Project Title:	**High-Temperature Superconducting Power Cable**
Organization(s):	**Oak Ridge National Laboratory**
Presenters:	David Lindsay (Southwire Company), Jonathan Demko (ORNL)
FY 2003 Funding:	$1,800 K (DOE to ORNL)

Project Purpose and FY 2003 Objectives: Southwire Company 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, Georgia, continues to run, accumulating over 22,000 hours at full load to date and running unattended over the last 24 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 2003, ORNL has worked with Southwire to research and improve the overall design and capabilities of the HTS cable system including:

- Fabrication and testing of multiple 1-2 meter single-phase cables to evaluate three different wire architectures, optimize ac loss, study over-current response and heat transfer characteristics.
- Complete electrical and thermal performance testing and analysis of an innovative, 5-m tri-axial HTS cable, designed for 1300 A_{rms} including 3-phase terminations, at ORNL.
- Design, fabricate, and install a 5-m tri-axial, 3 phase cable for 3,000 A_{rms} per phase (AEP reqr.).
- Continued development and testing of cryogenic dielectric (CD) material including model cables to 34 kV, and conduct cable aging studies. Tested cast dielectric materials for high voltage strength, partial discharge, and thermal shock. Improved x-ray imaging of internal defects in solid dielectrics.
- Initial design of cable subsystems for a long-length cable installation at Columbus, Ohio, in partnership with Southwire and American Electric Power (AEP).
- Continued research improving cryogenic system performance with industry and NASA.

FY 2003 Performance and FY 2004 Plans: The design of the 5-m tri-axial 3000 A_{rms} cable and associated 3-phase terminations was completed in the 2^{nd} quarter of FY 2003. The 3-phase cable will be manufactured by Southwire and expected delivery to ORNL is in July 2003. Final assembly of the terminations, initial cooldown, and initial dc/ac testing will take place during the fourth quarter of FY 2003. The component R&D completed for the tri-axial cable terminations, especially in the dielectric and heat transfer areas, will directly benefit the pressurized termination concept. A 1.25-mYBCO cable will be made in the 3^{rd} quarter and tested in the 4^{th} quarter of FY 2003. R&D on aging of CD model HTS cables is continuing with an emphasis on correlating the aging with partial discharge signals. A 34 kV model cable has been made and tested for partial discharge and BIL. The Southwire team worked closely with ORNL staff conducting the Cryogenics Assessment Study to ensure cable cryogenic issues were addressed in this FY 2003 DOE initiative. They are also working on cryostat performance and reliability issues with international vendors and via a collaboration with NASA-Kennedy Space Center.

Plans for FY 2004

1. Complete electrical testing of the 5-m tri-axial, 3-phase, 3,000 A_{rms} cable at ORNL,
2. Test model cables and terminations to higher ac voltages (up to 69 kV),
3. Complete design of the long length cable at AEP-Columbus and begin long lead procurements.

FY 2003 Results: Significant progress has been made towards the project objectives:

30-m HTS Cable. In April 2000, the cable was placed into extended service and has logged over 22,000 hours of full power operation since that time. The performance of the superconductor was tested in April 2001 and again in June 2003. There has been no measurable change in the critical current of the superconductor providing further credence to the viability of this promising technology. 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.

Cryogenic Dielectric Studies. High voltage experiments on model cables to assess the expected life of the cable dielectric system remain in progress. Partial discharge (PD), considered to be the major aging mechanism of cryogenic cable dielectrics, is being studied using a state-of-the art partial discharge detection system. Several new insulation tape materials have been formulated with the goal of optimizing mechanical and electrical characteristics. Initial breakdown and PD tests have been performed on model cables with one of the materials along with PPLP (polypropylene laminated paper) that is currently used in HTS cables under development in Japan and elsewhere. The experiments indicate that PPLP has a lower ac breakdown strength than Cryoflex for equal insulation thickness. Development was conducted on potential materials for the dielectric insulation in the 3-phase terminations that require high breakdown strength and high thermal conductivity at 77 K and 300 K. Development of cast dielectric materials for high voltage strength and partial discharge were performed for use in cable auxiliaries, such as terminations. The team worked on improved x-ray imaging of voids in cast dielectric materials as well as the detection of voids by partial discharge signature. Measured energy dissipation due to partial discharge in model cables was studied as a new way of rapidly assessing cable aging at cryogenic temperatures.

Tri-axial Cable. The tri-axial cable consists of three concentric superconducting phases made of BSCCO-2223 HTS tapes that are separated by layers of Cryoflex cold-dielectric tape, which provides the phase-to-phase electrical insulation. A copper braid is added as the grounding shield. The completed tri-axial cable is enclosed in a flexible cryostat and has circulating liquid nitrogen cooling the outside of the cable. A comprehensive test program has been carried out on the 1.3 kA 5-m cable since the fall of 2002 that includes dc testing, measurement of cable heat loads and over-current tests. AC testing of the cable has included measurements of ac loss and induced currents in the Cu-shield and operation with intentional phase imbalances. In 2003 ORNL and Southwire are building a 3-phase termination designed for 3 kA_{rms} per phase that will be a full-scale prototype of the cable to be installed at the AEP Bixby substation under the SPI program. Analysis and detailed design was completed to implement the required upgrade from the existing 1.3 kA design to the 3 kA per phase design. Fabrication activity has begun for the termination long-lead-time components. A 5-m tri-axial cable with 3 kA phase current was wound. This higher capacity cable will include a comprehensive high current test program similar to the one conducted on the 1.3 kA cable, but expanded to include high voltage characterization.

Short Sample Cables. Three short cables (1-m to 3-m in length) were fabricated and tested to evalute the ac loss performance of different BSCCO-2223 wires and winding configurations. In addition, another 1-m single-phase cable with high voltage dielectric applied was tested to evaluate the overcurrent and heat transfer characteristics of the cable.

Second Generation Conductor Cable. A 1.25-m-long cable is being fabricated from second-generation YBCO coated conductor. The dc performance and ac loss will be measured for the first time on a second-generation conductor cable.

Research Integration: The design, assembly, and operation of the cable test facilities at ORNL and the 30-m demonstration cable at Southwire Company have been totally integrated efforts drawing upon scientists, engineers, and technicians from Southwire, NKT, ORNL, 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 and 30-m cable systems were procured via competitive subcontracts.

Three HTS cable technical papers were presented at the Applied Superconductivity Conference in August 2002 and will be published in the upcoming *IEEE Transactions on Applied Superconductivity*. Four technical papers are planned for the Cryogenic Engineering Conference in September 2003. An invited paper, pertaining to test results on the 1.3 kA, 5-m tri-axial cable tests, was presented at the 15th International Symposium on Superconductivity in Yokohama, Japan, in November 2002, and is in press for an upcoming issue of *Physica C*.