Technical Progress in Applications Development

SUPERCONDUCTING TRANSFORMER PROJECT (INTERMAGNETICS GENERAL CORPORATION/ORNL/ WAUKESHA ELECTRIC SYSTEMS/ROCHESTER GAS AND ELECTRIC COMPANY)

This report covers only the nonproprietary Oak Ridge National Laboratory (ORNL) contributions to the HTS transformer project for FY 1997. Other than ORNL, the organizations participating in the project are the Intermagnetics General Corporation (IGC), Waukesha Electric Systems (WES) of General Signal Corporation, and the Rochester Gas and Electric Company (RG&E). Rensselaer Polytechnic Institute provided consulting under subcontract to IGC. The project objectives are (1) to develop a low-cost, wind-after-react HTS conductor suitable for use in transformers and other ac apparatus; (2) to establish the markets, technical and economic feasibility, and benefits to society of HTS power transformers of medium (30 MVA) to large rating; and (3) to design, build, and test an ~1-MVA single-phase HTS demonstration transformer. During the previous two years of this research effort, significant progress in achieving the first two objectives resulted in the decision to continue into the demonstration phase with construction of the ~1-MVA single-phase HTS demonstration transformer. The construction and test of components have been the major thrusts of the FY 1997 effort. Additional efforts included a more detailed analysis of the commercial design and the 5-MVA alpha prototype that is scheduled to follow the 1-MVA demonstration.

Several key findings of the design studies are presented in an article in the July 1997 issue of the *IEEE Spectrum*. In particular, the finding that HTS transformers can be designed to provide up to 2× overload (albeit with increased refrigeration load) without loss of transformer life. This enables utilities to buy transformers with lower ratings or to place more capacity in the same location. In contrast, overloading a conventional liquid-filled transformer to 110% rating for only 100 days during a typical 30-year operating period (< 1% of operating time) reduces the life of the unit by 25%. This overload benefit is in addition to the reduced losses and reduced fire and environmental hazard offered by HTS units.

In FY 1997, the team

- constructed the major components needed for a 13.8/6.9-kV, 1-MVA HTS transformer using 30-MVA-scale conductor and core and winding cross sections and initiated final assembly. The major components were
  - 2 km of Bi-2212 tape
  - winding, pretesting, and assembly of the 1-MVA coil set
  - coil instrumentation and sensors
  - HTS cold mass subsystem (namely, the IGC primary and secondary HTS coils, the 77-K radiation shield, support plates, and cryogenic subsystem)
  - core and tank assembly
- updated 30-MVA reference design
- completed preliminary conceptual design of a 5-MVA HTS transformer to power the WES transformer manufacturing plant

Construction and Testing of Major Components at ORNL

Bushing Subsystem

As stated in prior reports, it is desirable to use as many components from existing transformer technology as possible. A test to confirm the ability to use conventional tank and welding technology was initiated in FY 1996,

and the tests conducted in FY 1996 established this ability. A full-scale bushing was tested at ORNL to measure the thermal performance of the bushings under simulated operating conditions. The tests were designed to closely simulate the internal liquid nitrogen tank geometry. The test setup is shown in Fig. 2.1. The tests verified that the thermal and materials compatibility performance could be met with conventional bushings and tank. There was no damage to the bushing with temperatures on the terminal of 249 K and on the shield of 276 K (Fig. 2.2).

Cooling and Cold Mass Support Subsystem

ORNL had lead responsibility for design and procurement of the 80-K cold mass, liquid nitrogen, and cooling loop subsystems. The bulk of fabrication and assembly are complete on the

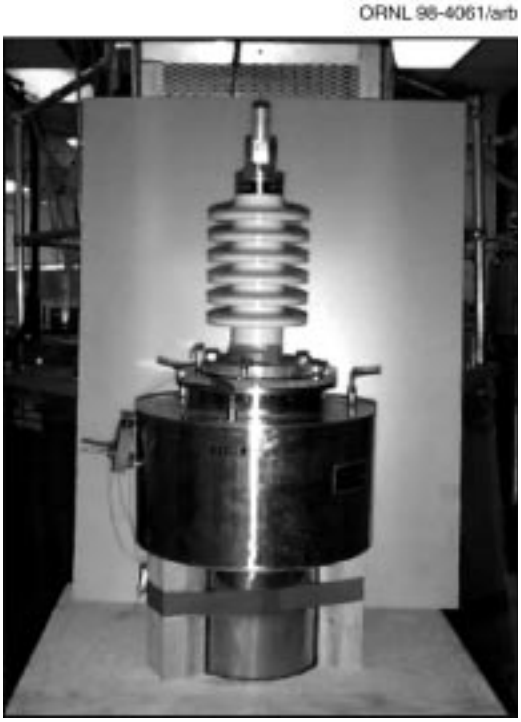

Fig. 2.1. Test setup for measuring the thermal performance of bushings under simulated operating conditions.

