Project Title:	**HTS Transformer: Waukesha/IGC-SuperPower Superconductivity Partnership Initiative Project**
Organization(s):	**Oak Ridge National Laboratory**
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Project Purpose and FY 2004 Objectives: The objective of the current Phase II Superconductivity Partnership Initiative (SPI) project with Waukesha Electric Systems (WES), SuperPower, Inc. (SP), and Energy East, is to demonstrate the technical and economic feasibility of HTS transformers of medium (30 MVA) to larger ratings. An alpha-prototype 5/10 MVA, 3-phase, HTS transformer, with primary/ secondary voltage ratings of 24.9/4.2 kV and 100-kV BIL has been designed, fabricated, and tested. ORNL's original FY 2004 objectives were to:

- Participate in completion of tests on the 5/10-MVA unit and its installation on the utility grid at the WES plant.
- Critique and provide technical input to the 30-MVA transformer reference design.
- Continue measurements of dielectric, thermal, and mechanical properties of candidate cryogenic electrical insulation materials for transformer design ratings of 30 MVA and above. Topics would include partial discharge, ac and impulse breakdown strength, tan delta, thermal shock resistance, thermal conductivity, and heat capacity.
- Investigate mechanical and electrical compatibility between various components of the insulation system.
- Investigate the incorporation of second-generation YBCO materials into the 30-MVA reference design, including ac loss, over-current capability, and fault current limiting issues.

FY 2004 Performance and FY 2005 Plans: Project activities focused on repair and testing of the 5/10-MVA transformer as described below. Various difficulties encountered and the ultimate high-voltage failure of the unit during the factory floor testing prevented the team from making further progress on the 30-MVA reference design. Electrical insulation tests continued on solid materials and epoxies. A new proposal for follow-on work in FY 2005-6 is under discussion. This 2-year interim project will supply further data required for design of the Phase-III prototype commercial 30-MVA transformer. The plan for this project basically continues with the above list of objectives. The 5/10-MVA unit is being disassembled and inspected during the remainder of FY 2004, in order to find the reasons for the failures and determine what material and design improvements are needed for successful operation.

FY 2004 Results: Cooldown and testing of the 5/10-MVA HTS transformer during summer of 2003 had shown good operation of the cryogenic system and successful short-circuit operation up to 1.4× rated current. However, heat loads from residual gas leakage and a high-resistance short around phase C limited operation times under high current to several hours. Also, recurrent plugging of the liquid nitrogen (LN) tank vent line had caused difficulties with refill. The unit was untanked for checkout and repair in August 2003. Leak measurements showed that new leaks had developed in the LN connections to the low-voltage (LV) leads. These were repaired with Stycast epoxy. Plugging of the LN tank vent line was traced to pinholes in the burst disc that evidently resulted from a partial inversion during a cooldown pressure excursion. The short circuit around phase C was found to result from contact between the inner radiation shield cylinder and the inner bore of the phase C coil set. A wedge was gently driven into the gap to deflect the shield inward from the coil bore, and G-10 insulation was inserted into the space and secured tightly. All three phases then had low excitation currents. After the transformer was reassembled, global leak checks showed more than an order of magnitude reduction in the LN system leak rate. Cooldown was carried out without incident in late October 2003. During November, the transformer was disconnected from all its utilities, loaded onto a flatbed truck, and transported while still cold about two blocks to the WES main plant for installation on their test floor. Normal temperatures and vacuum were quickly re-established at the new site. Preliminary electrical tests showed that no damage had occurred.

Testing on the transformer resumed in December with three-phase short-circuit tests. The tests done in June 2003 were repeated with 116 A (100% rating), 80 A, and 60 A line current on the HV windings. The coil temperature-time curves in these two tests showed very similar behavior, indicating that the short circuit around Phase C was not the source of the excess heating. A further extensive program of short-circuit testing showed that the transformer could run at 63 A continuously and at 85 A for several hours without overheating, which was adequate performance for installation in the WES substation. A major source of heating was from release of cryopumped nitrogen from the residual leaks when the coil temperatures rose above 40 K. However, the coils also appeared to generate excessive electrical losses, particularly on Phase A, which may have conductor damage. Operation at up to twice the rated operating current was carried out with additional cooling by circulating liquid helium in the auxiliary circuits on the coil cooling shells. The current was held for an hour at values of 74, 105, and 127 A with stable conditions. However, the HTS leads were approaching their maximum safe temperatures. The current was raised to 200 A for about 15 minutes and then to 230 A. After about 3 minutes at 230 A, the coil temperatures started running away even with maximum helium flow, and the power was shut off. The coils still operated properly at 60 A with normal cooling, indicating that no conductor damage had occurred from the over-current tests.

In late March 2004, three-phase open-circuit high-voltage tests were attempted. After about 2 minutes on the third voltage step, with 1368 V on the LV side and 8.2 kV on the HV side, a snap was heard and the voltage collapsed. The power supply fuses were blown and a spike in the tank vacuum was seen. Ratio tests showed that Phase B now had high excitation current. Megger tests at 500 V showed only 1 MΩ between the LV and HV windings, but a high value of 500-1000 MΩ between both windings and ground. Capacitance tests showed high dissipation factors, particularly between the LV windings and ground. However, dc resistance measurements on all windings showed no changes from previous values, indicating that the conductor had not been damaged. During further high-voltage tests on Phases A and C with Phase B shorted, another breakdown occurred during the step between 13 and 15 kV. After this, there was only a 22-Ω resistance between the HV and LV windings. The transformer is being disassembled and inspected for damage.

Materials testing at ORNL included measurements on 1) small samples of Stycast FT with simulated voids to understand the partial discharge inception voltage and signatures as a function of pressure in the void, 2) breakdown and partial discharge of solid filled epoxies for different gaps and volume for information on scaling at large gaps and volumes, and 3) the effect of naturally-occurring voids on breakdown and PD inception. Laboratory data indicates significant decreases in both breakdown strength and PD inception voltage as the gap and volume increases and when defects in the form of voids are present in filled epoxies. Voids were found to occur even when the epoxies are properly de-aired, as a result of shrinkage during the curing process. The cause of failure of the three phases cannot be clearly ascribed to voids until dissection has been accomplished to determine the actual cause of failure. However, previous cold partial discharge testing on the Phase B coils at the WES site appeared to indicate the presence of voids.

Research Integration: ORNL team members visited SP and WES on eight occasions to carry out repair and testing on the 5/10-MVA transformer. Several of these visits extended to as much as two-weeks. To provide low-voltage, high-current ac test power independent of the WES production test equipment, ORNL loaned a large, 3-phase variac bank to WES in February. Collaboration within the team continued to proceed smoothly, with each member contributing in its particular area of expertise. Papers and presentations on the 5/10-MVA cooling module design were given at the 2003 CEC/ICMC Conference, and on fabrication and testing of the 5/10-MVA unit at the 2004 IEEE-PES Summer Meeting.