary to operate the HTS based electrical bus is located external to the ORNL facility and co-located with the 13.8 kV ac to dc rectification.
- For the superconducting bus option, each electrical termination, i.e. the transition from the 77 K region to the room temperature region, occupies ~16 ft^2 per termination.

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.

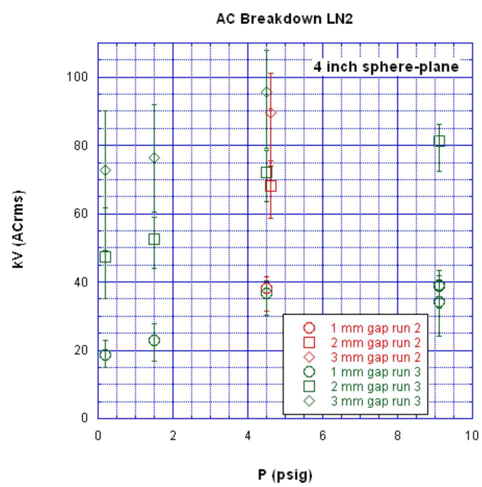
Interactions:

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

Subtask 1.4.2: Development of high-voltage HTS power transformer.
S. W. Schwenterly, D. R. James, I. Sauers, and A. R. Ellis

Objectives:
High-temperature superconducting utility power transformers offer prospects for improved efficiency, smaller size and weight, lessened environmental hazard, better overload tolerance, and longer lifetime in comparison with conventional power transformers. The current U.S. utility power transformer inventory is aging and will soon require replacement, offering a large potential market for advanced superconducting transformers. ORNL is collaborating with Waukesha Electric Systems (WES) and a utility partner to continue development of HTS power transformers. Objective of this project is to perform R&D on issues necessary to extend the transformer operation to higher voltages required for compatibility with the existing power grid. A commercially viable HTS transformer will have to operate at voltages in the range of 138 kV and above, and withstand 650-kV impulse.

Highlights:
HTS Program CPS Control Milestone met - Complete 30-in. test dewar and carry out HV tests.
Initial measurements on ac breakdown in liquid nitrogen (see figure) were performed in the new 30-in. (762 mm) diameter dewar that was reported in the first quarter progress report. Successful testing of this large volume dewar in February 2007 satisfies the control milestone, and represents an enhanced capability at ORNL for device demonstration testing. Data obtained in this equipment will be used in the design of high voltage insulation for superconducting transformers under a collaborative agreement with WES.



AC breakdown in pure liquid nitrogen gaps for sphere-plane electrode geometry.

The electrode geometry was a 4-in. (101.6 mm) diameter stainless steel sphere for high voltage to a grounded plane. The finish on the sphere was a typical industrial grade. The bushing arrangement allows for changing the gap in place with the electrodes still immersed in LN_2 which greatly speeds up data acquisition. The breakdown voltage generally increased slightly with increasing pressure of LN_2 as expected. A 3-mm gap at 9.1 psig was not run due to exceeding the ac voltage rating of the high voltage bushing. The symbols are the average value of at least 10 breakdowns and the error bars are the minimum and maximum breakdown values.

Technical progress:
1) High-voltage "dummy" test coil being fabricated.
S. W. Schwenterly visited the WES plant March 19-21 to finalize designs and test plans for a new high-voltage test coil that will be wound by WES. This coil will be made with copper dummy conductor and will closely simulate the geometry proposed for the high-voltage winding of the 24-MVA, 115/13.09-kV transformer that is the goal of our current SPE proposal. Conductor for the coil has been insulated with WES's proprietary synthetic material. The coil

will contain multiple samples to allow determination of breakdown voltage statistical distributions. It will be immersed in liquid nitrogen for the tests. An existing dewar at ORNL is being refurbished for the tests and will be shipped to WES. Tests will be carried out at WES with both full-wave and chopped-wave impulse voltages as well as 60-Hz ac voltages. WES personnel are making impulse voltage distribution calculations on the 24-MVA design for comparison with the test results. On other design issues, a new potential supplier has been identified for the composite dewars that will be required for the transformer.

2) Testing of tape insulation for HTS transformers.

