PROJECT TITLE:	**High-Temperature Superconducting Power Cable**
ORGANIZATION:	**Oak Ridge National Laboratory**
PRESENTERS:	**David Lindsay (Southwire Co./Ultera), Jonathan Demko (ORNL)**
FY 2006 FUNDING:	**$1,300 K (DOE to ORNL)**

Project Purpose and FY 2006 Objectives: Ultera (a joint venture between Southwire Company and nkt cables) and ORNL have jointly developed, built and demonstrated a series of cold-dielectric, high-temperature superconducting (HTS) power cables for this Superconductivity Partnerships with Industry (SPI) project. The 30-m cable at Southwire's wire-manufacturing complex in Carrollton, GA continues to run, accumulating over 38,000 hours at full load to date and running unattended over the last 60 months. This cable is rated at 12.4-kV, 1,250-A, 3-phase, 60-Hz, and 27-MVA. The cable was placed into full service in April 2000 for an extended testing period under industrial conditions. In FY 2006, ORNL has worked with Southwire Company to research and improve the overall design and capabilities of HTS cable systems including:

- Finalize the design of cable subsystems for a 200-m cable installation at Columbus, OH in partnership with Ultera, Praxair and American Electric Power (AEP).
- Designed and fabricated triaxial cable terminations for the 200-m tri-axial, 3-phase, 3,000 A_{rms} cable that was assembled and installed at the AEP Bixby Substation in Columbus, Ohio. Supported cool-down and off-line testing of the cable prior to grid tie-in.
- Continued development and testing of cryogenic dielectric (CD) materials including terminations and triax cable splice joints. Tested solid dielectric materials for high voltage ac withstand and impulse strength, partial discharge, and thermal shock.
- Conducted thermal-hydraulic calculations of the 200-meter HTS cable system. The analysis was used to determine safety relief valve requirements under 1) the expected fault currents and 2) an unlikely catastrophic loss of thermal insulating vacuum scenario in a cable cryostat. ORNL also supported system failure modes analysis.
- Continued research improving cryogenic system performance with industry.

FY 2006 Performance and FY 2007 Plans: The assembly of the 200-m tri-axial 3000 A_{rms} cable and associated 3-phase terminations was completed in the spring of 2006. The 3-phase cable was manufactured by Ultera, The termination parts were manufactured by machine shops in Tennessee, Georgia and Ohio. The assembly of a splice joint in the 200-meter cable and cryostat was performed in the field at a manhole on the AEP Bixby substation site. Assembly of the cable and terminations was completed in April. The Southwire team participated in several team meetings at the AEP facility and a successful SPI Readiness Review in May. The issues identified by the independent review team were addressed prior to cooling down the cable. The cryogenic system was commissioned in June and purging of the cable, cool-down and off-line electrical testing were completed by the end of June. Low voltage electrical testing included dc voltage-current (VI) characterization up to 5000-6000 A limited by available portable power supplies. High voltage testing included a very low frequency high voltage test at 0.1 Hz to 20 kV_{rms} and a high voltage soak at 13 kV_{rms}, 60 Hz.

Plans for FY 2007

1. Test model cables and terminations to higher ac voltages (up to 69 kV), investigate ac breakdown strength and partial discharge inception and examine scaling to higher BIL levels; and continue development and testing of improved dielectric tapes and other materials for use at higher voltages.
2. Conduct test of short sample (1- to 5-meter) second generation HTS cable sections to measure dc V-I characteristics, ac loss, and stability to over-current faults.
3. Instrument and test a 5-meter vacuum multi-layer insulated cable cryostat at the ORNL HTS Cable Test Lab for thermal-hydraulic response to a loss-of-vacuum event.
4. Conduct preliminary design and component R&D of a dc cable system.

