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
October 1, 2006, to December 31, 2006

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

Superconductivity Program
Quarterly Progress Report

For the Period
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For
U.S. 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	On track
• Operational MOCVD system providing J_c greater than 2 MA/cm^2.	June 30, 2007	Ahead of schedule
Section 1.2: Conductor Research.		
• Improve in-field performance flux-pinning factor to less than $\alpha = 0.2$.	May 31, 2007	On track
• Deposit multi-functional epitaxial buffer that can replace at least 2 standard buffers with J_c of 2 MA/cm^2.	July 31, 2007	On track
Section 1.3: Innovative and Enabling Technologies.		
• Commissioning of enhanced ac loss testing capability.	March 31, 2007	On track
• 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	Ahead of schedule
Section 1.5: Research and Technical Support.		
• Short sample 2G wire with I_c of 750 A/cm (SuperPower)	July 31, 2007	Ahead of schedule
• 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 researchers received awards for "World Class" performance.
Three ORNL HTS projects have received Exceptional or Outstanding Accomplishment Awards from the Office of Electricity Delivery and Energy Reliability. These awards are given to HTS projects that received "World Class" or "Excellent" ranking from the judging panels at the 2006 US DOE Superconductivity Program Annual Peer Review. ORNL projects that received these awards are:

- High Temperature Superconducting Power Cable (with Southwire Company),
- SPI Readiness Review Program (with LANL and DOE-Golden),
- ORNL-SuperPower CRADA: Development of IBAD-Based 2G Wires (with SuperPower).

In addition, Wire Development Group, of which ORNL is a participant, also received an award.

HTS program members are recipients of UT-Battelle/ORNL Awards Night recognition.
Parans Paranthaman, Amit Goyal, and Tolga Aytug were acknowledged at the 2006 Awards Night ceremony as recipients of the Science and Technology award for "Excellence in Technology Transfer." The award recognized their contributions for the development, patenting, and transfer of high throughput buffer layer technology being commercialized by SuperPower, Inc., that enabled the achievement of world record performance in SuperPower's long-length, second generation superconducting wires.

Alvin R. Ellis, Isidor Sauers, Jonathan A. Demko, Robert Duckworth, Christopher M. Rey, D. Randy James, and Michael J. Gouge, along with three employees of Southwire Company, were honored for accomplishments in "Engineering Research and Development." The team was acknowledged for its achievements in the invention, development, design, fabrication, and successful testing of the world's most compact superconducting power cable.

ORNL HTS researcher elected to the Board of Conference on Electrical Insulation and Dielectric Phenomena.

IEEE-CEIDP 2007

Enis Tuncer of the ORNL Fusion Energy Division was elected to the Conference on Electrical Insulation and Dielectric Phenomena (CEIDP) Board during the October 15-18, 2006, meeting in Kansas City. Tuncer is also serving on the nominations committee of the CEIDP. Meanwhile, Isidor Sauers, also in the Fusion Energy Division, has completed the first year of a two-year term as the general chair of CEIDP. Both of them are performing research on high voltage dielectric materials. During the meeting, ORNL researchers presented four papers that covered work related to the HTS cable project and the cryogenic dielectrics initiative.

These papers were published in the 2006 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, IEEE Conf. Pub. No. 06CH37829:

1. *Breakdown Statistics of Polyimide at Low Temperatures*, E. Tuncer, I. Sauers, D. R. James, A. R. Ellis, and M. O. Pace.
2. *Electrical Properties of a Commercial Resin*, E. Tuncer, I. Sauers, D. R. James, and A. R. Ellis.
3. *Non-Uniform Field Breakdown and Surface Flashover in Liquid Nitrogen Gaps for HTS Application*, D. R. James, I. Sauers, E. Tuncer, A. R. Ellis, K. Tekletsadik, and D. W. Hazelton.
4. *Partial Discharge Measurements in a High Temperature Superconducting Tri-axial 5-m Model Cable at Liquid Nitrogen Temperature*, I. Sauers, D. R. James, E. Tuncer, A. R. Ellis, M. O. Pace.

Prominent participation of ORNL HTS staff in the Materials Science and Technology 2006 Conference and Exhibition.

The Materials Science and Technology 2006 Conference and Exhibition, held October 15 - 19 in Cincinnati, OH, jointly represented the American Ceramic Society, the Association for Iron and Steel Technology, ASM International, and The Minerals, Metals and Materials Society. The meeting serves as a comprehensive forum for materials science and engineering technologies. ORNL HTS researchers participated prominently in both the organization of symposia, and as invited and contributed speakers. Those involved and their activities included:

<u>Program Organizers:</u>

- M.P. Paranthaman and A. Goyal: *High Temperature Superconductor Wires & Tapes.*
- A. Goyal: *Microstructural and Textural Requirements for Functional Materials.*
- T. Aytug and S. Sathyamurthy: *Nanostructured Materials: Synthesis, Characterization and Applications.*

<u>Presenters:</u>

R. Feenstra, A. Goyal, T. Aytug, S. Sathyamurthy, M.S. Bhuiyan, S.H. Wee, and M. P Paranthaman.

A. Goyal was also presented an award for the ASM-IIM Distinguished Lectureship at a Special Awards Luncheon hosted by the ASM for the ASM leadership.

ORNL researchers participated in the 19th International Symposium on Superconductivity.

Amit Goyal and Robert Duckworth presented invited talks at the ISS 2006, meeting held in Nagoya, Japan, from October 30 – November 1, 2006. There were 693 papers, both oral and poster presentations, presented in five broad technical areas. There were 534 papers from Japan and 159 papers from foreign participants. Goyal presented an invited overview talk on flux-pinning with 3D self-assembled nanodots and co-chaired the opening session on Wires, Tapes and Characterization. Duckworth presented an invited talk on "Low ac loss geometries in YBCO coated conductors." Both talks were very well received.

ORNL HTS staff participated in "Day of Science" outreach activities at ORNL that attracted 250 university students and faculty.

More than 250 students and faculty from 45 colleges and universities across the nation, including many historically black colleges and universities (HBCUs) and minority education institutions, gathered at ORNL on October 16, 2006, for the Fifth Annual Day of Science and DOE-sponsored Minority Education Technical Assistance Workshop. Their slate included talks and presentations, one of which was HTS, and a series of pre-interviews for possible internships. Charles Greene, executive director of the White House Initiative on HBCUs and luncheon keynote speaker, discussed the importance of nurturing relationships between students, faculty and administrators at the nation's HBCUs. Greene stressed that educators and administrators must be supportive of students who wish to pursue an education in math or science, and noted that support from institutions such as ORNL is extremely helpful.

Day of Science visitors watched a demonstration of superconducting technology by the Materials S&T Division's Patrick Martin.

Patricia Hoffman, DOE-OE, visited ORNL HTS Program.

Patricia Hoffman, DOE-OE Director of R&D, visited ORNL on October 26-27, 2006. As part of the OE Program, Hoffman was briefed on the FY 2006 accomplishments, capabilities, and planned activities of the ORNL HTS Program. She also toured the ORNL Rolling Facility, Materials Processing Facility, Accelerated Coated Conductor Lab, Cryogenic Dielectric High Voltage Test Lab, Applied Superconductivity Lab, and the Cable Test Facility. Among the many capabilities seen by Hoffman was the 3-m long, tri-axial cable with a splice in the center being set up for testing at 77 K in the ORNL HTS Cable Test Facility. The cable splice was initially tested for fault over-currents at an Ultera lab in Denmark. DC current tests at ORNL will verify that the cable was not damaged by earlier qualification testing.

Pat Hoffman and Mike Gouge look over an HTS tri-axial cable.

