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CRADA Final Report for ORNL95-0381

Development of Superconducting Transmission Cable

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CRADA Final Report for ORNL95-0381

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ABSTRACT

The purpose of this Cooperative Research and Development Agreement (CRADA) between Oak Ridge National Laboratory (ORNL) and Southwire Company is to develop the technology necessary to proceed to commercialization of high-temperature superconducting (HTS) transmission cables. Power transmission cables are a promising near-term electric utility application for high-temperature superconductivity. Present HTS wires match the needs for a three-phase transmission cable: (1) the wires must conduct high currents in self-field, (2) there are no high forces developed, and (3) the cables may operate at relatively low current density. The commercially-available HTS wires, in 100-m lengths, make construction of a full three-phase, alternating current (ac) transmission cable possible.

The Electric Power Research Institute has estimated that about 2,500 miles of underground cable are installed in the U.S. today. The increased demands placed on existing rights-of-way in large urban centers require utilities to identify new approaches to meet their customer's power demands. As needs for greater throughput into congested urban areas, along with legal, environmental, and regulatory forces, make it more difficult to install new overhead lines, it is expected that the percentage of underground cables in the nation's network will grow.

If completed through the pre-commercialization phase, this project will result in a new capability for electric power companies. The superconducting cable will enable delivery with greater efficiency, higher power density, and lower costs than many alternatives now on the market. Job creation in the U.S. is expected as U.S. manufacturers supply transmission cables to the expanding markets in Asia and to the densely populated European cities where pipe-type cable is prevalent.

Finally, superconducting cables may enable delivery of the new, diverse and distributed sources of electricity that will constitute the majority of new installed electrical generation in the world during the coming decades.

STATEMENT OF THE OBJECTIVES

The objective of Phase I-A was to develop and construct a low-cost, 1-m HTS cable prototype and to test the cable within 15 months of the start of work. In Phase I-B, the team: performed detailed cable analysis, design, and development activities to further refine the cable design based on the most likely commercially-available wire; developed new lower loss cable layering and winding concepts; tested short cable prototypes; and compared experimental measurements with calculated losses.

Southwire had primary responsibility for providing 1000 m of purchased Bi-2223 silver-clad tape and providing overall design guidance for the cable design. Southwire provided the flexible corrugated or plain pipes for cable making, engineering and technician support for project planning, design and fabrication of certain test equipment, and wound the HTS tapes to form the 1-m cables. They carried out scanning electron microscope work needed to characterize certain project materials and provided the cable low voltage insulation and dielectric materials in consultation with ORNL.

ORNL was primarily responsible for characterization and analysis of the HTS tapes, assisting Southwire in developing conceptual designs for the cable, testing partial cables for dc and ac current and other properties, assisting in the detailed cable design, and designing and constructing the 1-m cable test apparatus and coordinating tests at ORNL with input from Southwire. Analysis of the experimental result was carried out jointly.

BENEFITS TO THE DOE FUNDING OFFICE'S MISSION

The sponsoring office at the U.S. Department of Energy (DOE) is the Office of Energy Efficiency and Renewable Energy. The project assisted the DOE Superconductivity Program for Electric Power Systems in meeting the program mission, which is to develop, with U.S. industry, the technological base needed to proceed to commercialization of electric power applications of high-temperature superconductors. Underground transmission cables are expected to be the first commercial application in the electric power sector.

DOE also benefitted by obtaining access to the latest superconducting tape materials and by Southwire's expertise in insulation and dielectric materials and their operation in an underground environment. Southwire, as a result of their manufacturing expertise in conventional copper underground cables and their manufacture of special aluminum conduit materials, provided DOE with industrial experience in cable-making and high- voltage breakdown testing at a unique test facility in Carrollton, Georgia.