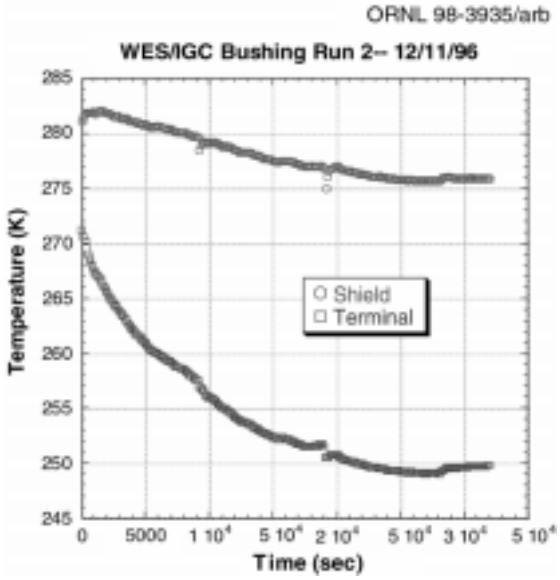

Fig. 2.2. Tests of conventional bushings show no damage to terminal at 249 K and to shield at 276 K.

cryogenic portion of the 1-MVA prototype transformer. The main tasks accomplished were

- assembly of the windings onto their upper and lower support plates,
- fabrication of all the interconnecting cooling system piping,
- checkout and repair of all winding sensors,
- design and fabrication of the liquid nitrogen tank high-current feedthrough (Fig. 2.3),
- design and procurement of the cryocooler heat exchanger, and
- design and procurement of the liquid nitrogen shield (Fig. 2.4).

The equipment was shipped to the WES plant in September. The shipment consisted of the high and low voltage superconducting winding assembly with its liquid nitrogen shield and cryogenic support legs, the turbopump and vacuum controls for the vacuum tank, and the cryocooler. The cryocooler, a Cryomech GB-37 unit, had been in storage at ORNL for several years, so its performance was tested and verified. The liquid nitrogen shield was fabricated by an outside vendor to ORNL conceptual designs and specifications and was

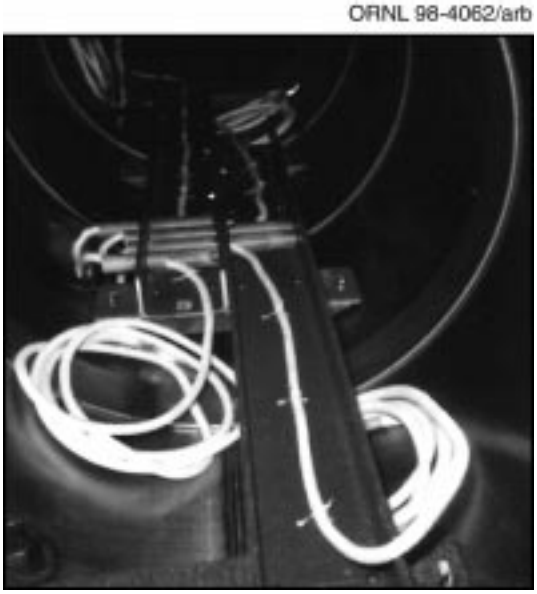

Fig. 2.3. Liquid nitrogen tank high-current feedthrough.

shipped to ORNL for fit-up to the coils. The liquid nitrogen tank was also fabricated externally and shipped directly to WES. The cryocooler heat exchanger and HTS current lead assemblies for the winding were fabricated externally and will be shipped directly to WES.

Electrical Insulation Systems in Electric Power Equipment

Solid, liquid, and vacuum will be present in all HTS equipment designs. In particular, interfaces between solid/vacuum, liquid/vacuum, and liquid/solid dielectrics under ac and impulse conditions in a cryogenic environment present several unanswered questions. To address some of these issues, ORNL has initiated activities to examine the solid/vacuum and liquid/solid interfaces under the electrical and vacuum conditions appropriate to HTS equipment.

Specifically, three stages of a five-stage (100 kV per stage) impulse generator were set up and an experimental test apparatus was completed. Also a new 150-kV ac power supply with low partial discharge sensitivity has been

Fig. 2.4. Liquid nitrogen shield.

received and will be put into service. A stainless steel vacuum chamber, equipped with a 1-ft high-voltage bushing, was returned to service for conducting surface flashover studies in vacuum. The chamber was cleaned and stainless steel electrodes were installed. The electrodes, with profiled (“Rogowski”) edges, provide a plane-plane geometry for either vacuum gap or gap plus dielectric spacer. The bottom electrode is mounted on a linear motion drive with a vacuum feedthrough, permitting an externally controlled variable electrode gap setting. With a 100 L/s turbo molecular pump installed directly onto the vacuum chamber, the system has been pumped down to a pressure of 2×10^{-7} torr, which is more than adequate for testing under conditions that would be encountered for the superconducting systems in which the solid/vacuum dielectric interface is present. Higher pressure in a variety of background

gases can be maintained via a controlled leak. Initial test of the complete system has been performed using disk-shaped spacers, 38 mm in diameter, made of G-11. Three spacer thicknesses, 1, 3, and 5 mm, were made for the initial series of impulse breakdown/flashover tests. Tests with longer spacers are planned. The need for surface flashover studies on solid/liquid nitrogen systems is being examined.

HTS UNDERGROUND CABLE PROJECT WITH SOUTHWIRE COMPANY

Introduction

This report covers only the nonproprietary ORNL contributions to the HTS Underground Cable Project with Southwire Company for FY 1997. During the fiscal year, the project made a transition in the contractual arrangement with Southwire Company from a CRADA to a superconductivity pilot center agreement. For this multiyear joint development project, Southwire will construct a 30.5-m-long, three-phase HTS cable complete with electrical and thermal insulation, outer enclosures, and cable terminations to demonstrate the feasibility of this promising electric utility application. The cable will be installed between two overhead utility towers and will supply 1.25 kA of current at 12.5 kV to the utility and building wire manufacturing plants located at Southwire Company Headquarters in Carrollton, Georgia. The cable will be tested during FY 2000 under real-use situations and will demonstrate Southwire's expertise in HTS cables and confidence that this technology can be supplied to the electric utility industry. To reach this goal, a 5-m-long single-phase HTS cable rated at 12.5 kV and 1.25 kA was designed during FY 1997 and will be tested at ORNL during FY 1998 in a laboratory environment as a proof-of-design concept.