A proposed synthetic tape wrapped on copper tape (as a surrogate for HTS tape) has been tested in open bath liquid nitrogen in a crossed tape arrangement which has previously been described. Results indicate that butt gaps tend to lower the breakdown strength.

A total of 48 measurements have been made and are plotted in a Weibull probability plot shown in Fig. 1. The plot appears to be linear with the exception of the two lowest points at 10.7 and 15.4 kVrms. These two data points do not appear to be consistent with the rest of the data suggesting that another breakdown mechanism was involved such as the presence of a bubble trapped under the tape. If these two points are removed and the probabilities are recalculated and then replotted, the data becomes linear as shown in Fig. 2. The data follows a Weibull distribution from the highest breakdown value to the lowest.

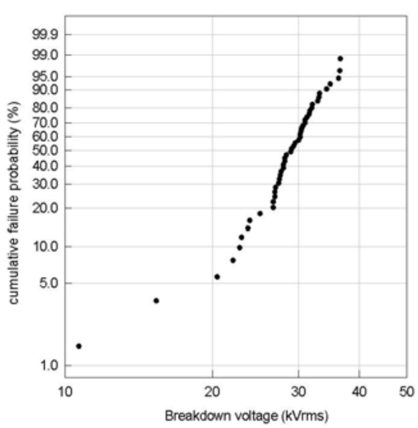


Fig. 1. Breakdown data on synthetic tape wrapped on copper in a crossed tape geometry in liquid nitrogen.

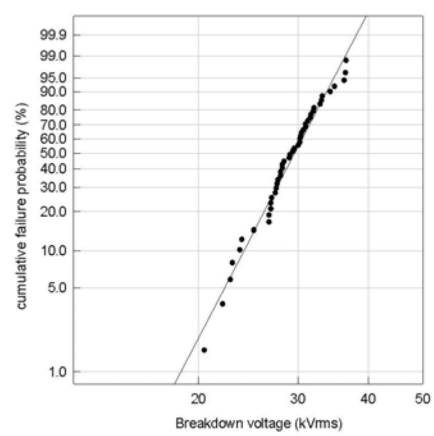


Fig. 2. Breakdown data from Fig. 1 replotted without the two lowest breakdown values.

After breakdown, the tapes were examined for the breakdown location relative to a butt gap on either tape. The data were then divided into three groups: (1) no butt gap on either tape, (2) a butt gap on one of the tapes and (3) a butt gap on both tapes. The data were organized according to the breakdown location and replotted, shown in Fig. 3. The mean values for the three types of breakdown locations are given in the following table, indicating that the butt gaps tend to lower the breakdown strength.

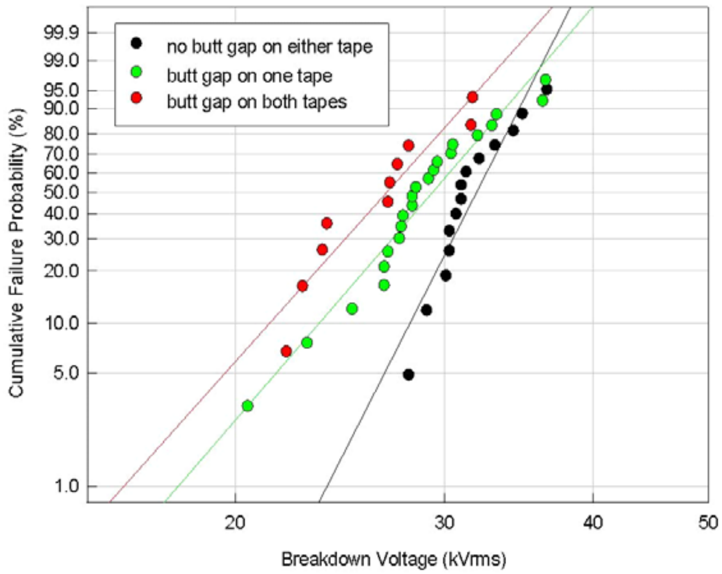


Fig. 3. Effect of butt gap on breakdown probability distribution.

Table 1. Mean breakdown values according to location.

