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CR-03-0683

Fusion Energy Division

**CRADA Final Report
for
CRADA Number 03-0683 with SuperPower, Inc.**

**Superconductivity Partnerships with Industry Project with SuperPower, Inc.
Design, Fabrication and Testing of a Superconducting Fault Current Limiter
(SFCL)**

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Purpose and Background

The purpose of this project was to conduct R&D on specified components and provide technical design support to a SuperPower team developing a high temperature superconducting Fault Current Limiter (SFCL). ORNL teamed with SuperPower, Inc. on a Superconductivity Partnerships with Industry (SPI) proposal for the SFCL that was submitted to DOE and approved in FY 2003. A contract between DOE and SuperPower, Inc. was signed on July 14, 2003 to design, fabricate and test the SFCL. This device employs high temperature superconducting (HTS) elements and SuperPower's proprietary technology. The program goal was to demonstrate a device that will address a broad range of the utility applications and meet utility industry requirements. This DOE-sponsored Superconductivity Partnership with Industry project would positively impact electric power transmission reliability and security by introducing a new element in the grid that can significantly mitigate fault currents and provide lower cost solutions for grid protection.

Scope of Work

The project will conduct R&D on specified components and provide technical design support to a SuperPower-led team developing a SFCL as detailed in tasks 1-5 below. Note the SuperPower scope over the broad SPI project is much larger than that shown below which indicates only the SuperPower tasks that are complementary to the ORNL tasks.

SuperPower is the Project Manager for the SFCL program, and is responsible for completion of the project on schedule and budget. The scope of work for ORNL is to provide R&D support for the SFCL in the following four broad areas:

- Assist with high voltage subsystem R&D, design, fabrication and testing including characterization of the general dielectric performance of LN2 and component materials.
- Consult on cryogenic subsystem R&D, design, fabrication and testing.
- Participate in project conceptual and detailed design reviews.
- Guide commercialization by participation on the Technical Advisory Board (TAB).

SuperPower's in-kind work for the SFCL will be provided in the following areas:

- Work with ORNL to develop suitable test platforms for the evaluation of subsystems and components.
- Provide cryogenic and high voltage subsystem designs for evaluation.
- Lead the development of the test plans associated with the subsystem and components and participate in test programs at ORNL.
- Based on the test results, finalize the subsystem and component designs and incorporate into the respective SFCL prototypes.

FY-2003 R&D Progress

During the past year, SuperPower, Inc. has developed a new concept for a matrix fault current limiter (MFCL). This consists of an array of HTS elements that are arranged to simultaneously

go normal in a fault. The fault current is shunted to a parallel array of normal reactive elements that effectively limits the maximum current in the fault and allows downstream breakers to open. After the fault clears and the breakers re-close, the HTSC elements quickly return to the superconducting state and restore normal operation. SuperPower's concept is aimed at transmission-level voltages of 138 kV or more, and offers good prospects for successfully achieving these voltages. ORNL participated in a Technical Review Committee (TRC) meeting in June, 2002. The participants at this meeting determined that the basic concept employed in the MFCL is sound. SuperPower then formed a Technical Advisory Board (TAB) and held the first meeting in January, 2003. The purpose of the TAB is broader than the TRC, and will meet regularly during the project to offer guidance to make sure the program objectives are met. The first TAB meeting was well-attended by representatives from DOE and a mixture of industrial companies, utilities, national laboratories, and universities. The reports of the TAB have been favorable, with no major technical deficiencies identified. SuperPower has requested that ORNL be included as a national laboratory partner on the SPI. A draft statement of work has been developed and agreed to by both parties. Proposed tasks would include:

- Support in design and fabrication of components for the MFCL cryostat.
- Modify an existing, sub-cooled, pressurized liquid nitrogen cryostat system at ORNL to design and conduct tests to verify the MFCL cooling concept.
- Prepare a cryostat system that will be used to design and perform larger-scale cryogenic or combined HV/cryogenic tests on MFCL components (HV current leads, HTS modules, etc.), during the course of the MFCL prototype development.
- Support development for assembling and testing of MFCL cryogenic subsystems.
- Participate and assist with qualification tests for all prototypes, including beta-prototype final acceptance tests.

ORNL participated (with several other scientists/engineers from national laboratories, utilities, industry and universities) in a 1-day technical advisory committee meeting and a 2-day conceptual design review of the HTS Matrix Fault Current Limiter project at SuperPower, Inc. on June 10-12. A detailed list of reviewer comments (chits) was assembled by SuperPower that will be tracked through focused development plans and subsequent design reviews.