ORNL has been working with Southwire in two broad areas: (1) providing technical expertise and analyses to assist Southwire in the design of an HTS cable and (2) performing tests of various components using unique laboratory facilities at ORNL in support of the HTS cable design. An HTS cable design process as shown in Fig. 2.5 has evolved and been defined for the 5-m and 30-m HTS cables. Progress and results by ORNL in the development of an HTS cable during FY 1997 are summarized in the following areas:

- short sample testing of HTS tapes
- prototype cables
- electrical dielectric testing
- cable termination
- refrigeration system

Short Sample Testing of HTS Tapes

A series of short sample property tests (207 in this reporting period) were performed on the

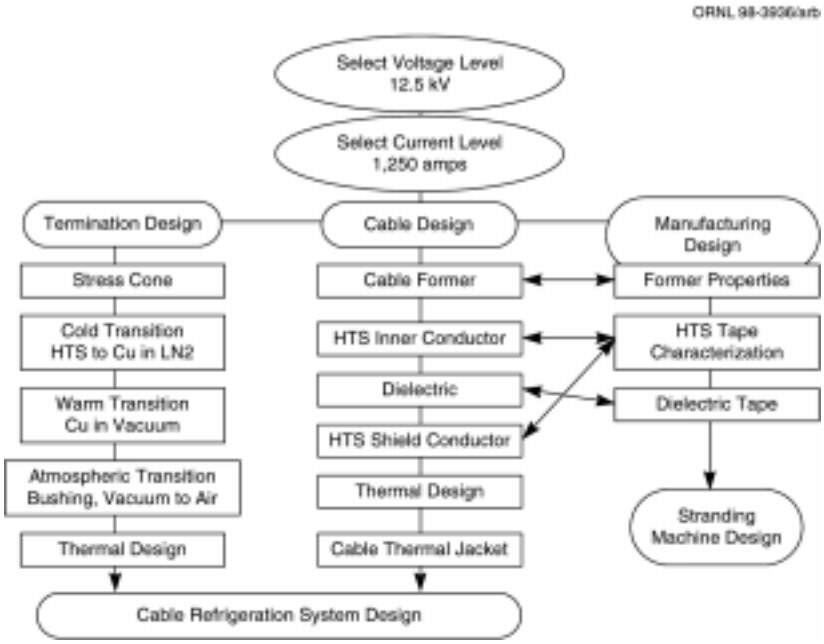

Figure 2.5. HTS cable design process.

Bi-2223/Ag HTS tapes acquired by Southwire. The critical currents (I_cs) in a background magnetic field (I_{cB}s) of HTS tapes were measured as functions of thermal cycling, strain, and applied magnetic field. I_cs were measured first on straight tapes in liquid nitrogen (LN_2). After the tapes were warmed in dry air, they were wound on a 1-in.-diameter mandrel at a pitch of 87° (worst case pitch). The tapes were quenched in LN_2 again, and then their I_cs were measured while in various magnetic fields. The samples were warmed, quenched, and measured repeatedly until four thermal cycles and measurements were completed. The average reduction in I_c in self-field (I_{c0}) between straight and wound sample measurements (first and second cycles) was 29.9%. After four cycles, the measured average reduction of I_{c0} was 41.1%. The I_{cB} drop was 15.3% for an applied field (B) of 100 gauss and 50.3% for B of 1000 gauss.

A study of I_c enhancement was performed after additional manufacturer's processing on HTS tapes acquired by Southwire. I_c measurements were made to determine the characteristics and integrity of pressed and sintered 1-ft tapes. The tapes were first measured straight in LN_2, warmed to room temperature, wound on a 1.5-in. mandrel at a pitch of 30°, then quenched into LN_2. The effect of strain and cycling reduced I_cs an average of 28.9%.

HTS tapes from three suppliers have been evaluated to determine their performance. Additional I_c measurements of these tapes were made after they were reprocessed with additional heat treatment steps both with and without pressing. I_cs were measured straight and then curled at a pitch of 85.5° on a 1-in.-OD mandrel for all three manufacturers' tapes. The scatter in I_c measured straight and then wound from each of the suppliers is summarized in Table 2.1.

Table 2.1. Percentage of scatter in I_c of suppliers' tapes

	Company A	Company B	Company C
Straight	34.0	2.1	15.1
Wound	19.6	23.4	34.7

I_cs of these suppliers' tapes were compared with additional heat treatment steps both with and without pressing. In all cases, the additional O_2 heat treatment increased the I_cs of the tapes.

Ranges of HTS strain tolerances, measured as a function of I_c, with varying tape pitches on different mandrel diameters have been evaluated. The effect on I_c from strain developed while winding tapes on different mandrel diameters from 0.50 in. to 1.50 in. was studied. Tape pitches used were 15° and 30°. The larger diameter mandrels had low losses in I_c from strain on HTSC tapes. I_c winding angle dependance was measured for two sets of suppliers' tapes. The tapes were wound on a 1-in.-OD thin-walled stainless-steel mandrel at pitches of 15°, 30°, 45°, 60°, 75°, and 90° with respect to the mandrel's long axis. Table 2.2 summarizes the percentages of the specification currents.