Section 1.1: Wire Development

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

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

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

<u>Objectives:</u>

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.

<u>Highlights:</u>

Completed technical design to increase the coverage area of ORNL slot-die coater.

ORNL is in the process of modifying its slot-die coater such that alternative 2G wire prototypes can be readily completed by AMSC's pre-pilot processing facilities for rapid testing. Previously, we have prepared 1 cm-wide samples with LZO solution buffer coated at a slot-die speed of 120 m/hr. Subsequent cap layer and YBCO were completed at AMSC, with J_c's in excess of 3 MA/cm^2. These AMSC steps, however, require additional adjustments because of the substantial difference in sample-handling widths. With modification of our slot-die coater, completion of 2G wire prototypes and testing will occur more rapidly and readily. Technical design of the modification has been completed, with physical slot-die modification to follow.

ORNL reel-to-reel slot die coater for solution deposition.

<u>Technical progress:</u>

ORNL continues to work closely with AMSC on scale-up and performance issues related to the development of RABiTS-based 2G HTS wire. Numerous samples have been examined for their texture characteristics. In addition, extensive testing of critical current characteristics of AMSC wires have been performed under self-field and in the presence of applied magnetic fields. Steady progress is also being made in the area of substrate improvement.

Status of milestones:

- Short sample RABiTS using slot-die MOD CeO_2 cap-layer with I_c of 300 A/cm. (April 30, 2007): On track.
- Fabricate MOD LZO barrier buffer with homogeneous texture and a mosaic less than 2 degrees using a slot-die coating system on 4-cm-wide RABiTS. (July 31, 2007): On track.
- Demonstrate an I_c greater than 800 A/cm on 4-cm-wide continuously processed RABiTS with a solution LZO buffer. (August 31, 2007): On track.

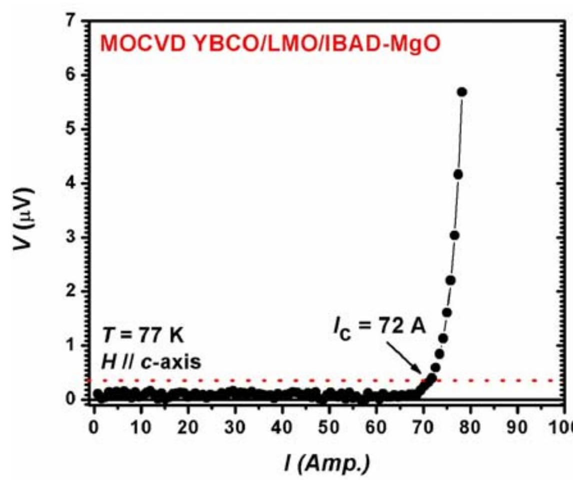
Interactions:

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

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

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 equipment. 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:
ORNL established MOCVD HTS deposition capability.
With continuing development of the MOCVD REBCO process, SuperPower has produced long-length 2G wires with world record performance of length × critical current. Recently as part of the CRADA, we at ORNL have established a MOCVD HTS deposition capability by using SuperPower's MOCVD lab-scale R&D system. This reverse technology transfer of system hardware and know-how is highly unusual, and reflects the close collaboration and trust developed in the course of this CRADA. Purpose of this new task is to assist SuperPower in accelerating the performance enhancement of their 2G wire. High J_c YBCO films were successfully deposited on IBAD-MgO/LMO templates provided by SuperPower. Initial trials resulted in a short sample with high critical current of 72 A, which validated the SuperPower MOCVD approach.



I-V curve of a MOCVD YBCO film deposited on SuperPower's IBAD-MgO/LMO template.

Technical progress:
ORNL continues to collaborate closely with SuperPower on scale-up and performance issues related to the development of IBAD-MgO-based 2G HTS wire. Numerous SP samples have been examined for their critical current characteristics under self-field and in the presence of applied magnetic fields. In addition, steady progress is being made in the area of substrate improvement, and in the understanding of SP 2G wire losses and stability characteristics.

Status of milestones:

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

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.

Technical progress:
Previous experiments have shown that by controlling secondary recrystallization, long, continuous single crystals of Ni and Ni-3at%W can be made with the same dimensional tolerance as RABiTS. The time for processing is also similar to that needed for RABiTS. The work in this project has been hampered in obtaining good starting foil for the experiments. We are in t he process of completing fabrication of a Ni-7.7at%W substrate for conversion into a single crystal substrate.

Ultra-high magnetic field processing (UHMFP) is an emerging materials technology that offers significant advantages over conventional thermo-mechanical processing. ORNL researchers have recently demonstrated that magnetic processing can develop more homogeneous microstructures, reduce residual stresses, improve mechanical properties, and enhance mach inability. We believe that by affecting the thermodynamics through UHMFP, it may be possible to obtain pure cube texture in high W-content Ni alloys. Experimental setup has been completed in this quarter, and initial testing will follow.

Status of milestones:

- Fabricate a meter-long, strengthened single-crystal, Ni-alloy- based substrate with reduced magnetism using a process which can be extended to long lengths. (September 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, 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.

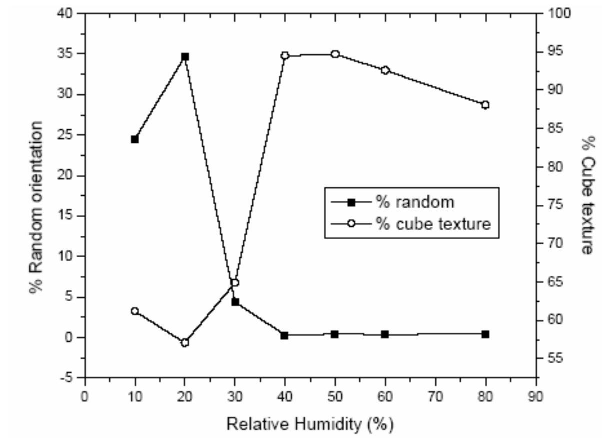
Highlights:
Solution) technique has been successfully used to grow potential seed layers with improved out-of-plane textures.
Typically, Yttrium Oxide (Y_2O_3), Titanium Nitride (TiN), and Magnesium Oxide (MgO) buffers have been grown directly on textured Ni-W substrates using physical vapor deposition (PVD). These buffers are of particular interest because they impart improved out-of-plane textures onto the substrate. High current YBCO films have been demonstrated on these seed layers. Now, we have succeeded in growing both La_3TaO_7 (LTO) and La_3NbO_7 (LNO) seed layers with improved texture directly on Ni-W substrates using solution MOD method. These seed layers could be used for all-MOD buffer/REBCO architectures. As measured from the XRD Omega scans, both LTO and LNO textures improves by over 0.5-1° compared to the underlying Ni-W substrate texture.

Table: Texture data for La_3NbO_7 and La_3TaO_7 films on cube textured Ni-W substrates.

Oxide Films	FWHM Values			FWHM Values of Ni-W substrates		
	Δω (004) Φ = 0° (deg.)	Δω (004) Φ = 90° (deg.)	Δφ (222) (deg.)	Δω (002) Φ = 0° (deg.)	Δω (002) Φ = 90° (deg.)	Δφ (111) (deg.)
La_3NbO_7	6.56	4.87	7.44	7.82	5.28	7.48
La_3TaO_7	3.8	3.6	7.5	7.6	5.4	7.8

Technical progress:
Relative humidity found to have significant effect on crystallization of epitaxial solution buffers.
Ambient relative humidity (RH) during solution coating process was found to significantly influence the crystallographic texture and microstructure of the processed films. Using Y_2O_3 seeded textured-Ni-5at.%W substrates, we have determined that there is a threshold humidity level above which highly oriented lanthanum zirconium oxide (LZO) films can be processed. However, below the threshold level, a significant portion of the film grows with a random

polycrystalline orientation. Using the correct processing conditions, we have demonstrated an I_c of 336 A/cm using MOD-YBCO with AMSC on these improved LZO templates with sputtered CeO_2 cap. This result indicates that with proper process controls, solution buffer with properties comparable or exceeding that of its PVD counterparts may be used in 2G wire fabrication.