A conceptual design was completed to modify an existing high-pressure nitrogen cryostat for the cooling concept tests. Figure 1 shows a cross-section of the modified cryostat. A vacuum-insulated cold finger projects down into the pressure vessel. A 10-cm-high copper cooling skirt attached to this cold finger simulates the cooling skirt that will be attached to the cryocooler in the actual device. Cooling for the 3-5-atm nitrogen in the pressure vessel is provided by liquid nitrogen boiling in the cold finger. A heat source will be energized below the cooling skirt, and temperatures will be measured in several locations in the pressure vessel. Because the surface area available for boiling heat transfer is limited in this design, another version using forced-flow nitrogen in cooling tubes wrapped around the skirt is also being investigated. The cryostat is also provided with another port to allow installation of high-voltage lead bushing assemblies.

Fig. 1. Cross-section of pressurized nitrogen cryostat.

FY-2004 R&D Progress

A cryogenic cooling test cryostat was described above. While this is being designed and built, preliminary cooling tests are being performed using an existing cryostat, shown in Figure 2. Liquid nitrogen at 77 K is circulated through the coil of copper tubing at the lower end, which is immersed in pressurized supercritical nitrogen. This coil simulates the cooling ring that is attached to the cryocooler in Superpower's design. The foam discs above the coil simulate the vacuum above the pressurized tank that would surround the MFCL array. A disc heater mounted below the coil simulates the array heat load. Two temperature sensors are mounted above and below the G-10 plate that is on top of the coil. Initial tests at 3 atm and 5 atm supercritical nitrogen pressure indicate that the lower sensor (which is closer to the heater) stays about 2 K warmer than the one above the plate for power inputs up to 300 W. Good temperature stability was obtained.

Fig. 2. Existing cryostat for preliminary MFCL cooling tests.

Next the temperature was measured at various locations for different heater power levels. The basic setup was modified to increase the temperature sensors from 2 to 12. The G-10 plate that was just above the cooling coil in the earlier experiment was also replaced with a copper plate. The results (Fig. 3) show that the temperature profiles are relatively independent of heater power. Because the cryostat has no high-current bushing to provide a heat load, the liquid level tends to rise within 20 cm of the top plate, as can be seen by the sharp temperature increase that occurs at this location in Figure 3. Below the liquid level, there was very little temperature difference between the two radial sensor locations.

Fig. 3. Temperature profiles at various locations.

Design of a new top flange to be fitted with a 50 kV high voltage bushing was completed and the flange was fabricated at a local machine shop. Dielectric testing in support of the MCFL SPI program commenced in August 2004. Technical staff from SuperPower came to ORNL on August 9-13 for safety training and indoctrination, badging and initial high voltage experiments on candidate MFCL dielectric materials. Testing continued during a second round of experiments on September 13-23. Extensive high-voltage testing was carried out on a prototype 52-kV, 250-kV BIL high-voltage bushing/lead assembly for the MFCL. Breakdown tests were also carried out in liquid nitrogen (LN) using various electrode geometries relevant to the MFCL design. During the first series of tests on the bushing/lead assembly (see Figure 4), negative impulse tests resulted in breakdowns in the range of 63 kV to 80 kV in 3-atm, 300-K nitrogen gas and 2.2-atm, 77-K nitrogen gas. Tracking was found on a Teflon sleeve around the high-voltage lead. After increasing the thickness and length of this sleeve, no further tracking was observed at these voltages. Another large series of ac and impulse breakdown tests was carried out in an open bath of LN using sphere-plane and coaxial electrode sets.

Fig. 4. Assembly of 52-kV bushing into high-pressure cryostat.

FY-2005 R&D Progress

1. Technical Advisory Board Meetings

ORNL personnel participated as a member of the MFCL Technical Advisory Board (TAB) at the program review meeting held at SuperPower's plant on November 17, 2004. At this meeting, SuperPower summarized successful proof-of-concept tests on the Pre-Prototype MFCL unit at KEMA. Other reports summarized progress on design of the 138-kV Alpha unit, improvements

by manufacturer Nexans to the HTS elements, and high voltage insulation test results. Utility participant AEP summarized studies on specification and application of the commercial Beta unit in their system. Another TAB meeting was conducted at SuperPower, Inc. on June 28, 2005 in conjunction with a DOE Readiness Review. Discussion focused on reliability/lifetime issues of the bulk BSCCO matrix elements and high voltage R&D and design. There were increasing concerns in these areas, as well as the slower pace of development with the high voltage design effort and the significantly higher cost anticipated to complete the program. Consequently, the MFCL program has been placed in a “reduced effort” status by SuperPower, with a final decision on the future direction for the program to be made in 2006.