TECHNICAL DISCUSSION OF WORK PERFORMED

Tests of Three Prototype HTS Transmission Cables

During the initial phase of the CRADA, two 500-A-class and one 2000-A-class prototype cables were constructed. The cables and short samples of the Bi-2223/Ag HTS tapes were tested systematically at ORNL. The cables were tested with both dc and ac currents in liquid nitrogen. Both cables achieved design currents; however, substantial degradation in comparison with the short-sample critical currents (I_cs) was observed. A simple calorimetric technique was used to measure the ac losses of the cables. A method of utilizing the broad resistive transition of the HTS cable was devised to calibrate the ac loss. Different ac-loss behaviors were observed on the insulated and uninsulated cables.

Short Sample Testing

A series of short sample tests were performed on the Bi-2223/Ag HTS tapes acquired by Southwire. Seventy-eight samples for the winding of the first cable and 11 samples for the winding of the second cable were measured. These 1-in.-long samples were tested in liquid nitrogen with up to 0.5-T magnetic field parallel and perpendicular to the wide face of the tape. Figure 1 shows the measured zero-field short sample I_cs (at the 1-μV/cm criterion) along the length of the spool used to wind the second cable. Critical current varies significantly (by a factor of two) along the length of the tape. A mean I_c value of 20 A was measured (the end-to-end value was 17 A). Similarly, a mean I_c value of 19 A was measured for the tapes used to wind the first cable (the end-to-end value was 12 A). Apparently, damaged spots on a large spool were apt to be skipped when short samples (about 1-in. long) were taken.

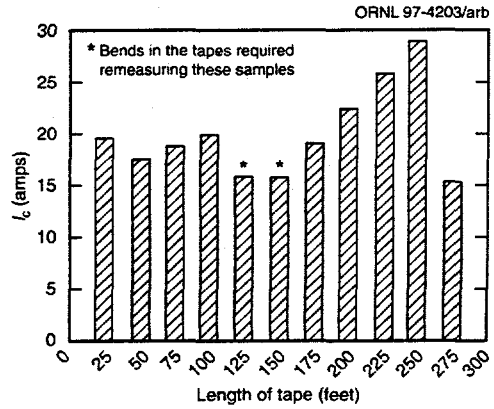

Fig. 1. Short sample of I_c along the length of the tape for use in cable 2.

Magnetic fields degrade the Bi-2223/Ag HTS tapes significantly at liquid nitrogen temperatures. At a background field value of 0.01 T, the present tapes showed an average of 10% degradation in I_c with field parallel to the wide face and 50 % degradation with field perpendicular to the wide face of the tape.

Bending tests were performed on selected samples of the HTS tapes. In a series of tests, I-V curves of 3-in.-long samples were measured before and after being wrapped side-by-side around a 1-in.-diam former. The samples from the lower-I_c spool showed an average degradation of 30%; those from the higher-I_c spool showed an average degradation of 53%.

Bending tests were also performed with samples about 30-cm long by wrapping them with lay angles of up to 30°. Critical current degradation between 40 and 50% of the 1-in.-long short sample values was observed.

Prototype Cables

Two prototype 500-A-class transmission cables were fabricated by Southwire using the 3.5 × 0.22 mm HTS tested tapes. The 1.2-m-long cables were made by spirally winding the tapes on a 22-mm (7/8-in.) copper former with lay angles of about 15°.

For the first cable, no insulation was used to electrically separate the tapes. The ends of the tapes on the first layer were soldered onto the former. Successive layers were wound with alternating twist angles, and the ends were soldered to the previous layer. Seventy-three tapes were wound in four layers in the first cable. Figure 2 shows a picture of the cable assembled and ready to be lowered into the test dewar. The main body of the cable was enclosed in a micarta pipe filled with wax to establish adiabatic conditions to measure the temperature rise (and thus the ac loss) of the cable.