Breakdown location	Mean value (kVrms)	Standard deviation (kVrms)
No butt gap	31.6	2.4
Butt gap on one tape	28.9	3.8
Butt gap on both tapes	26.5	3.4

Status of milestones:

- Complete 30-in. test dewar and carry out HV tests. (July 31, 2007**): Met Feb. 23, 2007**.
- Complete cryogenic cooling, ac loss, and HTS coil design aspects of transformer conceptual design and engineering analysis. (Sept. 30, 2007): On track.

Interactions:

Close collaboration with WES continues in this project. There were site visits by both ORNL and WES personnel for technical design, testing and planning activities.

Subtask 1.4.3: Reliance Electric CRADA: HTS Industrial Motor.
C. Rey and 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 hp 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 high as $1 billion 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.

Technical progress:
ORNL in collaboration with Reliance Electric is establishing a test facility capable of characterizing the critical current (I_c) of 2G YBCO coated conductor tape. The goal of the collaboration is two-fold. First, the ORNL-Reliance team will study the critical current of 2G YBCO tapes as a function of temperature, magnetic field, and magnetic field orientation. Second, the team will investigate the splice resistance of 2G YBCO tapes under similar conditions of temperature, magnetic field, and magnetic field orientation. The information is necessary for the design, fabrication, and testing of 2G wire-based motors.

The test apparatus will operate in the conduction cooling mode and is capable of measuring in the temperature range from 80 K to 30 K and in background magnetic fields ranging from 0 to 6 T, with transport currents up to 330 A. The test apparatus is capable of measuring five different samples, each with separate orientations of the transport current with the background magnetic field. The sample holder is will accommodate five separate samples up to 5-cm in length in the following orientations: 0˚, 30˚, 45˚, 60˚, and 90˚. A fundamental understanding of the critical current as a function magnetic field and magnetic field orientation is crucial in the future design and operation of HTS based electric utility applications and devices. The test apparatus is being fabricated at local shops and low temperature tests are scheduled to start in May 2007.

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): On track.

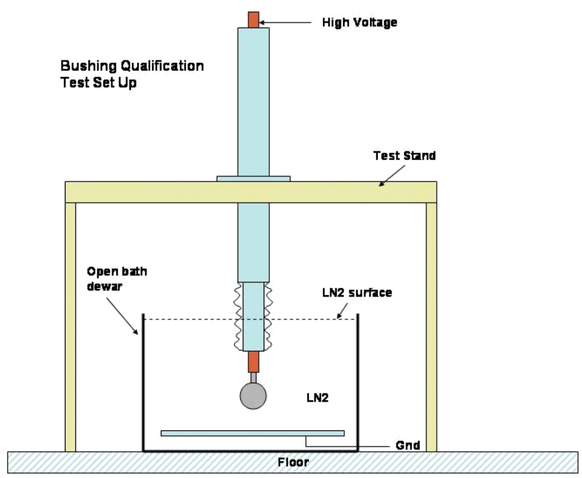
Interactions:
Work includes close collaboration with Rockwell Automation. Results are communicated to Rockwell to assist in their motor development and planning activities.

Subtask 1.4.4: Fault current limiter CRADA with SuperPower.
D. R. James, A. R. Ellis, I. Sauers, and E. Tuncer

Objectives:
ORNL has teamed with SuperPower 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 and provide 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.

Technical progress:
Test setup being prepared for HV qualification of bushing.
Preparations are being made for HV qualification testing of a bushing to be used in LN2. SuperPower is furnishing the bushing and team members from SuperPower will come to ORNL in April to conduct the tests in conjunction with ORNL staff.

A schematic of the basic test setup is shown in the figure. Tests will include partial discharge, ac withstand, and positive and negative lightning impulse (1.2 μs rise/50 μs fall time) withstand. The impulse voltage level will be the standard BIL (Basic Impulse Insulation Level) of 650 kV for this class of bushing. To verify performance of the bushing, tests will be done in air at room temperature to establish a baseline. The tests will then be done in LN2 and repeated again in air and results compared. Electric field calculations and preliminary testing have been done to verify the type of termination and air gaps needed for the withstand tests. High voltage tests will also be conducted on a mockup of the fault current limiting elements provided by SuperPower. These tests will be performed in an open LN2 bath.