2. High Voltage R&D

Experiments were conducted to systematically determine the AC breakdown voltage and the flashover length of fiberglass reinforced plastic (FRP or G-10) for sphere-plane and rod-plane geometry in liquid nitrogen (LN). Tests were performed at different gap spacings and creepage lengths, providing data that will be used for scaling up to higher voltages. Dr. Kasegn Tekletsadik of SuperPower, Inc. visited the ORNL high voltage labs in March 2005 to perform measurements in collaboration with ORNL staff. Measurements were made in liquid nitrogen at 1 atm pressure in an open bath. The sphere diameter for the LN gaps were 0.5, 1, 1.5 and 2 inches with gaps from 1/16 to 5 inches. Also studied was surface flashover of FRP (G-10) for sphere- and rod-to-plate on the surface immersed in LN. Flashover lengths were varied from 1 to 13 inches. The rod is a 2 inch diameter cylinder with end squared off and sharp edge. Surface flashover along the inside of a G-10 cylinder with sphere and rod were also performed. These non-uniform field geometries were used to simulate practical configurations and obtain design data for real systems. The 1 atm pressure represents a worst case condition where bubbles may form and reduce breakdown strength. In an actual system, the pressure will be higher which improves breakdown strength up to about 3 bar. Also open bath allows many measurements to be made in a relatively short time for many different conditions which would not be possible if a pressurized dewar was used. The preliminary conclusion from this recent work is that for both LN gaps and surface flashover, the breakdown voltage does not increase significantly beyond a certain gap – i.e. there is a saturation effect with gap. We believe this is due to the fact that for a highly non-uniform electric field at large gaps, the electric field at or near the electrode surface does not decrease significantly as a function of gap. This has been calculated using electric field code software. This may imply that a critical field strength exists at the electrode such that when this value is exceeded, the discharge will initiate and self-propagate across the gap much like lightning does in the atmosphere. The data is being analyzed to see if this supposition is valid. If so, then we may have a basis for a design rule under certain conditions which will allow scaling up to higher voltages – namely the electric field would have to be kept below this critical field which can be calculated for specific designs (radii of conductors, gaps, etc.).

Figure 5 shows tracking observed on surface flashover of the G-10 plate from the high voltage rod to the ground plate. The tracks occur from multiple breakdowns at different gaps. The tracks are similar to lightning discharges that occur in air and appear to be self-propagating. Figure 6 shows the test rig for surface flashover inside a G-10 tube to the ground plate. There are two G-10 alignment plates with holes to set the flashover gap for the plane G-10 flashover studies. The spacer at the bottom allows LN2 to enter the inside of the tube. Figure 7 show tracking along the

G-10 spacer plate. These tracks occurred between the high voltage lead and ground external to the actual test gap and show the treeing self-propagating nature of the discharge as it seeks a path to ground. These occur when the test gap in LN is very large. Some tracks are 12 inches or more in length and occurred at around 180 to 200 kV_{rms}.

Fig. 5. Tracking observed on G-10 plate from high voltage rod to ground plate.

Fig. 6. Test rig for surface flashover inside G-10 tube to ground plate.

Fig. 7. Close up of the tree showing the statistical nature of the discharge as it propagates.

Experiments continued on the ac and impulse breakdown voltages for liquid nitrogen gaps in rod to plane non-uniform electric field. The purpose of this work is to establish baseline data and design guidelines for leads and bushings for the MFCL. Previous data focused on the effect of varying the gap in the rod-plane geometry. Here the focus was on the effect of varying the pressure of liquid nitrogen with a fixed gap. Pressure is an important parameter since it relates to the effect of bubble formation in the liquid. Higher pressures generally increase the breakdown strength which is in part due to suppression of bubbles or reduction in size of the bubbles. Figure 8 shows the effect of increasing pressure on the ac 60 Hz breakdown voltage. Consistent with other data in the literature, the breakdown voltage increases with pressure to about 3 atm and then somewhat flattens out. From a design point of view this means that increasing the pressure beyond 3 atm will not substantially increase the breakdown voltage and other design features such as gap and triple junction must be optimized to achieve desired voltage levels.

Fig. 8 – Effect of pressure on breakdown voltage in liquid nitrogen in a non-uniform gap.

During these tests it was observed that initial filling and refilling the liquid nitrogen in the cryostat had a significant effect on the breakdown voltage. Breakdown voltages were lower following a filling cycle and increased over a period of several hours until the value stabilized. This effect may be due to bubble formation caused by turbulence from filling or introduction of gas bubbles from the initial part of the filling operation. Bubbles may also be formed by thermal loading from leads during the initial fill. However, 10 successive breakdowns at a given gap and pressure were measured to determine an average breakdown value. Of course the breakdowns themselves generate some bubbles and these may contribute to the spread in values.