Variation of percent random-oriented and cube textured LZO in the films as a function of relative humidity for samples processed at 1100 ºC for 15 min.

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 (September 30, 2007): On track.

Interactions:

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

Subtask 1.2.3: HTS processing for critical current and pinning enhancement.

T. Aytug, M. Paranthaman, K. J. Leonard, S. Kang, P. M. Martin, L. Heatherly, A. Goyal, A. O. Ijaduola, J. R. Thompson, D. K. Christen, K.-H. Kim, S.-H. Wee, J. Li, R. Meng, I. Rusakova, C. W. Chu

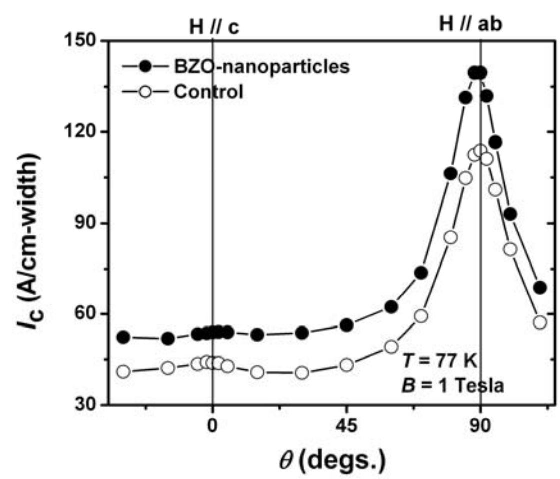
Objectives:

U.S. HTS wire manufacturers are now producing 2G wires with reasonable properties in relatively long lengths. To meet the performance requirements of practical commercial applications, however, it is necessary to further improve the HTS transport properties. For example, operation of high-field equipment (motors, generators, air-core transformers) requires performance levels of J_e of 15-30kA/cm^2 at 55-65 K, 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 CRADAs with U.S. HTS wire manufacturers to further improve the HTS superconducting properties.

Highlights:

Substrate surface decoration by nano-particles found to enhance flux pinning in YBCO.

Recently, a collaborative team of researchers from ORNL, the University of Tennessee, and the University of Houston, has performed a study that points to a simple, economic process to increase the flux pinning and critical current density in REBCO coated conductors. The work involves YBCO films grown on both single crystal and textured metal substrate surfaces that were pretreated with second-phase nano-scale particles. The nano-particles were applied using simple solution approaches and yielded growth defects in the deposited YBCO coatings. These defects contributed to prevent dissipative vortex motion, and thereby increased J_c. Compared to untreated samples, HTS on treated surfaces showed higher J_c's for all applied magnetic field angles. Ultimate objective of this approach is to produce cost-effective enhancements in the properties of commercial coated conductors by a simple pretreatment applicable to all technical substrates.

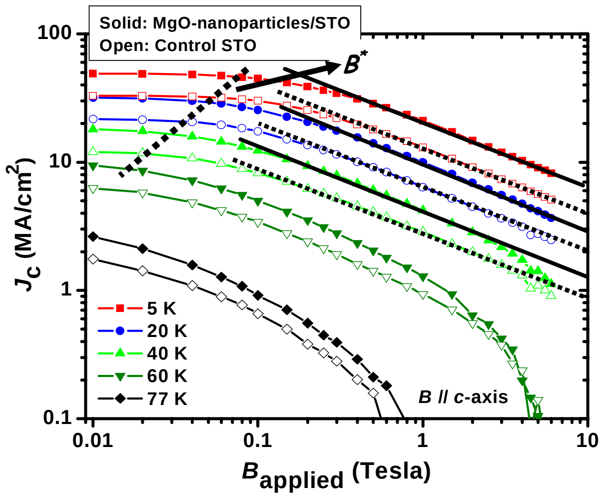


Angular J_c dependencies of 3 μm-thick YBCO deposited on biaxially textured metal tapes with and without $BaZrO_3$ nano-particle modifications.

Technical progress:

Pinning analyses conducted on substrate surface treated conductors.

Performance and flux-pinning analyses were conducted on YBCO films that were deposited on substrate surfaces decorated with various types of nano-particles. For example with MgO nano-particles, magnetization J_c revealed a roughly 50% improvement at all temperatures and fields. We have observed several common features for YBCO deposited on both surface treated and untreated substrates. These include a region of nearly constant J_c up to a characteristic crossover field of B^*, followed by a rollover to a power-law regime ($J_c \propto B^{-\alpha}$) at intermediate fields, and finally a precipitous decay of J_c on approaching the irreversibility field, B_{irr}. We have consistently obtained values for the power law exponent $\alpha \sim 0.5$-0.54 for both modified and control YBCO films, indicating similar field dependencies and no apparent change in pinning mechanisms. These α-values are also similar to those obtained on surfaces decorated with other nano-particles. It is believed that the pinning mechanism cannot be simply flux line shearing since TEM observations revealed no indication of c-axis extended defects, and angularly dependent data give little indication of pronounced correlated disorder near the c-axis. Rather, the dominant mechanism is likely due to uncorrelated large dilute defects with associated δT_c from non-superconducting particles and strain fields. With similar pinning mechanism, difference in performance is initially attributed to an increased pinning strength produced by nano-particles in the surface decorated samples. Much work remains to understand the influence of nano-particle size and density on the induced growth defects in HTS coatings of different thicknesses.



Comparison of magnetic field dependence of magnetization J_c for two 0.3 μm thick YBCO films grown on substrate surfaces with MgO nano-particles (solid symbols) and without (open symbols).

In addition to substrate treatment, pinning modifications by aligned nano-particles as well as inclusions through composition variation/doping are also ongoing.

Status of milestones:

- Improve in-field performance flux-pinning factor to less than $\alpha = 0.2$. (July 31, 2007): On track.
- Understand formation mechanism of columns of self-assembled nanodots. (September 30, 2007): On track.

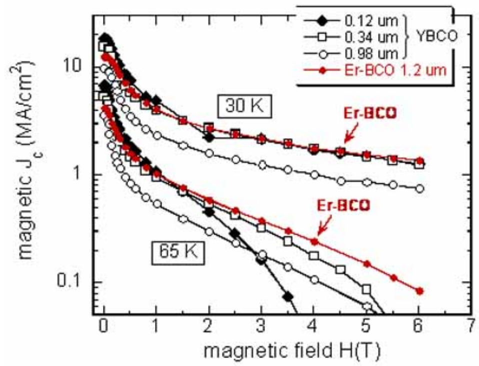
Interactions:

Interactions include extensive collaboration with the University of Tennessee on transport characterization and pinning analysis, and with the University of Houston on property determination.
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.
R. Feenstra, S.-H. Wee, A. Goyal, H, Christen, M. P. Paranthaman

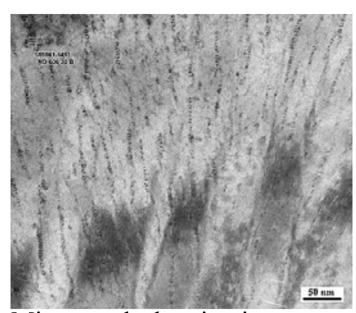
Objectives:
While performance and pinning enhancements are concentrated on YBCO, (mixed) rare-earth HTS have so far been neglected. The main reason for the emphasis on YBCO is because it is the most studied HTS 1-2-3 compound and ample results are available for comparison. Other rare-earth and mixed 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:
Excellent properties demonstrated in ex-situ REBCO films on RABiTS using the BaF_2 process.
Electron-beam evaporation represents a flexible and convenient method of depositing precursors of arbitrary thickness for the *ex situ* BaF_2 process. This is particularly suitable for the study of differences in the conversion among various REBCO systems. We have deposited and converted single-RE ErBCO on AMSC RABiTS. ErBCO films with a thickness of 1.2 μm were found to convert similarly to YBCO. As a preliminary result, a high critical current value of ~ 330 A/cm at 77 K (sf) was obtained. This value is comparable to that for the best YBCO films of this thickness produced by the ORNL BaF_2 process. The magnetic field dependence of J_c was improved relative to that of recent YBCO on the same RABiTS template, indicative of a higher irreversibility field H_{irr}. The latter observation hints at an improved average pinning strength.