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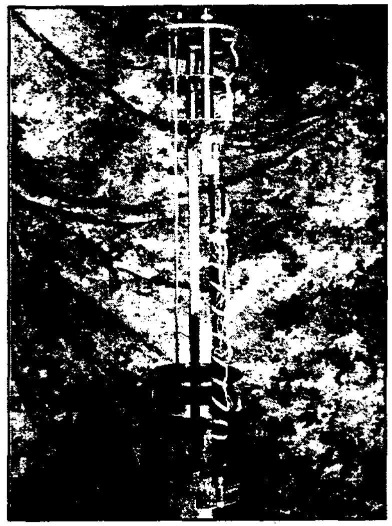

Fig. 2. Cable 1 assembled for both dc and ac current tests.

The second cable was fabricated in a way similar to the first cable, except that Kapton tape was used between layers for insulation. Sixty-six HTS tapes were used in the second cable.

The third Southwire cable was wound from similar HTS tapes as were used in cables 1 and 2. The tapes were wound in 10 layers on a 1-in.-diam stainless steel former. Similar to layers in cable 2, the successive layers were insulated from each other with Kapton tape. Two hundred HTS tapes were used in winding this cable.

DC Current Measurements

The electrical tests of the cables were carried out in liquid nitrogen with the HTS cable held upright in a 1.6-m-deep dewar.

DC I-V of Cable 1

Four voltage taps were placed on the cable, separated from each other by about 30 cm, and were labeled as V_1 to V_4. Figure 3 shows the I-V curves of the

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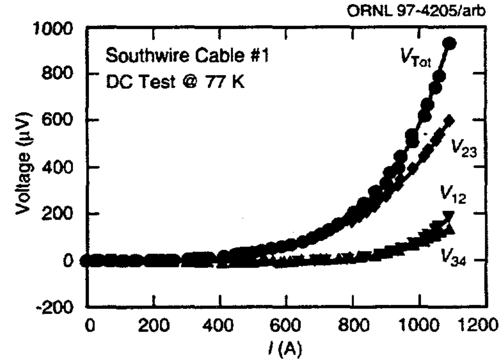

Fig. 3. DC I-V curves of cable 1 at the first cooldown.

different sections of the cable and of the whole cable (V_{Tot}). Gradual resistive voltage rise was seen for currents starting at about 400 A. All resistive voltage of the cable came from the midsection (V_{23}) at currents up to 650 A, caused by visible damage near the middle of the cable. Nevertheless, the overall I_c of 670 A at the 1-μV/cm criterion is higher than the design value of 500 A.

DC I-V of Cable 2

The layers of cable 2 were insulated from each other with Kapton tape, and separate current leads were brought out for each layer. Thus the cable could be tested as a whole or separately on individual layers. When the cable as a whole was tested, an I_c of 560 A was measured. Notice also that because of the broad resistive transition, both cable 1 and 2 can be operated stably at more than 1 kA.

During the test of the outermost layer of cable 2, the liquid nitrogen bath was pumped to lower temperatures. Figure 4 shows the I-V curves of this layer at three different temperatures of the liquid nitrogen bath. The I_c o-f this layer increased from 149 to 186 A when the bath temperature was lowered from 77 to 69 K. Thus an increase of about 25% in current-carrying capability can be achieved in the cable by operating with subcooled liquid nitrogen (at about 69 K).

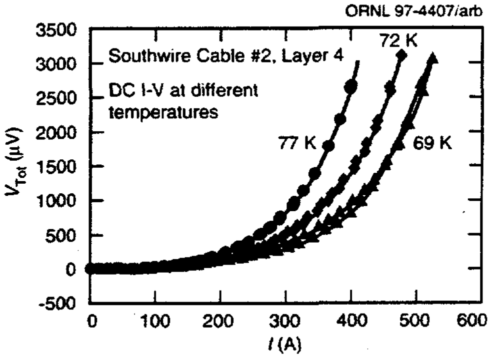

Fig. 4. I-V curves of outermost layer of cable 2 at three different bath temperatures.