Test setup for qualification testing of a bushing to be used in LN2.

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 subassemblies at ORNL. (Sept 30, 2007): On track.

Interactions:
ORNL has been working closely with SuperPower on the design of SFCL. There were frequent discussions in preparation for the HV bushing test.

Subtask 1.4.5: Cryogenic dielectric R&D and design rules.
E. Tuncer, I. Sauers, D. R. James, and 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:
1) New cell design led to improved measurement setup for electrical properties of cryogenic dielectric materials.
The measurement setup for electrical properties of materials was improved with a new cell design, which is used in the cryocooler. Initial tests on the unfilled polyvinyl alcohol (PVA) showed good temperature stability in the cell. Previously, large temperature gradients were observed on film samples. Dielectric properties of the PVA were measured between 15 K and 350 K with 5 K steps.

2) Dielectric test setup for insulated tapes completed.
Test apparatus has been developed to perform dielectric tests of insulated tapes in liquid nitrogen (LN2). Figures 1 and 2 show the experimental setup in which one of the tapes is arranged perpendicular to three tapes for multiple measurements without having to remove the tapes from the liquid nitrogen bath. Each tape is wrapped with five layers of dielectric strips, so the total number of strips of electrical insulation between the two tapes is 10 layers. Each strip layer is nominally 0.003 in. (0.076 mm) giving a total of 0.76 mm of insulation between the two tapes. An average of 6 measurements yielded a breakdown strength of 30.9 ± 5.4 kVrms/mm in open bath (1 bar) liquid nitrogen.

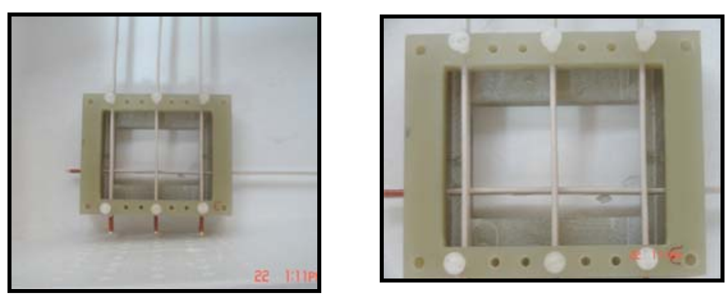


Fig. 1. Experimental setup for measuring breakdown of insulated tape in open bath liquid nitrogen. In the photos the horizontal tape is at ground potential and each of the vertical tapes are ramped at high voltage until breakdown while the other tapes are floating

Fig. 2. Tape assembly in Styrofoam dewar, connected to voltage divider.

<u>Status of milestones</u>:

- Quantify ac and impulse breakdown in LN2 as function of gap and electric field profile. (August 31, 2007): On track.
- 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.

Subtask 1.4.6: SPI/SPE Readiness Reviews.
M. J. Gouge

Objective:
Several previous HTS demonstration projects had technical failures that precluded successful demonstration on the electric grid. These failures could have been avoided or circumvented if objective technical reviews were performed at critical go/no-go junctures. Recognizing this, the program initiated a Readiness Review process that has contributed greatly to the success of the remaining demonstration projects. The goal of the reviews is to enhance the probability of successful completion of demonstration projects by focusing on early identification and resolution of technical issues. Reviews are conducted by a small group of experts independent of the demonstration project teams with emphasis on an objective technical in-depth review.

Technical progress:
SFCL Readiness Review Report issued to DOE.
A report was issued in March 2007 to DOE-OE and SuperPower documenting the December 18, 2006, Superconductivity Partnership with Industry (SPI) Project Readiness Review conducted at SuperPower as part of a more general "DOE/EPRI project re-engagement" meeting.

It had been nearly 18 months since the previous readiness review and the basic fault limiting technical approach had changed as well as several key project staff and major participants. SuperPower placed the Matrix Fault Current Limiter (MFCL) project in a "reduced effort" status following a readiness review in the summer of 2005. The program remained in that status until mid-2006. At that time, a newly reconstructed SuperPower-led team established a new project technical baseline using 2G HTS tape-based elements as replacements for the bulk BSSCO matrix elements used in the MFCL device. The project name was revised slightly to Superconducting Fault Current Limiter (SFCL) project. Readiness reviewers were Mike Gouge (ORNL) and Bill Hassenzahl (AEA).