Magnetic field dependencies of J_c at 65K and 30K for a 1.2 μm ErBCO ex-situ film. Also included are characteristics of YBCO films of various thicknesses.

Technical progress:
Incorporation of self-assembled nanodots extended to NdBCO films.
Nano-scale columnar defects comprised of self-assembled BZO nanodot columns have been successfully incorporated into epitaxial NdBCO films grown on RABiTS via pulsed laser deposition (PLD). Cross-section TEM analysis showed that self-aligned BZO nanodot columns along the c-axis of the film have a dense and uniform distribution throughout the NdBCO matrix. Such artificial columns resulted in remarkable enhancement in flux-pinning of NdBCO films. Compared to pure NdBCO and YBCO+BZO films, NdBCO+BZO films have significantly improved in-field properties


Micrograph showing incorporation of BZO nanodot columns in a NdBCO film.

at all field orientations. Films with such extended columnar defects exhibited a high F_{pmax} of 9.5 GN/m^3 at 4T 77K and a H_{irr} of over 8 T.

Status of milestones:

- Establish the (compositions) type of effective (mixed) rare earth combinations for HTS films. (July 31, 2007): Behind schedule.
- Improve in-field performance flux-pinning factor to less than $\alpha = 0.2$. (May 31, 2007): On track

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. Results from other base program REBCO work 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 , M. P. Paranthaman, A. Goyal, L. Heatherly, R. Feenstra

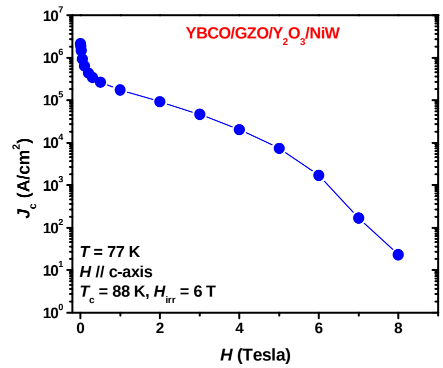
Objectives:

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:

ORNL researchers demonstrated growth of HTS films with a J_c of 2.4 MA/cm^2 on reactive sputtered GZO buffer.

A simplified RABiTS architecture of $Gd_2Zr_2O_7$ (GZO)/Y_2O_3/Ni-W template is presently under investigation. For comparison, standard commercial architecture is CeO_2 (75nm)/ YSZ (75nm)/Y_2O_3 (75nm)/NiW. GZO is being studied as a multi-functional buffer that can be deposited by high-rate commercially-selected reactive sputtering process, which can potentially replace the YSZ barrier and CeO_2 capping layers. We have successfully deposited epitaxial films of GZO on thin (10 & 75 nm) Y_2O_3 buffered Ni-W substrates. Preliminary results showed a J_c of 2.4 MA/cm^2 at 77 K and self-field for thin 0.2 µm YBCO films deposited by PLD. Much work remains to study the characteristics of thicker films (longer processing time to determine barrier capability). Also, whether epitaxial HTS can be deposited directly on GZO by commercial processes (MOD, MOCVD) needs to be determined.



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

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) On track.

Interactions:

Interactions include collaboration with the 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, S. W. Cook

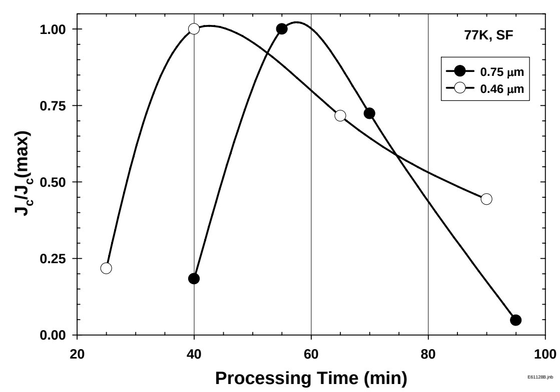
Objectives:

As they stand presently, as-manufactured 2G wires are approaching the performance current carrying metrics. However, these wires produce high ac losses in applied ac fields (>1 W/m) that slow their immediate implementation into HTS applications. Creating filaments within the HTS structure presents one interesting solution that can reduce the ac loss, but further work is needed to understand and optimize filamentized 2G wires. These include filament width and geometry, 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:

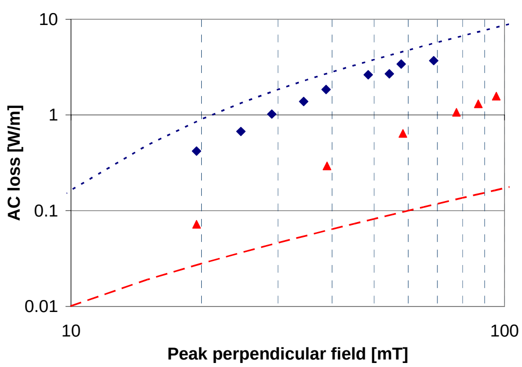
Inkjet fabrication of filamentary conductor reveals non-uniform precursor thickness.

Inkjet printing is being evaluated as a method to produce solution precursor filaments for HTS conversion. If successful, this represents a potentially high-rate cost-effective way to manufacture 2G wires with low ac losses. Recent results of this evaluation revealed that narrow inkjet filaments exhibited substantially lower J_c than wider filaments. We have determined that inkjet filaments deposited using the present solution and conditions have non-uniform thickness profile. This variation in HTS precursor thickness may present a challenge during thermal conversion. To illustrate this, two sets of filamentary inkjet precursor samples were prepared—one with an average filament thickness 0.46 μm and the other with an average filament thickness 0.75 μm. After processing, we have determined that different optimum conversion times exist for samples of differing thicknesses. These results suggest that, even for an inkjet filament that is optimally processed, the thicker regions of the filament are under-processed and the thinner regions are over-processed. This would lead to a J_c for the collective inkjet filament that is substantially lower than that if the thickness were uniform. Efforts are presently under way to increase J_c for inkjet filaments by a) reducing the thickness variations of the inkjet filament and b) reducing the sensitivity of the maximum J_c on processing time and filament thickness.

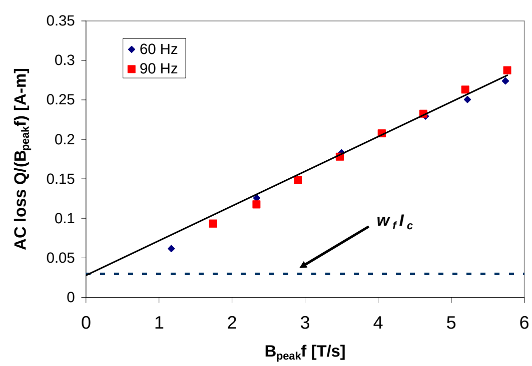


Critical current density versus total processing time for inkjet precursor filaments of two different average thicknesses.