DC Test of Cable 3

DC current test of the cable was performed with a 2-kA power supply. Broad and smooth resistive transition of the cable, similar to those of the previous two cables, was observed. A critical current of 1630 A was measured at the 1-μmV/cm criterion. At the power supply limit of 2 kA, the cable produced an average resistive voltage of 2.2 μV/cm.

Thermal Cycle of Cable 1

After a few cycles of cooling down and warming up of cable 1 for dc and ac current measurements, a series of continuous thermal cycle tests was performed. An I-V curve was measured, and the cable was pulled out of the liquid nitrogen bath. After it was warmed up to room temperature in air, the sample was lowered back down to the liquid nitrogen bath. Another I-V curve was measured. Figure 5 shows a series of these I-V curves at different thermal cycles. Significant degradation was observed on thermal cycling; however, the

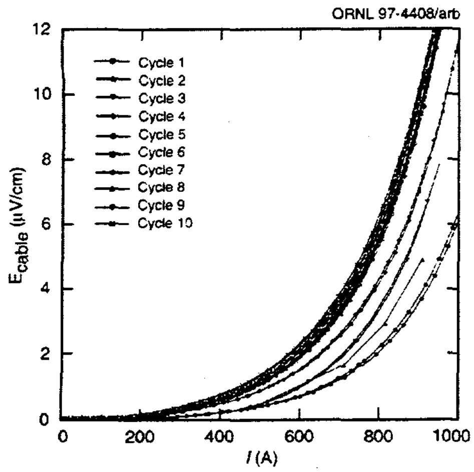

Fig. 5. I-E curves of cable 1 on successive thermal cycles.

degradation seems to level off after the fifth cycle. Critical current of the cable decreased from 670 to 460 A after 10 thermal cycles (a 30% degradation). Power law fitting of the I-V curves between 0.2 to 2 μV/cm also shows a decrease of *n*-value from 3.5 to 2.6.

Comparison of Short Sample and Cable I_c

The measured I_c per tape of cables 1 and 2 averages about 8.8 A. This is significantly lower than the average short sample value of 19.5 A measured on 1-in.-long short samples. As is described in the series of short sample measurements, several mechanisms can contribute to the degradation of the cable I_c. Short sample I_c measurements can be misleading because they can skip bad spots in the long lengths of the tape. Mechanical strain similar to that applied in winding the cable can degrade the I_c by about 50%. This can come from just handling the long lengths of the tape and from the bending applied in the cabling. The magnetic-field degradation by the cable self-field is well known. In addition, thermal-cycling degradation was also observed.

AC Current Measurements

Cables 1 and 2 were tested with 60-Hz ac currents up to 600 A rms. Steady rms voltages were observed at all test currents. A calorimetric technique was adopted to measure the ac loss of the cable at the applied ac currents. As is shown in Fig. 2, a micarta pipe filled with wax was used to thermally isolate the cable from the liquid nitrogen bath. A Cromel-Constantan thermocouple was attached to the middle of the cable to measure its temperature rise against liquid nitrogen at the same depth of the bath; temperature rise (ΔT) of up to 0.3 K was observed.

To calibrate ΔT against the power-loss rate, we used the broad resistive transition feature of the HTS cable itself. The cable was charged and held at a dc current above its I_c, where a resistive voltage can be measured. The ΔT of the cable was also measured under this dc current. The dc E·I product gave the average power loss for the measured ΔT. This technique was found to be more responsive than the heater wires tried on cable 1. Because I_c is not uniform along the length of the cable, power generation is not uniform, but this is true for both dc power and ac loss. Therefore, the calibration technique is a good simulation of the ac loss. In addition, Joule heating at the cable ends did not contribute to the measured temperature rise because the ends of the cable were immersed in liquid nitrogen. This was verified by the observation that in the dc current calibration runs no temperature rise was observed until the current greatly exceeded I_c.