Impulse voltage measurements (1.2/50 μ s) were also performed on the same rod-plane geometry for a small gap as a function of pressure. The up-and-down method was used to determine the 50% probability of breakdown (V50). In this method an impulse is made well below the expected breakdown value. If a withstand occurs, the voltage is raised one step and repeated. If a breakdown occurs, the voltage is decreased one step and repeated. In this way after a number of withstand shots, the voltage will level out to the V50 value. Both positive and negative polarities were measured from 0-44 psig. At lower pressures the negative polarity V50 was lower than the positive V50 but at higher pressures the trend reversed. This effect needs to be examined further.

3. BSCCO thermal property measurements

Heat capacity measurements were completed on a sample bulk HTS MFCL element. The melt-cast Bi-2212 sample tubes were provided by Nexans. The tubes were cast with a centrifugal process at a thickness of several mm and machined off to an OD of 2.5 cm and wall thickness of 1.6 mm. The tubes used in the actual MFCL device have copper contacts soldered to the ends, but bare tubes were used for these tests. The Bi-2212 tube length was 7.62 cm. An 80- Ω heater of 0.08-cm-diam chromel wire was spirally wound evenly over the tube surface. A 37- Ω thermometer of 0.08-cm-diam, 99.99% Pt wire was wound on between the heater turns. The spacing between individual turns on the sample was about 1 mm. Both the heater and thermometer wires were wound bifilar to reduce noise. A thin layer of Apiezon™ “N” grease was applied over the heater and thermometer wires to promote heat transfer. The mass density of the Bi-2212 material was 5.99 gm/cm³. The mass of the bare sample tube was 54.66 gm, and the heater and thermometer added 0.45 gm.

The sample tube was mounted in a small *Cryo Industries* variable temperature cryostat, which has been described in previous quarterly reports. The sample volume was a 3.81-cm-ID copper tube with a heat exchanger, silicon diode thermometer, and heater. A flow of liquid nitrogen controlled by a valve in the external transfer line cooled the heat exchanger, and the heater could be used for fine temperature control. The coolant gas did not exhaust through the sample volume. Instead, the sample was cooled to the desired temperature using exchange gas in the sample volume, and the exchange gas was pumped out to isolate the sample for measurements. Figure 9 below shows the installation of the heat capacity sample in the cryostat. The sample tube was supported on long threads for thermal isolation, and fine instrumentation wires were used to limit conduction heat loads to about 30 mW.

Fig. 9. Heat capacity sample installation

Two separate sets of data were taken, in the high-temperature range and at low temperatures. In the high-temperature range, the sample was cooled down from 300 K to 200 K with exchange gas in 20-K increments. At each temperature, the exchange gas was pumped out and several 1-min heat pulses were applied at 0.5 or 0.75 W. During a pulse the temperature rose by about 2 K. Another low-temperature set of data was taken starting at 88 K. In this case, the sample volume was kept evacuated and the sample heater was pulsed on and off to provide data at increments of about 3 K. The sample volume wall was controlled at about 2 K below the sample temperature to reduce radiation and provide a slight cooling rate when the heater was off. The heat capacity C_p was calculated from the ratio of the heat input to the difference between the temperature-vs.-time slopes when the heater was on and off. Figure 10 shows the heat capacity data for the full temperature range between 80 K and 300 K. The two sets of data approach each other in the middle temperature range. The contribution to the heat capacity by the heater and thermometer was about 1% and was not subtracted for these engineering measurements. Measurements by Junod et al. (*Physica C*, **229**, pp. 209-230, 1994) on a single-crystal Bi-2212 sample are shown for comparison. Our results are generally consistent with Junod's; the differences probably stem from the different sample morphologies and the slightly lower density of our sample (5.99 gm/cm³ vs. 6.56 gm/cm³ for Junod).

Fig. 10. Heat capacity of bulk Bi-2212 vs. temperature.

The observed heat capacity values have been fitted to the Einstein model, which gives the heat capacity as a function of the temperature T by

$$C_E = 3R \left(\frac{\Theta_E}{T} \right)^2 \left(\frac{e^{\Theta_E/T}}{(e^{\Theta_E/T} - 1)^2} \right), \quad (1)$$

where R is the gas constant, 8.3145 J/mol-K and Θ_E is the Einstein characteristic temperature. This approaches the Dulong-Petit value of $3R$ at high temperatures. Using 59.41 gm as the average gram molecular weight for the 15-atom Bi-2212 unit cell, and the observed sample density of 5.99 gm/cm³, experimental values of C_p/R are also plotted in Figure 10. These values do tend toward the limiting value of 3 predicted by Equation (1), but appear to be still rising faster than might be expected at 300 K. The line in Figure 10 shows the best fit of Equation (1) to the experimental values of C_p/R , using a value of 341 K for Θ_E . This value is comparable to reported Debye temperature values in the range of 370 K.

