PROJECT TITLE:	**Conductor Design for HTS applications**
ORGANIZATION:	**Oak Ridge National Laboratory**
PRESENTERS:	Fred List, Robert Duckworth, and Isidor Sauers
FY 2006 FUNDING:	$ 800,000 (DOE to ORNL)

Project Purpose and FY 2006 Objectives: The purpose of this cross disciplinary R&D project is to investigate the performance of HTS tapes with emphasis on YBCO coated conductors in the areas of conductor quench and stability, ac loss, thermal and dielectric properties. Fundamental understanding of these concepts will help with the integration of coated conductors into applications such as dc and ac transmissions lines, transformers, and motors. This is accomplished by studying the basic properties of single tapes and also examining how these conductors are integrated into prototype coils and cables.

FY2006 objectives are:

1. Understanding the role of copper (Cu) stabilization in the operational, stability limits and ac loss in non-filamentized and filamentized YBCO coated conductors.
2. Study how different techniques of Cu stabilization impact the high voltage properties of superconducting tapes.
3. Establish experimental facilities to characterize the reduction in ac losses of conductors made using both inkjet printing and laser scribing techniques.
4. Use inkjet printing of YBCO and silver precursors for the fabrication of low ac loss YBCO coated conductors.
5. Measurement of stability and ac loss in prototype YBCO coils and cables to better understand how features such as splices and slightly magnetic substrates affect performance as the length of YBCO is scaled up.
6. Investigate the use of polymer-based epoxies with and without nano-composite materials with improved breakdown strength and electrical properties.

FY 2006 Performance and FY 2007 Plans: For FY 2006, the quench dynamics of single YBCO tapes with different thicknesses of Cu surround stabilizer were determined at 77 K using over-current pulses and constant currents for sample lengths of 0.2 m to 1.0 m. In addition to addressing the stability in single tapes, the stability of a 0.3 T YBCO coil that was made from 120-m of YBCO coated conductor was characterized in a liquid nitrogen bath and in a cryocooled environment between 30 K and 40 K for different currents and current ramp rates. To determine the possibility of low resistance joints for magnets, a series of splice joints were characterized as a function of applied field at room temperature and 77 K and for different solders and surface preparations.

With respect to ac losses for FY 2006, ac losses as a function of applied ac field were measured for as-manufactured tapes from SuperPower (SP) and American Superconductor (AMSC) to understand the impact of the manufacturing process and the role of additional stabilization. The ac losses were measured in as a function of field for a set of stacked 2-mm wide SP conductors and were compared to those for a 4-mm wide conductor with similar critical current density. Equipment and solutions for inkjet printing of filamentary conductor were developed. The ac losses of non-filamentary conductor prepared by spin coating and inkjet printing were measured and compared to filamentary conductors produced by inkjet printing or laser scribing. To better understand the impact of materials on applications, ac losses and inductance were measured for a set of cables comprised of AMSC 2G tapes with Ni-5at%W substrates

For dielectric issues, fundamental evaluation of two tapes in a cross configuration was carried out to determine the impact of the Cu stabilization geometry on high voltage breakdown characteristics. Moving from a fundamental geometry, the impact of Cu surround stabilization on high voltage breakdown in turn-to-turn geometries that are often seen in HTS coils was evaluated. Because of the impact of dielectric materials on superconducting grid applications, preliminary work has been carried out to evaluate possible alternative dielectric materials that have improved breakdown characteristics and thermal properties at cryogenic temperatures.

Plans for FY2007 include:

1. Transitioning from single tape measurements to prototype YBCO coils in the areas of dielectrics, ac loss, and quench and stability.
2. Continue R&D on ac loss measurements using conductors that are comprised of assembled stacks of narrow tapes to examine the effects of twist pitch and also inkjet conductors with different filament configurations.
3. Establish a baseline process to fabricate longer lengths (20 to 50 cm) of conductors with filaments which may include continuous reel-to-reel printing from a multi-nozzle inkjet dispenser.
4. Determine optimum bridge spacing and bridge resistance in YBCO filaments with respect to quench and stability.
5. Fabricate a series of YBCO coils to examine whether the improvements that have been seen in the areas of conductor stability, ac loss, and dielectrics scale into larger components. Each coil will be dedicated to study ac loss

and conductor stability separately and will be made of nominal 4-mm wide YBCO conductor with the ability to replace either a coil section or coil set to study how areas like filamentization, tape splices, and improved thermal insulation improve the coil properties. Coil testing effort will be coupled with modeling to reduce testing and fabrication costs.