Status of milestones:
- Organize SPI/SPE session at 2007 Wire Development Workshop. (Jan. 31, 2007): **Met January 2007**.
- Conduct readiness review of SFCL project with revised matrix design (2G tape). (Feb. 28, 2007): **Met December 2006**.
- Conduct initial readiness reviews of new SPE projects to ensure realistic deliverables and competent teams. (Sept. 30, 2007): On track - *but depends on award timeline and project ramp-up rate.*

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 (American Superconductor)

Objective:

AMSC is currently 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, (3) and developing 2G wire architectures suitable for commercial and military applications.

Highlights:

1) *Critical current of AMSC's 344 superconductors exceeds 100 A at 77K, self-field*

- 117 A performance was achieved in a 70 meter length of standard 344 superconductors produced on AMSC's pilot manufacturing line.
- Average critical current (77K, self-field) of AMSC's production wire reaches the 80 – 100 A level.

2) *Improved manufacturing processes and rate enhancements provide path to volume production of 344 superconductors with commercial-level electrical performance.*

- Enhanced production rates and process modifications developed for full-scale production equipment will enable an annual production capacity of 720 km of 344 superconductors in December 2007.
- Processing rates consistent with achieving commercial cost targets with 10-cm strips have been demonstrated.

3) AMSC's 344 superconductors with stainless steel lamination used in successful Fault Current Limiter (FCL) demonstrations.

- Siemens and AMSC demonstrated the first successful test of a 2MVA FCL produced with 344 superconductors with a stainless steel laminate in February 2007
- Hyundai demonstrated an 8.3 MVA FCL, manufactured with AMSC's 344 superconductors. The unit achieved an AC withstand voltage of 143kV, nearly three times the 50kV targeted performance.

Technical progress:

1) Performance of 344 superconductors nears commercial level

- A critical current of 117 A (minimum) was achieved in a 70-meter length of 344 superconductors produced in AMSC's pilot manufacturing line. This performance level, achieved in a 0.8-µm YBCO film, is approaching the 120 A level required for early commercial applications.
- A critical current of 150 A was demonstrated in a 5-meter length of 344 superconductors fabricated with a 1.4-µm YBCO layer.
- R&D samples have achieved critical currents exceeding 550 A/cm-width providing a path to a critical current of over 200 A in 344 superconductors.

2) Process Improvements

- Modification of the pilot slitting line has reduced variability between alternating cuts, resulting in higher overall produce performance and increased product yield.
- A modified oxygenation process, introduced into pilot manufacturing line, has enhanced the in-field performance of 344 superconductors and significantly reduced processing time.

Status of milestones:

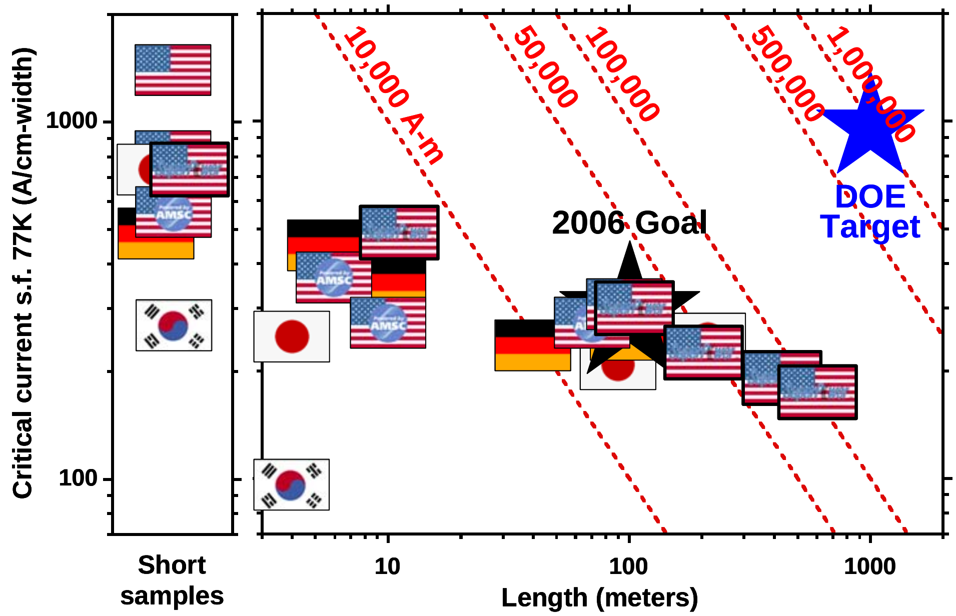
- 20 – 100 meter length of 344 superconductor wire with a critical current exceeding 100 A at 77K, self-field (July 31, 2007).
  - **Met January 2007** - 117 A (77K, self-field) over 70 m of 344 superconductor.
- 100 meter lengths of 344 superconductor with an Ic exceeding 120 A at 77 K, self-field.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