In order to verify that the MCP Bi-2212 melt-cast tubes can absorb the required fault energy without overheating, we have integrated our experimental heat capacity results in Figure 10 between 80 K and 220 K or 300 K. The total enthalpy change is about 210 J/cm³ from 80 K to 220 K and 390 J/cm³ from 80 K to 300 K. Thus, the total 9-cm³ volume of the sample tube could absorb 1.9 kJ in warming to 220 K and 3.5 kJ for a final temperature of 300 K. The Bi-2212 elements for the MFCL prototype would be considerably longer than the sample tube and should be able to absorb the required energy without excessive heating. However, heat generation in the elements is not completely uniform because additional heat is generated at the copper end connections. Failure of only one element in a series string of several hundred can cause increased losses, and tests at other labs have not verified the required reliability of the elements.

FY-2006 R&D Progress

No significant activity.

FY-2007 R&D Progress

Preparations are being made for high voltage qualification testing of a bushing to be used in liquid nitrogen (LN2). SuperPower is furnishing the bushing and team members from SuperPower will come to ORNL in April to conduct the tests in conjunction with ORNL staff. A schematic of the basic test set up is shown in figure 11. Tests to be done include partial discharge, AC withstand, and positive and negative lightning impulse ($1.2 \mu\text{s}$ rise/ $50 \mu\text{s}$ fall time) withstand. The impulse voltage level will be the standard BIL (Basic Impulse Insulation Level) of 650 kV for this class of bushing. To verify performance of the bushing, tests will be done in air at room temperature to establish a baseline. The tests will be done in LN2 and then repeated again in air and results compared. Electric field calculations and preliminary testing have been done to verify the type of termination and air gaps needed for the withstand tests. During this trip, high voltage tests will also be conducted on a mockup of the fault current limiting elements provided by SuperPower. These tests will also be performed in an open bath.

Fig. 11. Test set up for qualification testing of a bushing to be used in LN2.

A high voltage bushing which is planned to be used on the SuperPower HTS fault current limiter, has been tested at ORNL in both ambient air and in open bath liquid nitrogen. Tests included AC withstand, partial discharge and impulse (BIL) withstand. The bushing was furnished by SuperPower and shipped to ORNL. Previous calculations and impulse testing in air by ORNL determined the gaps and spacings needed to withstand lightning impulse voltages of 650 kV of both polarities. This is the first time this laboratory has performed testing at this voltage level. Based on this information, a non-conducting stand was designed and built of wood to hold the bushing in a vertical orientation which allowed a 60 inch (1.52 m) sphere to earthed-plane gap to be set. A lifting beam was purchased which allowed the bushing to be hoisted with a large 50 cm corona ring on the top lead. For the lower termination in air, two 22 inch (55.9 cm) diameter aluminum hemispheres were obtained and welded to form a sphere (Figure 12). The stand was also designed with a lower position which allowed the bottom part of the bushing to be immersed in an open bath of LN2. In this case a 6 inch (152.4 mm) diameter stainless steel sphere was used with a 6 inch gap to a grounded plane at the bottom of the dewar. Much smaller gaps can be used in LN2 since the dielectric strength of LN2 is much higher than that of air.

Fig. 12. Wayne Ordon of SuperPower inspects a 22 inch (55.9 cm) diameter aluminum sphere used as a bushing termination for air withstand tests.

Drew Hazelton and Wayne Ordon of SuperPower came to ORNL to participate in the tests which were done from April 16-20. The testing order followed was the same as the manufacturer. The bushing passed 5 successive negative lightning impulse voltages at 654 kV which verified the manufacturers factory tests. Partial discharge was tested up to 100 kVrms which was the limit of the equipment and found to be 1.1 pC at 99.9 kVrms. The bushing then passed a 60 sec withstand test at 200 kVrms which was the maximum voltage of the power supply. Partial discharge tests were successfully repeated which completed the air tests.

The open dewar was installed and bushing repositioned at the lower gap. A thermocouple was mounted on the bushing to monitor cooldown. Slow continuous addition of LN2 to the dewar allowed the bushing to cool down slowly and fill the bath after several hours.