Effects of cladding for handling, thermal cycling, strain, and shelf life have been explored. I_cs were measured first for straight samples and then for tapes wound on a 1.5-in.-OD mandrel at a 30° angle from the long axis in LN_2. There was a 2.6% increase in the mean I_cs after cycling and winding on the

Table 2.2. Percentages of vendor-specified (pitch=0) critical currents for suppliers' tapes

	Pitch (degrees)					
Supplier	15	30	45	60	75	90
Supplier A	113.9	82.5	80.8	63.7	72.1	36.8
Supplier B	95.0	74.4	64.4	65.5	67.8	64.3

mandrel. The cladding enabled the tapes to be handled without damage. Thermal cycling showed no obvious problems.

Prototype Cables

The testing of 1-m-long, hand-wrapped prototype cables continued in FY 1997.

- All cables contain pairs of oppositely wound HTS tapes with variations in construction techniques.
- Cable 3 was constructed in FY 1996 and tested in FY 1997.
- Cables 4 and 5 were constructed and tested in FY 1997.
- Cables 6, 7, and 8 were constructed; their dc characteristics were measured in FY 1997.

Prototype Cable Descriptions

The prototype cables are approximately 1-m long and were fabricated by helically winding Ag-sheathed Bi-2223 HTS tapes on a stainless-steel tube former. The prototype cable 3 consists of 10 layers of HTS tapes wound on a 25.4-mm-diam former with Kapton insulation separating each layer. The lay angle for the tapes was 15° in all the layers. In cable 4, the number of layers went back to four (as in cables 1 and 2), but the former diameter had increased to 38.1 mm. This larger diameter former was also used for all later cables.

The prototype cable 5 consisted of four layers of tapes with a lay angle of 30°. This larger lay angle was also used for all later cables. The inner pair of layers had no insulation between the layers, and the outer pair of layers were insulated by Kapton with the individual tapes separated by a thread. This prototype had voltage taps that enabled the voltage across the inner and outer pairs of layers to be measured.

The prototype cables 6 and 7 were made of HTS tapes purchased from a different manufacturer. Cable 6 has two layers of tapes and cable 7 has four layers. The prototype cable 8 was made of a new batch of HTS tapes made by the same manufacturer that made the tapes for the first five cables.

Experimental Apparatus and Procedure

A 3-kA dc power supply and a 2-kA ac power supply were used to energize the cables. The voltages from the shunts and voltage taps placed on the prototypes were read using a Keithly 2001 digital multimeter. Data were collected with a Labview 2.2 data acquisition software running on a Macintosh IIfx computer.

For prototype 5, the inner and outer pair of layers of HTS tapes were soldered to separate Cu end plugs at each end of the sample that were electrically insulated from each other. Clamps from the power supply cables could be attached to either or both end plugs of this cable. The main shunt was used to measure the total current supplied to the cable, and two additional shunts were used to measure the currents in the inner and the outer pair.

All measurements were made in a LN_2 bath formed by a styrofoam block. Because of the thermal isolation required for ac loss measurements, the prototype cables were enclosed in a micarta or G-10 cylinder filled with wax. Figure 2.6 shows the cable setup for both dc and ac measurements.

DC Measurements

The dc characteristics were measured for all prototype cables made in FY 1997. All I-V curves show a gradual voltage increase after a certain current, indicative of the broad resistive transition feature of the HTS tapes. The dc I_c for each cable was obtained using the 1-mV/cm criterion. Table 2.3 summarizes the measured critical currents on the various 1-m prototype cables (including the two cables tested in FY 1996).

The first four cables indicated that the cables made from the first batch of HTS tapes have an average I_c per tape of 8.6 A in the cable form. The variation in the construction

Fig. 2.6. Prototype cable setup for both dc and ac measurements.

parameters did not make much difference. The HTS used for cable 5 was re-treated by a third party before winding into the cable. This resulted in about a 34% increase in I_c per tape in the cable form. The 15.4 A I_c per tape measured on cable 8 indicated a 79% increase for the second batch tapes as compared to the first batch made by the same manufacturer. As was noted before, prototype cables 6 and 7 were made of HTS tapes purchased from a different manufacturer. This HTS tape has an oxide powder coating on the surface. Rough handling of the tapes to remove the coating for cable 6 may be the reason for the much lower I_c per tape obtained in this cable as compared with cable 7.

Current Distribution Measurements on Prototype 5

For prototype cable 5, the measurements were conducted for the conditions where the inner pair, the outer pair, and both pairs of layers were energized. The dc current voltage characteristics for prototype 5 are presented in Figs. 2.7 and 2.8 for the two pairs of layers. For the inner pair, there is a significant change in the characteristics when both pairs of layers carry current. The I_c drops from around 1000 A when the inner layers alone carry current to around 700 A when both the inner and outer layers carry current. This is attributed to magnetic field effects generated by the outer pair.