FY 2006 Results:
The quench dynamics of constant current and over-current pulses of a series of 4-mm wide, 30-cm long YBCO conductors with 20 µm and 38 µm of Cu surround stabilizer was compared to un-stabilized YBCO conductor. Both 20 µm and 38 µm of Cu surround stabilizer improved the ability of the conductor to operate in an insulated 77 K bath at a fixed current by more than 20%. It was also observed that for 0.25 s current pulses, followed by a constant current below the sample Ic, the fraction of current pulse to Ic went from 1.20 for the un-stabilized YBCO conductor to 3.74 (6.40) for a YBCO conductor with 20 (38) µm of surround Cu stabilizer. Normal zone propagation speeds between 0.2 cm/s and 0.7 cm/s were observed in Cu surround stabilized conductors.

The quench current for a 0.3 T YBCO coil that was made from 120 m of 344-2G conductors was affected greatly by the cooling conditions. Quench currents of 25 A and 32.5 A were found for temperatures of 35 K and 40K, while a quench current of 25.5 A in liquid nitrogen was measured. The difference was largely due to heating of the current leads, but the possibility of cryo-cooled magnets with low resistance splices was indicated.

AC losses in as-manufactured YBCO tapes from American Superconductor were marginally (~ 10%) impacted by the Cu lamination when measured as a function of both transport ac currents and ac fields. However, this increase was tied to a slight change in the hysteretic losses instead of the Cu eddy current losses. Measurements on samples with Cu laminated YBCO tapes from 2005 to 2006 have shown a slight reduction in ac loss approaching that of non-laminated YBCO tapes. A pair of electrically insulated 2-mm wide SP YBCO conductor had lower ac losses as a function of perpendicular ac field than a single 4-mm wide SP YBCO conductor with the same Ic. These were compared to spliced 2-mm YBCO wide conductors with low resistance solders to see how electrical coupling of the 2-mm wide conductors and segmentation of the conductor could decrease the ac loss. AC losses and inductance were measured in a set of cables in YBCO coated conductors with Ni-5at%W substrates and compared to previous results on BSCCO cables co-wound with Ni-5at%W tapes.

A single nozzle inkjet printing system has been developed for depositing YBCO and silver precursor solutions. The solutions and the methods by which they are processed have been tailored to accommodate the requirements of inkjet printing. Results from the processing of filamentary YBCO conductors of lengths between 3-cm and 6-cm and filament widths between 100-µm to 1-mm will be compared to similar laser patterned YBCO films that are made from the same precursor solutions.

The average high voltage breakdown at room temperature for a pair of crossed, Cu-laminated YBCO tapes that were separated by 25µm of kapton was 7.0 kV, which was comparable to results that were obtained for YBCO tapes with Cu surround stabilizer. The standard deviation of the Cu-laminated YBCO tapes (0.9 kV) fell in between the standard deviation of the Cu surround stabilized YBCO tapes (0.2 kV) and the un-stabilized YBCO tapes (2.0 kV). When YBCO tapes are vacuum epoxy impregnated in Stycast W19 in a turn-to-turn geometry, the presence of Cu surround stabilizer in 4-mm wide YBCO tapes decreased the probability of breakdown as a function of voltage when compared to as-slit, 4-mm wide tapes.

Multiple splice resistance measurements have been made on Bi-2223 and YBCO tapes at 77 K as a function of thermal cycle, currents, solder material, and surface preparation. Results indicate that splice resistances range from 10^{-6} ohm-cm^2 to 10^{-7} ohm-cm^2 for brass-laminated Bi-2223. Copper-laminated YBCO tapes show a slight reduction in splice resistance for the same surface treatments and solders.

Research Integration: This project has worked to strengthen the existing CRADAs that ORNL has with American Superconductor and SuperPower. Tapes with different substrates, stabilizers, and widths were provided by CRADA partners to investigate stability, ac loss, and dielectric concepts. Results are also communicated to peers working in the DOE SPI projects so conductor performance can be optimized for the particular constraints of a given application. Results from the characterization of the 0.3 T YBCO coil and the low ac loss inkjet conductors will be presented at the 2006 Applied Superconductivity Conference and published in 2007. Work on ac losses has lead to a DARPA project in collaboration with AMSC and Naval Research Laboratory.