FY 2006 Results: Significant progress has been made towards the project objectives during the fiscal year:
30-m HTS Cable. In April 2000, the cable was placed into extended service and has logged over 38,000 hours of full power operation since that time. The performance of the superconductor was last measured in June

2005 with no measurable change in the critical currents of the superconducting phases. There have been several cable outages due to the cryogenic system and this experience is being used in specifying technical requirements for the SPI project with AEP. During 2005, the system experienced a line-to-ground fault and direct lightning strike to the HTS yard – both with no damage to the HTS cables as demonstrated by the critical current measurements taken in 2005.

Cryogenic Dielectric Studies. The 5-meter triaxial cable was dissected to determine the location and possible causes of the breakdown that occurred during the extended impulse testing (after the required number of withstands had been met and the cable was impulsed to breakdown). The location was accurately determined using an audio technique. The cable performance met the requirements of the AEP Bixby installation. A conductor/dielectric splice and a former splice were fabricated by Ultera and sent to ORNL for high voltage testing. Partial discharge and impulse testing of the conductor splice was made and the splice met the requirements for the AEP Bixby installation. The former splice has been tested and the results of these tests will be reported as well. The statistics of multiple impulse withstands and the required safety margins have also been examined and will be discussed.

Tri-axial Cable. The triaxial cable consists of three concentric superconducting phases made of BSCCO-2223 HTS tapes that are separated by layers of Cryoflex^{TM} cold-dielectric tape, which provides the phase-to-phase electrical insulation. Copper is then added as the grounding shield on the outside of the cable structure. The completed tri-axial cable is enclosed in a flexible cryostat and has circulating liquid nitrogen cooling the outside of the cable as well as flowing in the former. Evaluation of the electrical testing and cryogenic operation of the 5-m tri-axial, 3-phase, 3,000 A_{rms} cable and terminations at ORNL was completed. The data was used to confirm the heat load and pressure drops expected at the AEP Bixby substation. Two 100-meter flexible cryostats were pulled into the cable ducts in January 2006. Two lengths of triaxial cable were pulled into the cryostat and a field splice was made in a manhole to join the cables and complete the 200-m circuit.. Thermal-hydraulic analyses were conducted to design the liquid nitrogen return line and to determine pressure safety relief requirements and relief valve sizes. Some of these results were presented at the cable generic issues session at the 2006 DOE Wire Workshop in January. A Readiness Review was completed in May and the issues identified were addressed promptly. The cool-down of the triaxial HTS cable occurred in June over a 2-day period.

HTS Cable Test Lab. The move of the ORNL HTS Cable Test Lab was completed. The low voltage power supplies have been tested including the 25 kA DC and 3000 A ac units. The liquid nitrogen system has been installed and is connected to a 7,500 gallon liquid nitrogen storage tank. This is a significant improvement over the former facility at Y-12 since the tank is located just outside the building wall as opposed to over 300 feet away at Y-12. Initial commissioning of the liquid nitrogen system is underway.

One technical paper on the testing of the 5-meter triaxial HTS cable was presented at the Cryogenic Engineering Conference in September 2005. Three abstracts were submitted to the Applied Superconductivity Conference in August 2006.

Research Integration: The design, assembly, and operation of the cable test facilities at ORNL, the 30-m demonstration cable at Southwire Company, and the 200-m demonstration cable at AEP have been totally integrated efforts drawing upon scientists, engineers, and technicians from Southwire, nkt cables, ORNL, Praxair, AEP and private industry. Private consultants, cryogenic equipment manufacturing firms, and superconducting materials suppliers have been used extensively during the project. Major components of the 5-m, 30-m and 200-meter cable systems were procured via competitive subcontracts. The project implemented an "HTS Insight Team" which is a select group of interested parties that will witness and provide the end-user's perspective with respect to commercial applications and requirements. Members of the HTS Insight Team were afforded the opportunity to be on-site in Columbus during cable pulling, splice and termination assembly, cryogenic system startup, and testing/energization. A short course on HTS cable technology and design will be presented by a team member at the 2006 Applied Superconductivity Conference.