Figure 6 shows the measured ac losses of the two cables as a function of the rms current. Also shown for reference are the respective dc I-E curves for two cables. Cable 1, which was not insulated, behaved like a cryoresistive conductor, showing power loss at all ac currents. Similar behavior was reported by Gannon et al.[1] Cable 2, which was insulated, showed no measurable ac loss until about 300 A rms, where the cable also started to show measurable dc resistive voltage. An average ac loss of about 0.2 W/m was measured at 400 A rms. Analysis of the loss data indicated that the measured loss is governed by the power law behavior of the HTS tape in the resistive transition.

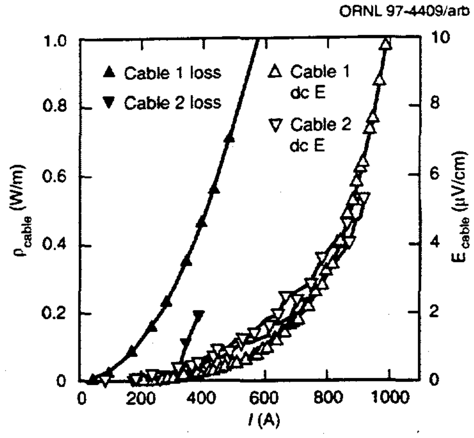

Fig. 6. The ac losses of both cables 1 and 2 in reference to their DC I-E curve. For the ac current, rms current is plotted.

Cable 3 was also subjected to ac current tests. Currents measuring up to 2.2 kA rms were charged and held for about 10 min. Steady voltage (mostly inductive voltage) was observed over the cable in each case.

Summary

Two prototype 500-A-class HTS cables have been designed, constructed, and tested. Both cables achieved dc critical currents greater than the design value of 500 A. Furthermore, because of the broad resistive transition, they can be operated stably at more than 1 kA. A third cable was tested successfully to >2000 A ac current.

Comparison of the cable I_c and the short sample values indicated a degradation of about 55%. Several mechanisms were identified as the probable cause of the degradation. Mechanical strain from handling the long lengths of the tape and from bending applied in winding the cable is thought to be the biggest source of degradation.

A calorimetric technique was used to measure ac losses of the cables. A scheme of utilizing the broad resistive transition of the HTS cable was successfully used to calibrate the loss rate. Loss measurements made on the cables with 60-Hz ac currents showed that insulation between the tapes is effective in reducing the ac loss of the cable.

Reference

[1]J. J. Gannon, Jr., et al., "Performance Summary of a 4,000-A High Temperature Superconducting Cable Conductor Prototype," *IEEE Trans. Appl. Supercond.* **5** (2), 953–56 (1995).

Phase IB

Design, Construction, Testing, and Analysis of Prototype HTS Cables

Three 1-m prototype cables have previously been built and tested. Based upon the performance of these three test cables, a fourth cable was designed, constructed by Southwire, and tested by ORNL to determine the ac and dc losses and current carrying capability of the cable. A theoretical model was used to verify the experimental measurements of the ac losses and overall performance of the cable. Additional 1-m prototype cables were constructed and tested to further the understanding of the loss mechanism.

Based upon the results of the 1-m cable tests, a design for a 5-m prototype cable was completed. When fabricated, the 5-m prototype cable will be a complete cable with conductor shield, electrical dielectric, dielectric shield, an HTS shield conductor, thermal insulation, and enclosed in a cryostat. The 5-m prototype cable will have one phase with an HTS conductor and the other two phases with a conventional conductor and operated at 12-kV and 1250 A.

HTS Tape Analysis and Evaluation

Critical current measurements of samples from the 1000 m of purchased Bi-2223 silver-clad type tape have been made and a draft specification for the purchase of additional tape has been prepared. The results of the critical current measurements were reviewed with the manufacturer and suggestions for tapes with higher critical currents were given to the manufacturer. As required, critical current measurements were made on new samples provided by the manufacturer and purchased by Southwire. The draft specification for HTS tapes was modified to reflect improvements in tape manufacturing capability. Tapes from three different manufacturers were evaluated by ORNL and Southwire.