Multi-filamentary inkjet-derived YBCO coated conductor reveals coupling losses.
Comparative measurements have been performed on inkjet-derived “un-filamentized” and filamentized conductors. Samples were fabricated using AMSC solution on AMSC RABiTS substrates. The unfilamentized sample was 9-mm wide, with inkjet lines deposited without any spacing to obtain a continuous precursor layer. The filamentized sample contains spaced filaments that are 0.5-mm wide with 0.1- mm gaps. These samples were converted into HTS at AMSC, and J_c’s were determined to be 2.6 and 1.0 MA/cm^2, respectively. The drop in J_c is believed to be influenced more by the slightly different conversion conditions rather than any effect of filament width to grain boundary size. AC losses were measured on companion samples as a function of field and frequency at 77 K. Curves for the estimated hysteretic loss of HTS indicate additional losses were present in the filamentary sample. When the ac losses and peak applied field are rationalized for the filamentary sample, the linear dependence of the losses indicated the presence of coupling. Despite the coupling losses still present, the intercept appears to closely match the measured critical current. Since this sample had no observable shorts, the nature of the coupling in these inkjet conductors will be investigated further through the cutting of filaments to isolate them from the substrate and magneto-optical characterization of the remaining samples.



Comparison of ac losses in filamentized and un-filamentized samples as a function of peak perpendicular field at a frequency of 60 Hz 77 K. Curves represent estimated hysteretic losses of HTS.



AC losses rationalized with respect to peak perpendicular field and frequency for the filamentized sample at 77 K

<u>Status of milestones:</u>

- Benchmark stability code for transient and steady state currents. (August 31, 2007): On track.
- Reduce ac loss by 10 times with filamentized HTS conductor. (July 31, 2007): On track.

<u>Interactions:</u>

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

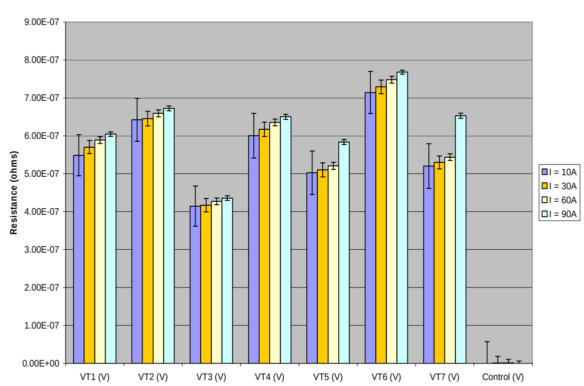
Subtask 1.3.2: Conductor design and engineering for practical HTS applications.
R. C. Duckworth, C. Rey, J. A. Demko, S. W. Schwenterly

Objectives:

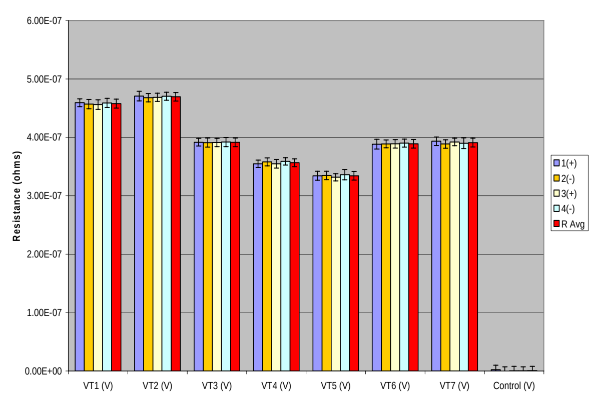
As long lengths of REBCO coated conductor become available from U.S. 2G wire manufacturers, the ability to study quench and stability and ac loss in superconducting cables and coils is possible. With the emphasis of using REBCO in the SPE solicitation by DOE, quantifying these and other issues on a short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

Highlights:

Surface preparation of HTS tape found to influence splice resistance.
Due to finite HTS wire lengths, splices will exist in most practical applications. ORNL has been investigating the splice resistance of HTS tapes as functions of: various factors, which is essential to the practical implementation of electric utility devices. Recently, we have performed a preliminary study on the "overlap resistance" (overlapping interface region) of lap joints. Tests were performed in pool boiling nitrogen at 77 K. Between 50 and 100 data points were recorded in 1 power-line cycle repetition rates to determine the average values and standard deviations of series of seven (7) joints. An eighth voltage tap was connected to unspliced region as a control mechanism. For 1G Bi-2223 tape (I_c = 115A) with brass laminated sheath, 0.25-in. joint overlap length, Sn(60-Pb(40) solder with *no surface preparation* at 77 K, the measured splice resistance was found to increase with current (10 A, 30 A, 60 A, 90 A). At an applied current of 10 A, the standard deviation is <10 % and decreases to <1 % at the 90 A level.
We have compared these samples with ones made with *a paste flux in which the surface was clean* with an ethyl alcohol wipe prior to and subsequent to "tinning" the surface. Although the splice resistance was of similar absolute value, the consistency between successive joints is slightly improved. Understanding and controlling the variables in splice fabrication remains a key parameter for the practical implementation of HTS devices.



Splice resistance of a Bi-2223 sample with brass lamination, 0.25-in.overlap, Sn(60)-Pb(40) solder and no surface preparation at 77 K.



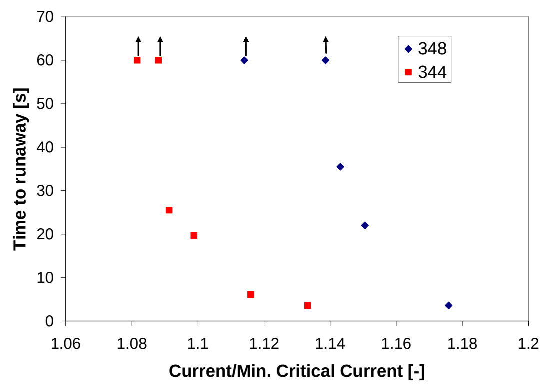
Splice resistance of a Bi-2223 sample with brass lamination, 0.25-in. overlap, Sn(60)-Pb(40) solder and paste flux at 77 K with a constant current of 60 A.

Technical progress:

Stability measurements performed on AMSC 344 and 348 2G wires.

With increasing versatility in stabilizer lamination at AMSC, it is important to determine how the method of stabilization could impact over-current and constant current stability. A series of experiments were carried out to characterization the stability of AMSC copper laminated 344 and 348 2G wires in liquid nitrogen (77 K). Major differences between the wires being the width of the copper layers and side solders. 2G wires, 1.1-m long, wound onto a G10 mandrel with 8 layers of dielectric thermal barrier tape were tested under constant and impulse dc current conditions; constant current mimics the operating characteristics of HTS motors whereas impulse current is more prevalent in cables and transformers.

Initial comparison of time to thermal runaway under constant current condition showed that there is some slight improvement with the 348 wire. The 348 wire was able to operate at a higher percentage of I_c. For the case of 60 seconds to runaway, the 344 wire could operate at 108% of I_c while the 348 wire could operate at 114% of I_c. As the conductor length gets longer, this difference should continue depending on the cooling conditions.



Time to thermal runaway as function of the ratio of operating current to minimum Ic for the 344 and 348 wires.