The voltage measurements in Fig. 2.8 were for three different HTS tapes in the outer layer. The connected data are for current applied only to the outer pair of tapes. The unconnected data

Table 2.3. Prototype cable construction parameters and measured I_c

Cable number	Number layers	Number tapes	Lay angle (°)	Former diam. (mm)	dc I_c (A)	I_c per tape (A)
1	4	73	15	22.0	670	9.2
2	4	67	15	22.0	560	8.4
3	10	200	15	25.4	1630	8.2
4	4	112	15	38.1	975	8.7
5	2 + 2	96	30	38.1	1100	11.5
6	2	51	30	38.1	365	7.2
7	4	108	30	38.1	1520	14.1
8	4	104	30	38.1	1605	15.4

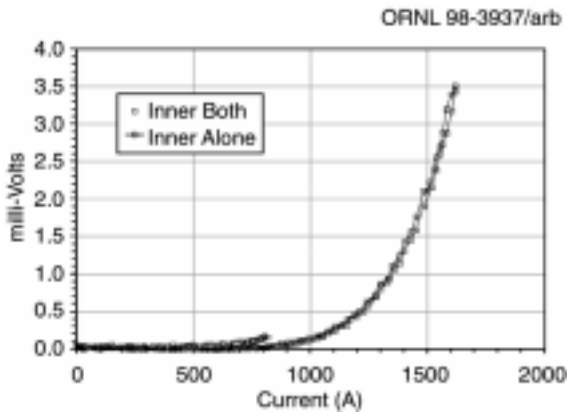

Fig. 2.7. Current voltage characteristics of the inner pair of prototype 5.

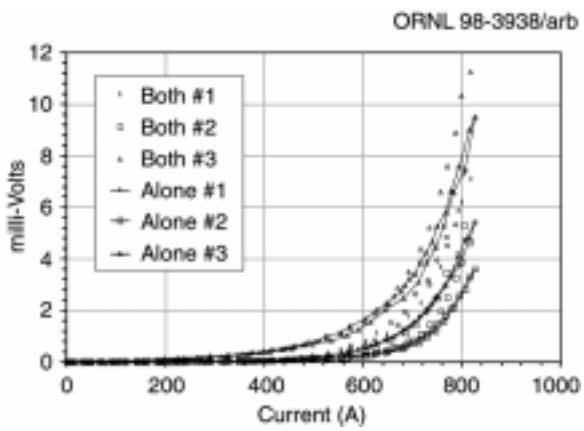

Fig. 2.8. Current voltage characteristics for three voltage taps on the outer pair of prototype 5.

are for both pairs of tapes carrying current. No significant voltage difference was observed between these cases. The different voltages between tapes are caused by variations in the tape characteristics and possible unequal currents in the tapes caused by the different joint contact resistance between the HTS tapes and the copper end plugs.

Current distribution of the inner vs outer pair of this cable was measured with ac as well as dc currents. The results are shown in Fig. 2.9 for both of these conditions. Because the trend did not change with the magnitude of currents, only data of higher dc currents and lower ac currents were shown in this graph. Under dc currents, the ratio of the current flowing through

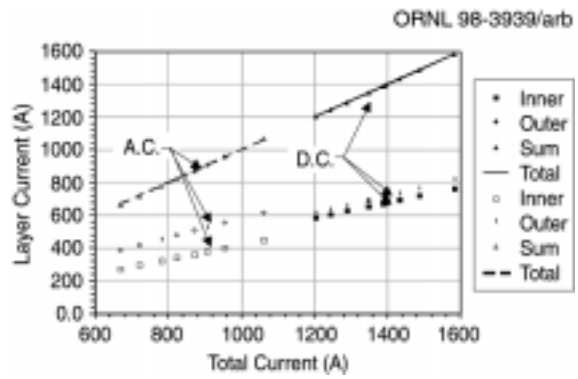

Fig. 2.9. Current distribution in HTS transmission cable prototype 5 under ac and dc conditions.

the outer pair to that flowing through the inner pair should depend only on the series resistance of each loop. Because the measured ratio is close to one (1.04), the series resistance was almost the same for each of the pair.

Under ac conditions, the inductive reactance could be important in determining the current distributions. Figure 2.9 shows that the outer layers carry a higher portion of the current under ac. The ratio of the current flowing through the outer pair to that flowing through the inner pair had increased to 1.38. This ratio is also found to be constant over the range of currents tested. Thus the inductances of the different layers of the cable play a significant role in determining the current distribution. Note that the present test setup included extra lead length and thus extra series resistance for the different pairs of the cable. Without this, the inductive effect could be even bigger.

AC Loss Measurements

A calorimetric technique was used to measure the ac losses in the prototype cables. The cable was enclosed in a micarta or G-10 tube filled with wax to provide a thermal barrier to the surrounding LN_2.The radial temperature difference of the cable resulting from ac currents was measured relative to the LN_2 bath. The calibration of the cable temperature rise to the power dissipated was accomplished by

passing dc currents through the cable at values higher than the I_c. This produces a resistive heating in the sample that results in a temperature rise, and the heating power can be determined from the measured current and voltage.

Figure 2.10 summarizes the ac loss data for cables 3, 4, and 5. Cable 3 had the highest ac loss at all measured currents. Possible causes for this higher than expected loss are (1) the larger number of layers (ten) of this cable than the other cables or (2) the current connection of this cable was made in a way that the current was introduced to the outermost layer of the cable, which aggravates the uneven current distribution.

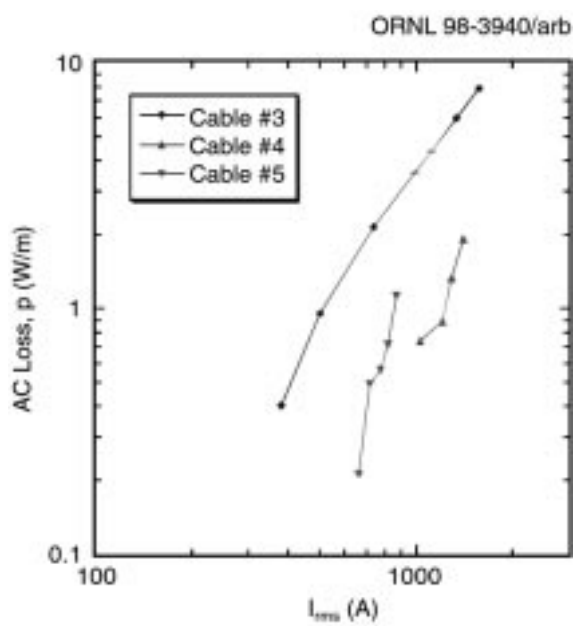

Fig. 2.10. Data on ac loss for cables 3, 4, and 5 as a function of the root mean square current.