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:
Research-grade MOCVD/IBAD 2G wire from SuperPower exceeds 700 A/cm performance.
High 2G wire I_c is necessary for many HTS power applications as well as a lower cost/performance ratio. SuperPower has been very successful in increasing 2G wire I_c using its proprietary Metalorganic Chemical Vapor Deposition (MOCVD) process. Recently, very high I_c samples have been obtained at SuperPower using its continuous reel-to-reel manufacturing equipment. These research-grade samples are ~3.5-μms thick and are deposited in 5 successive passes on SuperPower's IBAD-MgO/LMO templates. Transport measurements showed that these wires possess I_c's in excess of 700 A/cm-width. More importantly, detailed measurements indicated that overall I_c continues to increase with HTS thickness, thereby suggesting that much higher wire I_c's may be obtained by simply adding more HTS passes. Effort continues to further increase individual layer and overall wire I_c's. The thick film MOCVD process has been evaluated in longer R&D lengths up to approximately 10 m. Critical current values of nearly 600 A/cm in meter lengths and nearly 500 A/cm over 11 m have been achieved.

Technical progress:
Record long-length performances achieved by SuperPower at high production rates.
SuperPower has invested significant 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. Among these are a 103-meter length with end-to-end I_c greater than 300 A/cm, a 203-meter length with minimum I_c of 227 A/cm, and a 427-meter length with minimum I_c of 191 A/cm. In January 2007, SuperPower produced a 595-meter 2G wire with minimum I_c of 173 A/cm. This is the longest 2G wire yet manufactured in the world with a record 102,935 A-m performance. This is the first time that the 100,000 A-m milestone has been surpassed, and is almost double the performance of SuperPower's nearest competitor. Most importantly, these long length wires were manufactured at high rates, the slowest step having a speed of 45 m/h (135 m/h equivalent production rate for 4 mm-width wire). Even at these high production rates, there are no degradations in the performance and the wire uniformity. Another important accomplishment was achievement of tape speeds of 100 m/h or more over 300 m of 12- mm-wide wire (equivalent to 300 m/h of 4-mm-wide wire) in deposition of buffer layers atop IBAD MgO using all reactive sputtering processes, while maintaining texture values of 6 to 8 degrees.



Worldwide long length performance of 2G wires using technical substrates.

Status of milestones:

- Short sample 2G wire with I_c of 750 A/cm. (July 31, 2007): On track – *reached 720 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): On track, - *presently at 20 kA/cm^2 level.*.

Subtask 1.5.3: NIST-Boulder electromechanical studies for superconductor development subcontract.
J.W. Ekin, 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 significantly raises the delamination strength, even when the conductors are slit. More delamination testing is underway to verify this finding. Also, conductors with new geometries to improve the delamination strength are being prepared by industry and will be tested at NIST once they are received.

Technical progress:
1) New electromechanical test configurations for 2G wires.
We are presently testing new configurations for the determination of longitudinal compressive and tensile strain effects on 2G wires. The experimental setup is being adjusted in such a way that it can be operated without requiring the use of a servo-hydraulic test system. This will free up the servo-hydraulic setup for conductor delamination studies. Work has also begun on the engineering/physics modeling of the intrinsic strain effect. The data are 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. Sufficient data have been collected to enable us begin modeling the hard bending effect on critical current, and to correlate this effect with that of tensile and compressive strain on critical current.