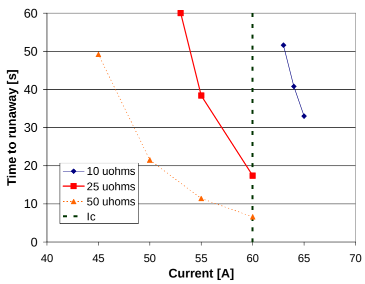
For the impulse test, we were unable to identify the maximum current each wire could take before failure due to inadequate power supply and long sample length. However, we could determine the amount of energy to degrade these wires from the integrated current voltage product. As seen in the table, initial results showed that 344 wire is slightly better than 348 in retaining I_c over length at higher energies. It should be noted, however, the current drops associated with 344 wire were greater. Further testing on shorter lengths of conductor is necessary to confirm this differential and determine the amount of current that is being utilized in each stabilization configuration.

Summary of impulse results for 344 and 348 superconductors.

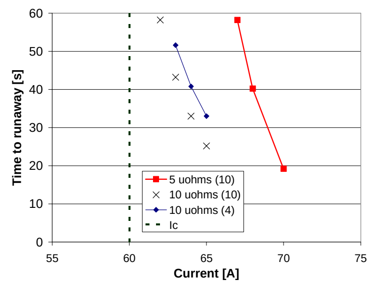
	344 superconductor	348 superconductor
Amount of energy to degrade conductor	1524 J/cm^3	1032 J/cm^3
Percentage of degraded conductor	10%	30%

Modeling of stability in potentially low ac loss 2G conductor design.

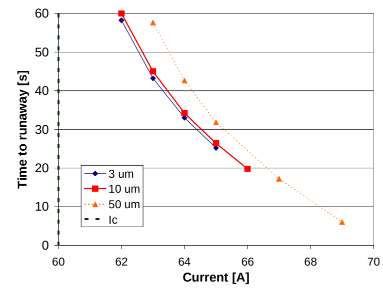
One potential way to reduce the ac losses is through the introduction of periodic non-superconducting bridges in the HTS wire. Careful consideration, however, is needed to ensure that the conductor stability is not compromised. A model is being developed to determine the effects of a given resistance on conductor stability. This model assumes a filamentary wire with n-value of 20, width of 4-mm, length of 1-m, I_c of 60 A at 77 K, and T_c of 90 K with stabilization coming only from the silver cap layer. Using this model, time to thermal runaway for different non-superconducting bridge resistance, number of bridges and the stabilizer thickness can be estimated. In a sample calculation, we found that the current at which runaway occurs drops below the sample I_c of 60 A when the bridge resistance is above 10 $\mu\Omega$. This factor appears to affect the stability the most as changes to the number of bridges only affects stability by 10%.



Effect of bridge resistance on the dependence of time to thermal runaway with respect to current for a filamentary YBCO sample with 4 bridges at a spacing of 25 cm, an I_c of 60 A, and 3 μm of silver stabilization.



Impact of number of bridges and resistance on the time to thermal runaway as a function of current for a filamentary YBCO sample with an I_c of 60 A and 3 μm of silver stabilization.



Time to thermal runaway as a function of current for different amounts of silver stabilization for a filamentary YBCO sample with an I_c of 60 A and 10 $\mu\Omega$ bridges spaced every 10 cm.

Also increasing the silver thickness will only provide slightly higher runaway currents.

Modeling of stability in as-manufactured copper stabilized 2G wires.
Localization of heating can contribute greatly to conductor stability depending on the amount and type of stabilizer. A model is being developed to better understand the formation of resistive zones in as-manufactured samples, and to facilitate fundamental investigation of properties that influence conductor stability. For a 60s constant current test case of a 30-cm- long 2G wire, thermal runaway was calculated to occur when the transient voltage reaches 1 mV/s, which is consistent with experimental values. A dominant parameter was found to be the n-value of the conductor; as the n-value is increased, the voltage in the superconductor forces more current through the stabilizer and the time to runaway is much shorter. Another dominant factor is I_c uniformity along the wire length. When a slight defect (lower I_c) was purposely introduced, the time to runaway was decreased. This influence suggests that the specification of the wire I_c along a given length could greatly impact conductor stability. Comparison between numerical and experimental results is under way to determine the necessary I_c resolution for stability prediction.

Status of milestones:

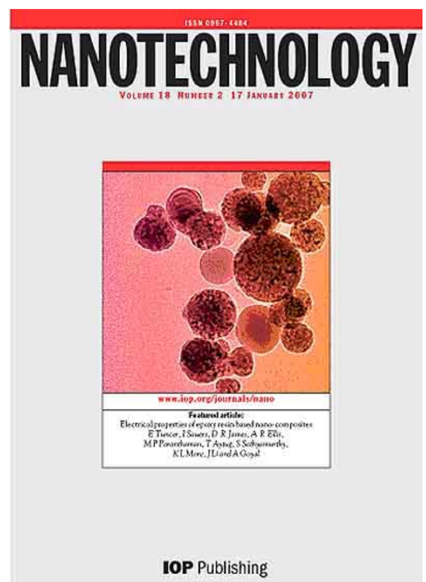
- Commissioning of enhanced ac loss testing capability. (March 31, 2007): On track.
- Establish the level of stability in spliced YBCO samples. (September 30, 2007): On track.
- Develop theoretical methodology for ac loss minimization in YBCO cables. (September 30, 2007): On track.
- Characterize ac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

Interactions:
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:
Micrograph of novel nano-dielectric material featured on cover of Nanotechnology.
An investigation on the dielectric properties and influence of particle size on breakdown strength of nano-composite dielectrics was recently published in *Nanotechnology* (Enis Tuncer et al., *Nanotechnology*, volume 18, 2007); see the following link (http://stacks.iop.org/0957-4484/18/025703). One of the figures (Fig. 4c) in the paper was selected for the cover for *Nanotechnology* volume 18, issue 2, and the article was featured in this issue.



Technical progress:
Steady progress is being made in the preparation and testing of the nano-dielectric materials previously reported. Work is also being performed on the identification of other potential base dielectric materials as well as novel nano-particles for inclusion.

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

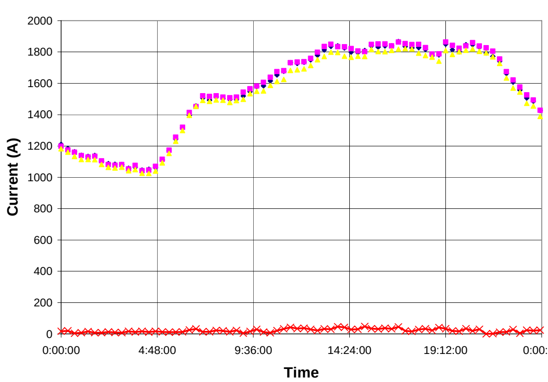
Section 1.4: HTS Applications

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.

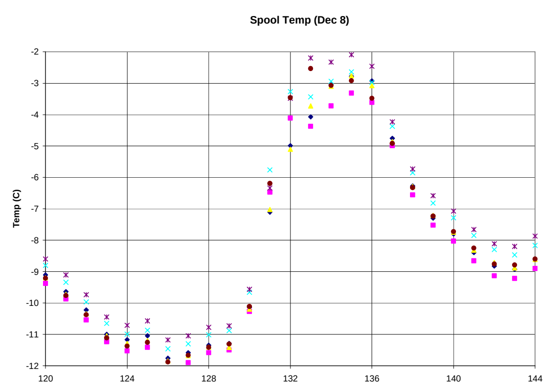
Subtask 1.4.1: HTS Cable System R&D.
J. Demko, M. J. Gouge, C. Rey, Robert C. Duckworth, R. James, and I. Sauers

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

<u>Highlights:</u>
Superconducting cable at AEP Bixby Substation operating reliably.
The cable has been on line since August 8, 2006. The AEP HTS cable continues to operate reliably according to design specifications, and is providing services to more than 8,600 customers. The plot below shows the substation load in amps at 13.2 kV for the three cable superconducting phases (magenta, blue and yellow) and the concentric neutral (red) over a 24-h r period in October 2006. The phase current peaked at 1,800 A which is lower tha n summer levels when air conditioning loads were significant. The lower red curve is the shield current which is near zero as the three ac phases are nearly balanced. During a 24-hr period on the coldest winter day in December (December 8, 2006, a low of -10 C or 14 F) in Columbus, OH, the cable spool temperatures (on each phase) ranged from -12 C to -2 C. This is a key parameter in that it indicates the design features are intact to provide good cable integrity.