To compare the ac loss data with a theory developed by Dresner, we plotted in Fig. 2.11 the loss data together with the theoretical prediction for the three different cables as a function of the peak ac current to the critical current ratio, I_p/I_c. In this theory, Dresner treated the cable as a cylindrical annulus. He also took into account the broad resistive transition of the HTS tapes such that the cable can be operated

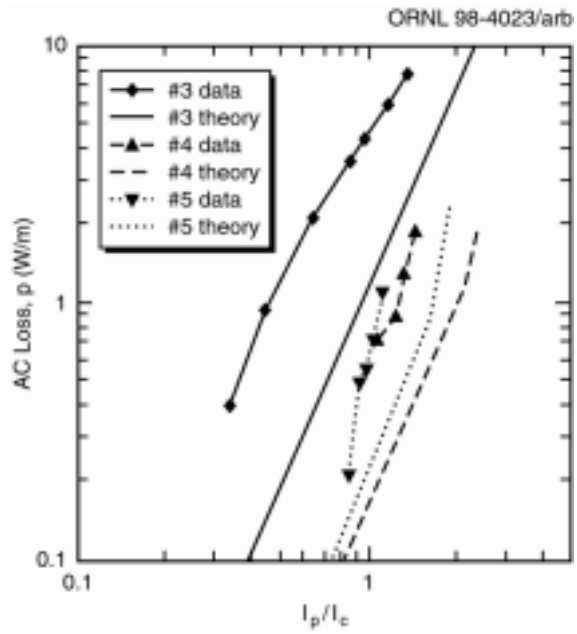

Fig. 2.11. Comparison of the ac loss data with a theory by Dresner.

beyond its I_c as was actually done in the experiments. In this plot it is seen that cables 4 and 5 had about the same ac loss for the same I_p/I_cs. These two sets of data had fair agreement with the theory. No adjustable parameter was used in the theoretical calculation. Cable 3 had a loss rate much higher than the theory for the possible reasons mentioned in the previous paragraph.

Prototype Cable Summary and Conclusions

Five additional prototype HTS transmission cables were constructed and tested in FY 1997. I_c measurements of the cables indicated that the cables made from the first batch of HTS tapes had an average I_c per tape of 8.6 A in the cable form. The variation in the construction parameters did not make much difference. A cable made with retreated tapes resulted in about a 34% increase in I_c per tape in the cable form. The 15.4 A I_c per tape measured on cable 8 indicated a 79% increase for the second batch

tapes compared with the first batch made by the same manufacturer.

Current distribution of the inner vs outer pair of prototype cable 5 was measured with ac as well as dc currents. The ratio of the current flowing through the outer pair to that flowing through the inner pair had increased from 1.04 under dc to 1.38 under ac. The inductances of the different layers of the cable play a significant role in determining the current distribution even in these short (1-m-long) cables. The inductive effect causes higher fractions of ac currents to flow in the outer layers.

The ac loss measurements of the prototype cables showed fair agreement with a theory developed by Dresner based on a cylindrical annulus model. Cables that consist of the same number of layers seem to have about the same loss at the same I_p/I_cs, in spite of the construction parameter differences.

Electrical Dielectric Testing

The ORNL Dielectrics Group is testing Cryoflex and other (either alternative or reference) materials for their breakdown strengths at ac and impulse voltage stresses. Two test apparatuses have been designed and constructed. One is an apparatus for testing tape samples, typically 1-in. wide in LN_2 at 1 atm pressure. The second apparatus is designed for testing sheet samples in LN_2 at pressures up to 15 atm. The tape tester design is based on IEC standard 243, which describes a method for high voltage (HV) testing of thin tapes and films. The ORNL design as shown in Fig. 2.12 permits testing of these tapes in LN_2 and possibly under tension. Because breakdown measurements are destructive to the material, the tape tester has five sets of electrodes, permitting the measurement of five breakdowns on a single sample.

The sheet testing apparatus utilizes a stainless steel chamber that can be pressurized to 15 atm. A novel dewar was designed and built, allowing HV breakdown experiments in