Cryogenic System Design and Specification

A design and specification of the cryogenic system was jointly designed and developed for the 30-m, three-phase, 12 kV, 1250-A demonstration HTS cable. The cryogenic system includes the cryostat for the HTS cable, the cryogenic termination enclosures, and the refrigeration supply. Preliminary design analyses were performed to determine the operating temperatures and cryogen flow rates as part of the specification. The specification were reviewed with potential vendors and modified based upon their comments and suggestions. A request for quotation was issued to potential vendors by Southwire to supply the various components of cryogenic system and the responses to these quotations were reviewed and evaluated jointly.

Dielectric System Testing, Simulation, and Specification

Electrical dielectric tapes were tested by ORNL at cryogenic temperatures to determine their performance. The electrical tests performed were partial discharge, electrical withstand, thermal cycling, and ac voltage breakdown. Based upon a 12-kV design voltage, electrical tests up to about 50 kV were performed.

Cable Termination Design

A high voltage cable termination was designed jointly. The termination provides the electrical connection between the HTS cable operating at cryogenic temperatures and external bushings operating at room temperature. The termination operates at 12-kV three-phase and a 1250-A load current. The fault current magnitude and duration was determined by reviewing the requirements of the existing overhead distribution line. The termination design considers the relief of electrical stresses and thermal stresses, and the mechanical contraction and expansion of the various components. Design consideration was given to requirements of factory construction and field installation. The termination design is applicable to the 5-m prototype cable, the dielectric test vessel, and the 30-m demonstration cable.

Summary of Technical Achievements

The following table describes the series of 1-m HTS cables jointly designed and tested under the auspices of the CRADA.

Date tested	Cable number	Number of layers	Lay angle (°)	Former diam (mm)	DC I_c (A)	AC I_{MAX} (A)
FY 1996	1	4	15	22.0	670	650
	2	4	15	22.0	560	420
	3	10	15	25.4	1630	2200
FY 1997	4	4	15	38.1	975	1420
	5	2+2	30	38.1	1100	900
	6	2	30	38.1		
	7	4	30	38.1		
	8	4	30	38.1		

Cables 6 to 8 were constructed using HTS tapes from three different manufacturers. AC I_{MAX} is the maximum RMS current tested.

INVENTIONS

Three invention disclosures were submitted by Southwire and ORNL staff members, and two U.S. patent applications were filed during the course of the CRADA.

Disclosure Number	Title of Disclosure
ERID 254C	Method for Winding 60 Hz Transmission Line Power Cables with High Temperature Superconducting Tape Material
ERID 301C	High Temperature Superconducting Cable End Connector
ESID 1884-X	A Continuous Winding Machine for a High Temperature Superconducting Cable

COMMERCIALIZATION POSSIBILITIES

Southwire Company continues to work toward actual utility demonstration of HTS cable, scheduled for the year 2000.

PLANS FOR FUTURE COLLABORATION

Southwire has proposed a Superconductivity Partnership Initiative project to the DOE to further develop the technology to the 30-m, 3-phase demonstration stage. ORNL is a team member. In the interim, the two parties are continuing work under a Superconductivity Pilot Center Agreement.

CONCLUSIONS

This CRADA has been a highly successful project between Southwire and ORNL. All major objectives were met or exceeded within cost and schedule.

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17-18. Office of Scientific and Technical Information, P. O. Box 62, Oak Ridge, Tennessee 37831.
19. Work for Others Office, U.S. Department of Energy, MS G209, Oak Ridge, Tennessee 37831.

APPENDIX A. PARTIAL LIST OF REPORTS AND MEMORANDUM PROVIDED BY ORNL TO SOUTHWIRE COMPANY UNDER CRADA ORNL95-0381

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