Load current on the HTS cable over 24-hr period.

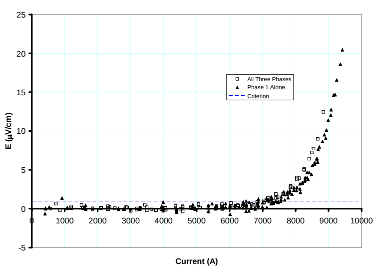


HTS cable spool temperatures for coldest day in December 2006.

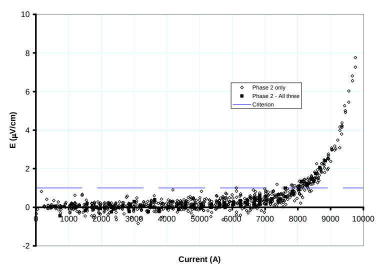
Technical progress:

DC test performed on a 3-meter tri-axial cable splice.

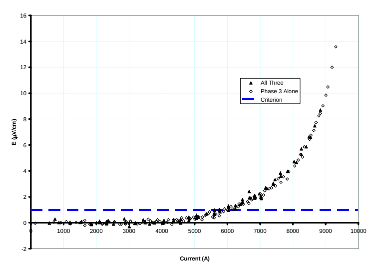
DC testing was conducted on a 3-meter-long section of a tri-axial HTS cable splice. The section had previously undergone design over-current testing to simulate fault currents by Ultera-Denmark). Results from dc tests showed that this cable exhibits I_cs in the 6,100-8,200 A range at 77 K. These values are comparable to dc I_cs of 7,000-8,000 A for a similar 5-m-long tri-axial cable tested at ORNL in 2005. The HTS tri-axial cable at the AEP Bixby substation operates under ac conditions at rms/peak currents below 3,000/4,230 A and thus there is a substantial margin between the ac peak and dc critical current, which minimizes the ac hysteretic losses. Two sets of dc testing were performed on the cable. The first round of testing was conducted on all three phases using jumpers. In this arrangement, the current flowing in phase 1 (innermost) and phase 3 (outermost) is in the same direction but opposite to phase 2 (middle). A second series of measurements were performed on individual phases. The measured voltage-current (VI) curves are compared in the following plots for the three phases under these two measurement conditions. The measurements show that the net magnetic field developed from the application of current to all three phases results in a slight decrease in the critical current of phase 1, the innermost phase. There was no measurable change in the outer two phases.



DC V-I characteristics for phase 1 alone and during simultaneous three-phase testing.

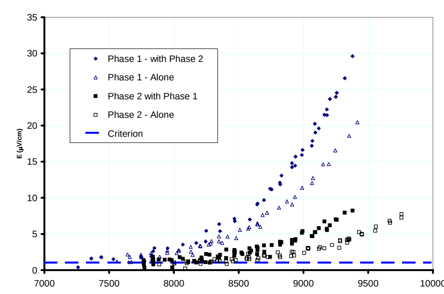


DC V-I characteristics for phase 2 alone and during simultaneous three-phase testing.



DC V-I characteristics for phase 3 alone and during simultaneous three-phase testing.

An additional measurement of the dc V-I characteristics was conducted on phases 1 and 2 with current applied in the same direction in both phases. The fields produced when the neighboring phase is energized cause a decrease in the I_c and an increase in the n-value.



V-I curve of phase 3 for high currents.

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. (September 30, 2007): On track.
- Evaluation of HTS cable system architectures for long length systems. (September 30, 2007): On track.

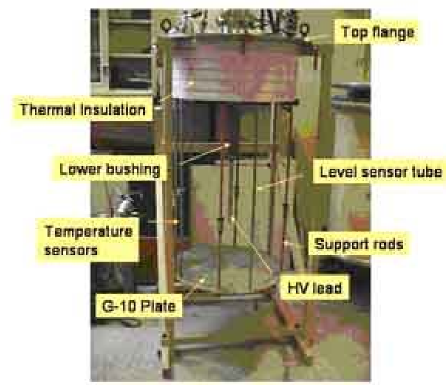
Interactions:

Work involves close and regular collaboration with Ultera (Southwire & 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

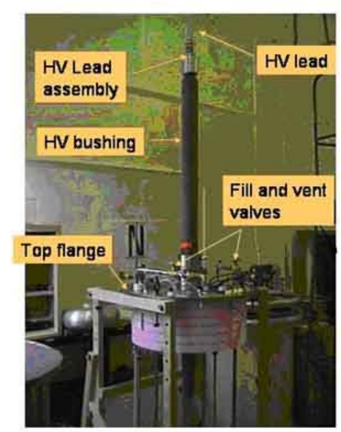
Objectives:
High-temperature superconducting utility power transformers offer prospects for improved efficiency, smaller size and weight, lessened environmental hazard, better overload tolerance, and longer lifetime in comparison with conventional power transformers. The current U.S. utility power transformer 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:
Completed assembly of HTS transformer high voltage test cryostat.
Assembly of the 30 in. (762 mm) cryostat was completed in December. The large volume of the test chamber will permit high voltage testing of practical components such as model coils, leads, surface insulation, standoffs, etc. as well as large LN2 gaps where there is little data at the higher voltages. Shown in the figures are the internal components and the completed assembly ready for testing. The design allows for changing the electrode test gap from zero up to 6 inches (152.4 mm) in the vertical direction in situ, i.e. the gap can be changed in liquid nitrogen (LN2) without having to warm up the system and remove the electrode assembly. This feature will greatly speed up the data taking process for LN2 gaps. There are also provisions for rotating the high voltage lead which will allow multiple samples to be tested in situ.



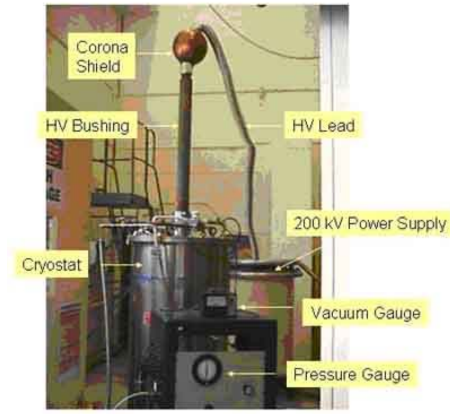
Lower assembly which will be inside the dewar. High voltage electrodes will be attached to the HV lead. Test fixtures will be supported by the G-10 plate.