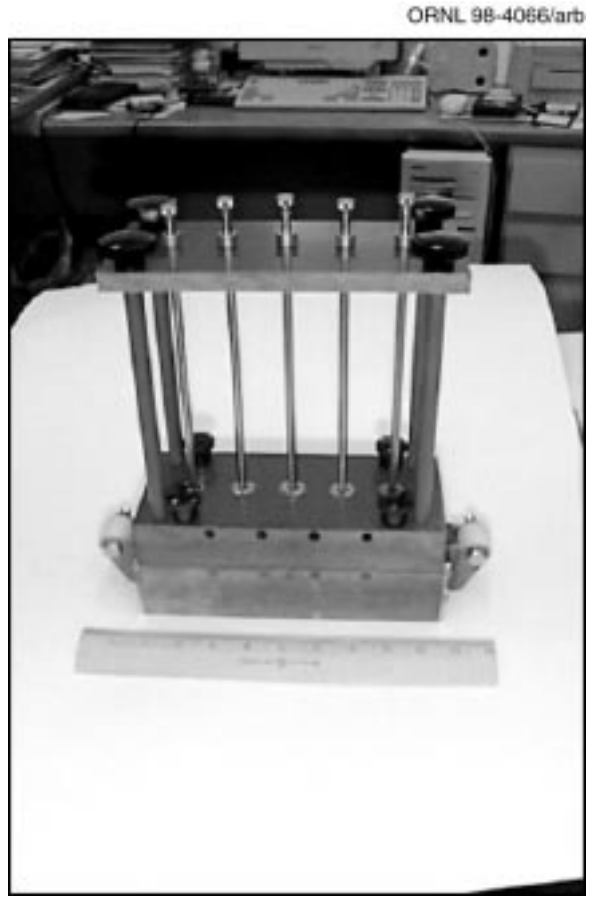

Fig. 2.12. Tape testing apparatus.

LN_2 at high pressure. The design of the dewar is unique in that it avoids the complexity, fabrication time, and cost of a more conventional double- or triple-walled chamber design and is shown in Fig. 2.13.

Much of the effort during this reporting period has been in the design and construction of the testing facilities and in the acquisition and set up of the HV supplies. The supplies includes two HV ac power supplies (100 kV manually controlled, made by American HV Test Systems, and a 150 kV, low noise, 3 pC, with Allen-Bradley programmable logic control, made by Phoenix Technologies) and a Haefely-Trench 500-kV impulse generator. The impulse generator was made operational at 300 kV with voltage rise/fall times of 1.2/50 ms and is shown in Fig. 2.14.

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Fig. 2.13. Sheet testing apparatus utilizes a stainless steel chamber.

ORNL 98-4247/arb

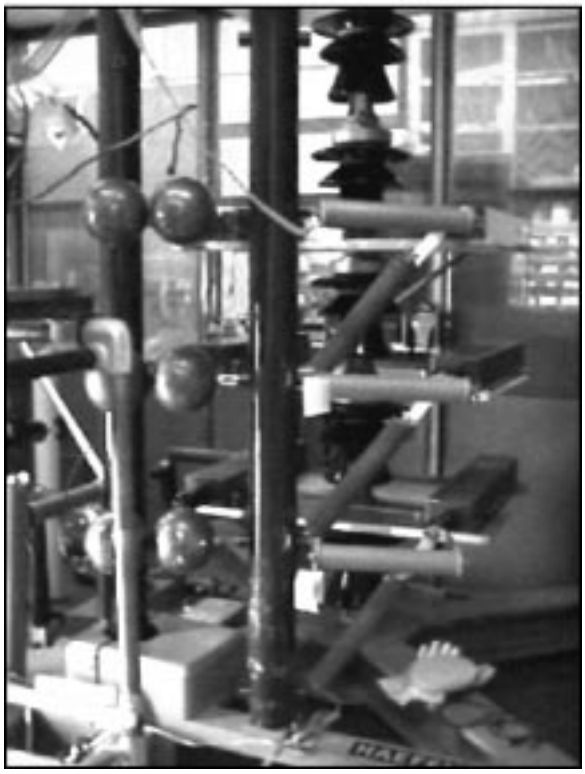

Fig. 2.14. Haefely-Trench 500-kV impulse generator.

Preliminary Measurements

Preliminary measurements of tape and sheets have been made to assess the operation of the equipment and to identify problems. Measurements have been made in air, LN_2 at 1 atm, and one single measurement in LN_2 at 4 atm. Whereas the primary focus of these studies is the material Cryoflex, other materials have been examined. During the next reporting period, we will obtain systematic impulse breakdown measurements where withstand data (i.e., voltages that the material can withstand without breakdown) are taken at increasing voltages until breakdown occurs (generally resulting in puncture of the material). Planned experiments include measurements on multiple layers of dielectric sheet samples that contain one or more holes to simulate butt gaps, corresponding to the spaces between tape layers in actual cable.

Whereas the data are too preliminary to report breakdown strengths, certain observations have been made. These include partial discharge, surface charging, and puncture. Generally, partial discharge and surface charging observed in air are suppressed in LN_2, particularly for Cryoflex. For tapes at atmospheric pressure, both Cryoflex and one of the other dielectric materials studied showed only marginal (if any) improvement in dielectric strength in LN_2 over that in air. At a pressure of 4 atm in LN_2, however, a significantly higher puncture voltage (impulse) was recorded than at 1 atm. Whereas actual breakdown strength data require systematic withstand tests, it appears that higher LN_2 pressures can be effective in improving the hold off strength of the material.

This is probably the result of the suppression of bubble formation in the liquid.

In preliminary tests on two sheets of Cryoflex in LN_2 at 1 atm, we were able to observe two withstand impulses at around 32 kV and a puncture breakdown at about 47 kV, indicating that the impulse strength is somewhere between these two values; however, none of the values given here can be used for design purposes until systematic experiments can be performed and replicated.

Model Cable Tests

Model cable tests are planned during the next fiscal year. Design and planning have commenced, including the acquisition of space to set up a new high-bay HV laboratory, to accommodate a 12.5-ft (including bushing) HV high-pressure dewar.