3) Stress-strain characterization of 2G wire joints set to begin.
Due to finite wire length, most practical HTS applications will contain splices (solder joints). Failure at these critical nodes will render the device inoperable. Therefore, it is necessary to determine and understand the splice characteristics at room and cryogenic temperatures to avoid failure during winding, field-splicing, installation and operation. We have received 15

commercial conductor samples containing splices from ORNL, and measurements will commence shortly. We are in the process of procuring a Nyilas-type extensometer to incorporate into our stress-strain facility that will improve the accuracy of our measurements. We will also adapt the software acquisition system accordingly.

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:
1) Results suggest that flux pinning and processing can be tailored by mixed-rare earth.
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. The single-phase region of the solid solution $Ba_{2-x}(Sm_{1+x-y}Y_y)Cu_3O_{6+z}$ was determined under various processing conditions so as to provide data for intrinsic flux pinning applications. Selected samples have been characterized by x-ray diffraction and DTA to obtain initial melting temperatures. Currently we are in the processing of submitting a paper concerning the understanding of melting temperature as a function of the ionic size of R^{3+}.

2) Phase relationships found to differ between films and bulk samples. Important implications for 2G wire development.
Phase relationships of the thin film Ba-Y-Cu-O system and the Ba-(Nd,Eu,Gd)-Cu-O system have been determined under 0.1% O_2 at 735 °C. These films were prepared using the BaF_2 *ex situ* techniques (e-beam evaporation and trifluoroacetate (TFA) approach). Results of high temperature x-ray diffraction indicated different phase relationships in the vicinity the high-temperature superconductor Y213 and Gd213 in films relative to bulk because of the absence of the green phase (BaY_2CuO_5 and $BaGd_2CuO_5$, respectively). 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. Using the combinatorial thin film synthesis approach with oxides as targets, we confirmed the difference in phase relationships and established that the presence of 'fluorine' is not the cause for the difference.

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 are also in the process of investigating the 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. Currently we are also collaborating with ORNL and AFRL to use the samples of this region to correlate with superconducting properties.

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

We successfully determined the phase relationships of Ba-Y-Cu-O and Ba-Gd-Cu-O systems in film form using $SrTiO_3$ as a substrate. So far we have eliminated the possibility that the different phase relationships in film and in bulk are due to the presence of 'fluorine'. We continue to investigate the reasons of the difference by processing the BaF_2 *ex situ* films under different conditions (i.e., different temperatures). We will also continue the combinatorial oxide film studies to determine the effect of different processing conditions on phase formation.

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 interact with ORNL, AFRL, and ANL 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 melting of $Ba_2RCu_3O_{6+z}$ phases; with ORNL, AMSC, and ANL on phase relationship studies of Ba-Y-Cu-O and Ba-R-Cu-O films; and with SuperPower on the future 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
Dominic Lee	Tsukuba, Japan	Nov. 2 - Nov.7	Attend 20th Int'l Symposium on Superconductivity (ISS07) and visit research centers.
	Jeju Island, Korea	Nov. 8 – Nov. 12	Attend Int'l Workshop on Coated Conductors for Applications (CCA07) and visit research centers..
Amit Goyal	Munich, Germany	June 23 – June 28	Attend hearing on RABiTS patent enforcement.
	Jeju Island, Korea	Nov. 6 – Nov. 12	Attend Int'l Workshop on Coated Conductors for Applications (CCA07) and visit research centers.
Ron Feenstra	Brussels, Belgium	Sept. 16- Sept. 20	Attend European Conference on Applied Superconductivity and visit research centers
Parans Paranthaman	Tsukuba, Japan	Nov. 2 - Nov.7	Attend 20th Int'l Symposium on Superconductivity (ISS07) and visit research centers.
	Jeju Island, Korea	Nov. 8 – Nov. 12	Attend Int'l Workshop on Coated Conductors for Applications (CCA07) and visit research centers.