The system is equipped with multiple sensors, transfer lines and pressure relief system for continuous monitoring and operation. The bushing is rated for 550 kV BIL (Basic Impulse Level). The pressure will be set between 1 and 2 bar absolute which will prevent bubbles from forming which can reduce insulation strength. The system was first pressurized to a few psig and checked for leaks. Following those tests the chamber was pumped down and checked for leaks under vacuum. Good vacuum was obtained. The cryostat was then filled with liquid nitrogen. Operation of the level sensor and multiple temperature sensors at different heights inside



Upper assembly showing the HV bushing and cyrogenic fill valves and lines.

the cryostat were verified as was pressure stability in the range from 0 to 9 psig. The temperatures in the test region of the dewar were found to be quite stable with time which will allow adequate time for high voltage testing of components and variable gaps. Gap settings can be changed externally without opening the pressure chamber of the cryostat. The partial discharge characteristics of the bushing were tested up to 145 kVrms and found to be consistent with earlier tests done in air and with the bottom end of the bushing immersed in LN2. Tests have begun late in the quarter on AC breakdown voltages of sphere to plane gaps in LN2 as a function of gap and pressure from 0 to 9 psig.



Completed 30-in. test cryostat with 200 kV high voltage power supply and bushing.

Status of milestones:

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

Interactions:

Close collaboration with Waukesha Electric Systems (WES) continues in this project. S. W. Schwenterly visited Waukesha November 6-10 for working meetings on technical details related to ongoing work. E. F. Pleva from WES visited ORNL in early December for technical discussions. Tom Golner of WES visited ORNL in November to discuss electrical insulation issues for the both the HTS transformer and Gridworks compact transformer projects.

Subtask 1.4.3: Rockwell CRADA: HTS Industrial Motor.
C. Rey, R.C. Duckworth

Objectives:
High-temperature superconducting motors offer prospects for improved efficiency, smaller size and weight, and better overload tolerance in comparison with conventional motors. HTS motors will have half the losses of conventional motors of the same rating. Applications will be for motors above 1000 horsepower for utility and industrial customers. A 5000 hp HTS motor could save a single customer $50,000 in energy costs per year. About 1/3 of U.S. electrical energy generated is used to power motors of this rating and above. Potential energy savings for the U.S. alone, if HTS motors fully penetrate the marketplace, could be high as $1B per year. Objective of this collaborative work with Rockwell Automation 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:
Work continuous on the determination of 2G wires voltage current characteristics at various temperatures. These characteristics are being compared with wire stability in order to obtain the values of respective quench currents.

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. (September 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, S. W. Schwenterly

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:
Work continues on the design and verification of SuperPower FCL. ORNL participated in the DOE Readiness Review of the SuperPower FCL project in December 2006. In addition, ORNL has been engaged in the development and tasks determination of a SuperPower Superconducting Power Equipment proposal.

Status of milestones:
- Participate in DOE Readiness Review to develop 2G matrix elements. (February 28, 2007): Met December 2006.
- Complete HV testing of SFCL matrix sub-assemblies at ORNL. (September 30, 2007): On track.

Interactions:
ORNL has been working closely with SuperPower on the design of FCL as well as on the SPE proposal to be submitted in February 2007.

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

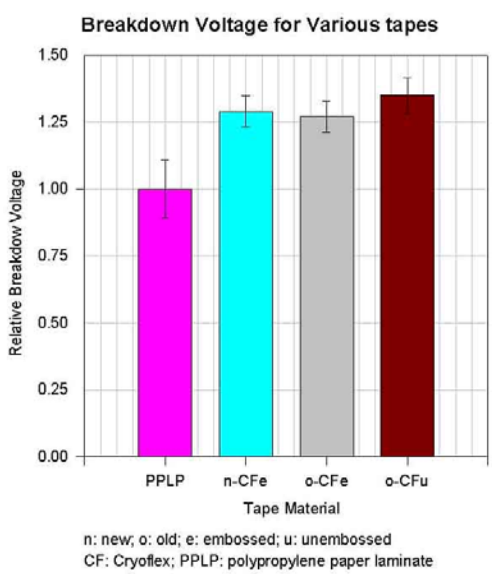
Objectives:

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

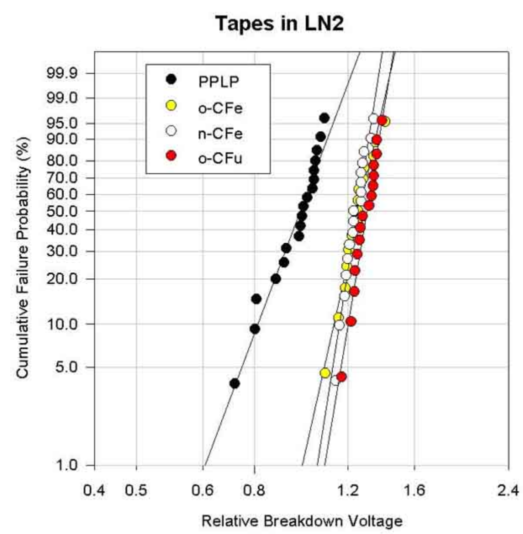
Highlights:

Breakdown of Cryoflex compared with PPLP in liquid nitrogen.
We have re-examined the breakdown strength of Cryoflex by evaporating electrodes on sheets of cryoflex. Results of multiple measurements were compared with PPLP (polyprolyene paper laminate) using the same electrode arrangement in liquid nitrogen (LN2). Significantly higher breakdown strengths were confirmed for Cryoflex.

Four materials were tested: old embossed Cryoflex (o-CFe), old unembossed Cryoflex (o-CFu), new embossed Cryoflex (n-CFe), and PPLP. The number of measurements made for each material are 12, 16, 17, and 18 respectively. Data shown in the figure represents the mean



Mean breakdown voltage for PPLP, n-CFe, o-CFe, and o-CFu



Weibull plots of breakdown voltage distributions of different tape materials in LN2 breakdown values normalized to that of PPLP, with standard deviations indicated by the error bars. All of the Cryoflex samples show a 25-30% improvement in strength over PPLP. This is consistent with previous breakdown measurements of model cables insulated with PPLP and o-CFe where the insulation consists of the tape/LN2 combination and where the Cryoflex insulated model cable has a 19% higher breakdown strength than PPLP. Weibull distributions of the data reveal the superior performance of all Cryoflex materials. When the data is extrapolated to a 1% probability of breakdown the difference in breakdown voltage between the different forms of Cryoflex is about 40% higher than PPLP.

Status of milestones:

- 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. (September 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 but not an audit.

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

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 Corp. 2G wire development subcontract.
M. W. Rupich (American Superconductor)

Status of milestones:

- 20–100 meter length of 344 superconductor wire with I_c exceeding 100 A at 77 K, self-field: On track.

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

Status of milestones:

- Short sample 2G wire with I_c of 750 A/cm: On track.
- Short sample 2G wire with a J_e of 30 kA/cm^2 at 77 K, 1 T (without copper stabilizer): On track.

Subtask 1.5.3: NIST-Boulder electromechanical studies for superconductor development interagency agreement. .
J. W. Ekin, N. Cheggour (NIST-Boulder)

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. (September 30, 2007): On track.

Subtask 1.5.4: NIST-Gaithersburg interagency agreement to investigate HTS phase equilibria and relationships.
W. Wong-Ng (NIST-Gaithersburg)

Status of milestones:

- Complete initial determination of single-phase regions for selected mixed lanthanides: On track.
- Complete initial study on processing relationships among phases in selected Ba-R-Cu-O systems as applied to films: On track.

Subtask 1.5.5: 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 1.5.6: TMS technical support subcontract.
P. Herz (Technology & Management Services, Inc)

Status of milestones:

- Complete remaining web-design tasks: On track.

Subtask 1.5.7: Bob Lawrence & Associates outreach subcontract.
Bob Lawrence (Bob Lawrence & Associates)

Status of milestones:

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

Subtask 1.5.8: Navigant HTS Technology and market Assessment subcontract.
David Walls (Navigant)

Status of milestones:

- Complete HTS Market Assessment Report for OE: On track.