Cable Termination

The cable termination provides the transition from the HTS conductor at LN_2 temperatures to copper wire at room temperatures. During FY 1997, the design for a 12.5-kV and 1.25-kA HTS cable termination was completed. During the 9-month engineering design, the electrical, mechanical, and thermal properties of components and subsystems of the termination were analyzed by Southwire and ORNL. Approximately 700 h of computer-aided design produced 22 drawings detailing the cable termination design. Purchase orders were placed for the first two cable terminations. Eleven purchase orders to eight different vendors were issued by Southwire. The first two cable terminations will be tested as part of the 5-m cable test during FY 1998. Four additional cable terminations will be built for the 30-m cable facility during FY 1998 and FY 1999.

Refrigeration System

A cryogenic refrigeration system is required to supply a steady flow of LN_2 at specified temperatures and pressures that are within the operating ranges of the HTS cable. A cryogenic refrigeration system design has been completed and contains the following components: (1) main LN_2 supply tank, (2) LN_2 supply vacuum jacketed transfer line, (3) surge tank, (4) LN_2 pump, (5) LN_2 subcooler assembly, and (6) subcooler vacuum pumping system. A schematic of the system is provided in Fig. 2.15.

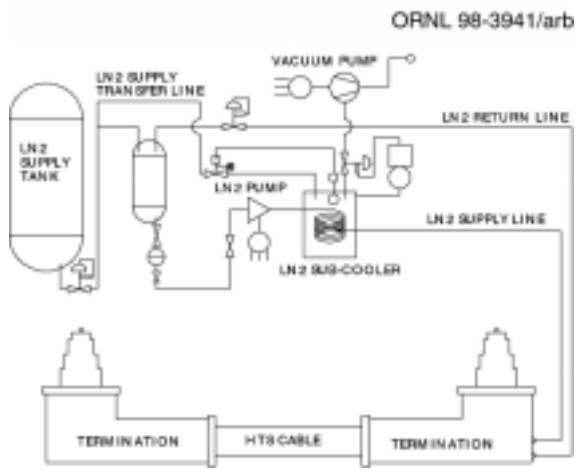

Fig. 2.15. HTS cable cryogenic system.

A skid-mounted cryogenic system that contains the surge tank, pump, subcooler assembly, and vacuum system is being fabricated by Air Products and Chemicals Company, Allentown, Pennsylvania. The LN_2 supply vacuum jacketed transfer line from the main supply tank to the HTS Cable Test Facility already exists at ORNL.

The cryogenic system has been designed to accommodate the different operating states that will exist during operation and testing of the cable. These are defined in the following descriptions:

- Warm—The state when the HTS transmission line is purged and at room temperature conditions.
- Cool-down—The state when the system is configured to gradually bring the HTS cable to operating temperature.

- Standby—The state when the HTS transmission cable is accepting LN_2 but the temperatures are too high to permit energizing the cable.
- Normal—The state when the HTS transmission cable is cold (i.e., the temperature everywhere along the cable is below the HTS transition temperature) and is ready to be energized.
- Warm-up—The state when the system is configured to allow the HTS transmission cable to warm up to room temperature.

FY 1997 Summary for HTS Underground Cable Project

Significant progress was made during FY 1997 in all aspects of the HTS cable design and component testing. These designs will be tested in FY 1998 with the construction of the 5-m HTS cable test facility.

- **Short Sample Testing of HTS Tapes**—On the basis of a series of short sample property tests (207 in this reporting period) on Bi-2223/Ag HTS tapes acquired by Southwire, the I_cs were found to be reduced as a result of thermal cycling, strain, and applied magnetic field. These effects can reduce the I_c by up to 50%. On the basis of measurements of HTS tapes from three manufacturers, differences were found in the I_cs without strain and with strain. Additionally, the variability of samples from individual manufacturers was also found.

- **Prototype Cables**—Five additional prototype HTS transmission cables were constructed and tested in FY 1997. I_c measurements of the cables indicated that the cables made from the first batch of HTS tapes had an average I_c per tape of 8.6 A in the cable form. A cable made of the second batch of tapes indicated a 79% increase in I_c per tape. Current distribution measurements indicated that the inductances of the different layers of the cable play a significant role in determining the current distribution even in these short (1-m-long) cables. The inductive effect causes higher fractions of ac currents to flow in the outer layers. The ac loss measurements of the prototype cables showed fair agreement with a theory developed by Dresner based on a cylindrical annulus model.

- **Electrical Dielectric Testing**—Two test apparatuses have been designed and constructed to test breakdown strengths at ac and impulse voltage stresses of Cryoflex. One is an apparatus for testing tape samples, typically 1-in.-wide in LN_2 at 1 atm pressure. The second apparatus is designed for testing sheet samples in liquid at pressures up to 15 atm. Much of the effort during this reporting period has been in the design and construction of the testing facilities and in the acquisition and setup of the HV supplies.

  Preliminary measurements of tape and sheets have been made to assess the operation of the equipment and to identify problems. Measurements have been made in air, LN_2 at 1 atm, and one single measurement in liquid at 4 atm. In preliminary tests on two sheets of Cryoflex in LN_2 at 1 atm, we were able to observe two withstand impulses at around 32 kV and a puncture breakdown at about 47 kV, indicating that the impulse strength is somewhere between these two values; however, none of the values given here can be used for design purposes until systematic experiments can be performed and replicated.

- **Cable Termination**—The design for a 12.5 kV and 1.25 kA HTS cable termination was completed. Purchase orders were placed for the first two cable terminations, which will be built and tested in FY 1998.

- **Refrigeration System**—A cryogenic system has been designed to accommodate the different operating states that will exist during operation and testing of the cable. The following five operating states have been defined: warm, cool-down, standby, normal, and warm-up.