The bushing again passed 5 consecutive negative lightning impulse shots at 653 kV in LN2. The partial discharge tests were repeated again to 100 kVrms where the level was less than 5 pC and hence passed the test. An open circuit test of the partial discharge system without the bushing indicated that most of the partial discharge detected was coming from the detector system and not the bushing. The 200 kVrms withstand test for 60 seconds was again passed as was a repeat of the partial discharge test. The tan delta and capacitance measurements were performed before and after each series of voltage measurements and found to be consistent. Impulse tests were again repeated in LN2 the next day with 5 consecutive negative withstands at 655 kV. The polarity was switched to positive and 5 consecutive withstands were obtained at 655 kV. Partial

discharge was also successfully repeated. Hence overnight immersion in LN2 did not adversely affect performance.

The bushing was allowed to warm up slowly over 48 hours and the high voltage tests were repeated in air at room temperature. The bushing successfully passed five negative impulses at 664 kV peak. The partial discharge test was passed at less than 1.7 picocoulomb at 100.6 kVrms. The bushing then passed a 60 second withstand test at 200.4 kVrms ac which was followed by a second partial discharge test which passed at 2.6 picocoulomb at 100.3 kVrms. Based on these tests, we do not believe the bushing was degraded by immersion in LN2 and is a viable candidate for use. These successful tests also demonstrated the ability to test large 138 kV class bushings to the 650 kV BIL level in the ORNL High Voltage facility.

Under routine conditions, the HTS Fault Current Limiter (FCL) will be operated at full line voltage and hence its assembly must be designed to withstand the high electric fields between its components and the grounded tank. Hence, it is necessary to perform high voltage tests on scale models to validate the design (Figure 13). During this quarter such tests were conducted at ORNL on a mockup supplied by SuperPower. Partial discharge, ac breakdown voltage, and impulse breakdown voltage were done first in air for comparison to results in liquid nitrogen. For these initial tests, only impulse breakdown was performed in liquid nitrogen in an open bath. These results will provide useful design guidelines for the full scale system.

Fig. 13. (Left) Conceptual drawing of the HTS Fault Current Limiter. (Right) Sketch of the mockup of the FCL matrix assembly for testing in an open bath.

Following successful testing of a 145-kV bushing at ORNL in the previous quarter, high voltage

tests were initiated on a mockup of the proposed FCL which was assembled by SuperPower and delivered to ORNL. The mockup model consists of components closely resembling an actual FCL including corona rings, simulated HTS elements, conductors, supports, coils and connections. The high voltage tests performed included partial discharge (PD) onset, ac breakdown, and impulse breakdown. The mockup was suspended in an open dewar with a grounded plate on the bottom and grounded cylindrical side walls (Figure 14). Tests were performed in air first to identify any potential problems and to compare with results for the mockup fully immersed in liquid nitrogen in an open bath at 77 K. Measurements in air were obtained as a function of spacing between the various components and the side wall for different orientations of the mockup. Initial impulse breakdown in LN2 have been obtained for voltages up to 480 kV. The breakdown data allows statistical evaluation using a Weibull distribution of failure probability. These results will help to determine the clearances needed in the actual device and estimate the failure probability for design purposes.

Fig. 14. (Left) Alvin Ellis sets the gap between the side wall and a component of the FCL mockup in an open liquid nitrogen bath. (Right) Open bath showing the high voltage connections for ac partial discharge testing.

FY-2008 R&D Progress

ORNL has teamed with SuperPower, Inc. (SP) on a Superconductivity Power Equipment (SPE) project that was awarded in 2007 and will commence in FY2008. The ORNL role in the SPE is to conduct high voltage (HV) R&D on specified FCL internal components and provide technical design support to a SuperPower-led team developing this innovative HTS FCL.

1. Effect of gas bubbles on liquid nitrogen breakdown

In a quench situation or in the case of loss of pressure in a liquid nitrogen filled system, bubbles may form which can affect the dielectric strength of the liquid nitrogen. An experiment has been set up to examine the effect of bubbles in liquid nitrogen on the ac and impulse breakdown strength. Experiments have been performed in both open bath and in a pressurized cryostat. The

electrode geometry was plane-plane using stainless steel electrodes with rounded (but not profiled) edges. In order to specifically locate gas bubbles within the gap spacing, a capillary tube was inserted into the gap. The tube was nominally 0.5 mm outside diameter and 0.25 mm inside diameter and located within the 2 or 3 mm gaps that were employed for the measurements reported here. Figure 15 shows a photograph of the electrode gap for a 2-mm gap. Dry nitrogen gas was supplied to the capillary tube from a compressed gas cylinder and the gas flow was maintained using a regulator over the pressure range 0-60 psig. For measurements made at 1 bar, a 15-psig head pressure was sufficient to maintain good bubble flow.

Fig. 15. Electrode gap showing capillary tube

For the open bath or 1 bar experiments, bubbles were found to reduce the breakdown strength of liquid nitrogen despite the fact that at 1 bar pressure the liquid is boiling. Figure 16 shows mean breakdown strengths for liquid nitrogen with and without nitrogen gas flowing into the gap and the corresponding Weibull plots for conditions of liquid nitrogen with and without bubbles. A dashed vertical line is drawn through the seven lowest data points on the Weibull plot to show the change in the probability curve shape at low probability.

Fig. 16. Breakdown data on liquid nitrogen showing the effect of bubbles on the breakdown strength. Red symbols: without bubbles; blue symbols: with bubbles.

The presence of nitrogen gas bubbles in the gap resulted in a 23% reduction in the breakdown strength of liquid nitrogen at 1 bar pressure. In order to validate the experimental technique and as a check of the nature of the gas on the breakdown strength, we substituted helium for the nitrogen gas and found an increased reduction of breakdown strength due to the lower dielectric strength of helium compared to nitrogen at 77 K. Figure 17 shows the effect of helium bubbles on the breakdown strength of liquid nitrogen, showing a 34% drop in breakdown strength.

Fig. 17. Effect of helium bubbles on the breakdown strength of liquid nitrogen.

2. Preliminary results on partial discharge in G10 in liquid nitrogen.

Preliminary results on partial discharge (PD) for G-10 (Fiber reinforced plastic, FRP) in liquid nitrogen have been obtained in our laboratory and the most recent results presented at a poster session at the recent Applied Superconductivity Conference in Chicago, August 17-22, 2008. The results are included in paper 2LPL02 entitled “Electrical Insulation Characteristics of Glass Fiber Reinforced Resins,” by Enis Tuncer, Isidor Sauers, D. Randy James, and Alvin R. Ellis..

G-10 is one of the key dielectric materials used in cryogenic applications because of its excellent mechanical strength, low thermal contraction (which means it does not crack under thermal cycling), and machinability. However there is still insufficient data on dielectric properties at cryogenic temperatures, especially for thick samples at higher voltages, to allow good design rules for applications. The attached paper provides much needed data on ac breakdown voltages and PD onset voltages on relatively thick samples, nominally 6 mm (1/4 inch). Details of the test setup and samples are given in the paper.

For thick samples (~ 6mm and greater) between simple plane-plane electrodes, there is a tendency for the discharge to flashover around the sample rather than puncture through the

material which is desired to obtain a good breakdown voltage. In this case PD can also occur at the edge of the electrode which is undesirable. Hence special “recessed” samples had to be designed using electric field code calculations to try to prevent surface flashover and PD at the edges of electrodes. Based on those results, recessed samples with nominal 6 mm thickness were machined from larger bulk G-10 as described in the paper. Breakdown and PD inception voltages were measured for two different types of G-10, cryogenic grade (CRG) and FR4, the former being engineered specially for cryogenic applications and the latter being the more common grade containing a fire retardant. Five samples of each type were measured. The cryogenic grade had 14% higher average breakdown strength than the FR4, with strengths of 24 kVac/mm and 21 kVac/mm, respectively. However the average fields at PD onset were similar for both types at 4.3 kVac/mm.

Figure 18 below shows PD onset voltages (PD inception voltage, PDIV) for three different thicknesses of G-10 at room temperature in an oil bath using plane-plane electrodes. Increasing the thickness from 3 to 5 mm does not increase in the inception voltage by the same percentage. This result can be seen more clearly in Figure 19 below where the electric field at PD onset is plotted versus thickness for different samples under various conditions as shown. Above a certain thickness, in this case 3 mm, the PD onset field clearly decreases with sample thickness. This result may be due to a “volume effect” where thicker samples have higher probabilities for defects than thinner samples. Such defects may take the form of small voids or delaminations in the epoxy or epoxy-glass interface. As shown in the attached paper, the breakdown voltage also decreases with increasing thickness which is generally attributed to this volume effect. The PD onsets at 3 mm thickness agree for the sample in oil at room temperature and the sample at 77 K in LN2. This is most likely due to the fact that G-10 is generally not porous and therefore does not absorb either oil or LN2 and any voids present in the sample would not get filled by either liquid. Further work is needed at larger gaps to verify these results.

Fig. 18. Partial discharge inception voltage (PDIV) for G-10 samples of different thickness in an oil bath at room temperature. The electrodes were plane-plane geometry.

Fig. 19. Partial discharge onset field strengths for G-10 as a function of thickness.

FY-2009 R&D Progress

Effect of heater generated bubbles on liquid nitrogen breakdown strength

In previous work breakdown of liquid nitrogen was measured for three different electrode geometries in open bath, with and without bubbles. Bubbles were generated by a kapton heater and were directed into the inter-electrode gap spacing. The effect on breakdown strength was very small, so the next step was to place the electrode/heater assembly into a cryostat so that liquid nitrogen could be pressurized thereby eliminating bubbles due to normal boiling without additional external heating. A photograph of the electrode assembly is shown in Figure 20. Before being placed into the cryostat, the assembly was immersed in open bath liquid nitrogen to verify that the electrode alignment was correct, the gap was unchanged when cooled to 77 K and that bubbles generated by the heater were directed into the parallel plane electrode gap. Following these open bath tests, the entire assembly could be placed into the cryostat, ensuring that heater generated bubbles would flow into the gap as they did in the open bath.

In the cryostat liquid nitrogen was filled so that the entire electrode/heater assembly was immersed in liquid nitrogen. Breakdown data in Figure 21 show however that the heater generated bubbles had very little or no effect on the breakdown strength. In the figure are shown two sets of data corresponding to atmospheric pressure (0 psig), one when the assembly was in the open bath and the other when the assembly was in the cryostat. The two sets of data are in agreement within the error of the measurements. At higher pressures, 15 psig and 29 psig, the breakdown strength goes up with pressure as expected but there does not appear to be any effect of bubbles in what was expected to be a lowering of the breakdown strength. The results are consistent with the data obtained previously in open bath experiments reported earlier. The reason for this “null effect” is not clearly understood, but we know that the gaseous bubble

should have a lower dielectric strength than the more dense liquid. An additional experiment was performed to verify the lower breakdown strength of cold gaseous nitrogen in which the liquid nitrogen was removed only from the test region and while the cryostat was still cold due to the liquid nitrogen contained in the outer bath. The data shown in Figure 22 was measured at 1, 2 and 3 bar and the temperature at each pressure was recorded since the temperature was rising during the measurements. The breakdown strength in Figure 22a increased from 7.5 kVrms/mm at 1 bar to 16.5 kVrms/mm at 3 bar. These breakdown strengths are significantly lower than those recorded in liquid nitrogen. In Figure 22b the data are normalized to pressure and temperature corresponding to 1 bar and 300 K respectively and plotted as the peak breakdown field strength, resulting in a breakdown strength of around 3 kV/mm which is typical of nitrogen gas.

Fig. 20. (left photo) close-up of parallel plane electrodes and G10 tube which directs bubbles to the gap. (right) Entire electrode/heater assembly on support platform.

Fig. 21. Breakdown field strength as a function of heater voltage in liquid nitrogen for different pressures.

Fig. 22. Breakdown of cold gaseous nitrogen as a function of pressure: (a) Field strength as a function of pressure; (b) Peak field strength as a function of pressure after normalizing to 1 bar and 300 K.

To further explore and understand the effect of bubbles on liquid nitrogen breakdown a new electrode arrangement was designed in which the bubbles will be generated at the electrode surface and not in the gap. This arrangement may help in understanding why the breakdown strength was found to be unaffected by heater generated bubbles.

FY-2010 R&D Progress

Analyses have continued on breakdown data obtained for the hole-in-plane geometry where plane-plane electrodes were used and a heater was placed behind a small hole in the ground plane electrode. Breakdown data is plotted in Figure 23 as a function of heater power for pressures ranging from 1-2 bar at a liquid nitrogen temperature of 77 K, and a set of measurements were made at 1 bar and 73 K after pumping on the outer liquid nitrogen temperature bath to reduce the bath temperature and hence the liquid nitrogen temperature of the inner bath where the experiments were performed.

Fig. 23. Breakdown electric field strength as a function of heater power in plane-plane geometry with 2-mm gap and at different pressures. All data were obtained at 77K except for the plot in the bottom right at 73K.

The data show a break in breakdown voltage (indicated by the arrows) at low heater power to a lower and relatively constant breakdown voltage at higher heater power, where the break point increases with increasing pressure. No break was observed at 2 bar due to insufficient heater power.

FY-2011 R&D Progress

There was no significant activity in this final fiscal year. This CRADA with SuperPower, Inc. ends on June 30, 2011. The majority of the R&D work performed by ORNL under this CRADA was in the cryogenic dielectrics area and the sustained and outstanding contributions by Drs. Isidor Sauers, Randy James, Enis Tuncer and our master technician, Alvin Ellis, are acknowledged.