



REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY

Contract No. N00024-96-C-2108

**"High Performance HTS Conductors:
Long Length Production and Evaluation "**

Final Report

Prepared for:

**Dr. Robert Soulen
Naval Research Laboratory
Washington, DC**

Prepared by:

**Dr. Swarn Kalsi
American Superconductor
Westborough, MA**

19990201 014

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

End of FY98 Letter

A. Description of the technical research or development goals

The objective of the program was for ASC to address in a systematic manner the fundamental engineering issues associated with the fabrication of reliable, rugged, high power density HTS coils and systems. The goal is to provide solid technical support for the broad array of specific applications programs funded from other DoD sources. These include the HTS coil development program funded through NRL, the minesweeping program of NAVSEA/ONR, the airborne generator program presently funded by the Air Force, and programs currently under development in electric propulsion and advanced submarine technology.

B. Significant research or development results during the past year obtained:

The work was performed on the following tasks and significant results are summarized:

Task 1: Minesweeping Magnet Support: This task will directly support the construction of the Subsize Demonstration Model (SDM) ALISS coil under a Phase II SBIR awarded under topic N94-201. Specific areas to be addressed under this task include the development of low resistance in line splices in HTS conductor, the configuration and stress analysis of the SDM system, and verification tests of joints, thermal interfaces, impregnation, and coil support.

Layer winding and epoxy impregnation techniques for winding large coils were developed. Model coils have been built and tested. HTS conductor-to-conductor splices were made and embedded in the coil pack. All model coils provided acceptable results. This coil technology is now qualified for winding the final coil for the ALISS II minesweeping magnet under construction at ASC.

Task 2. Quench protection, modeling and detection: Analytic and three-dimensional Finite Element Method (FEM) analysis will be employed to predict quench propagation and temperature rise in existing and projected HTS coils. Measurement of relevant thermophysical parameters such as anisotropic thermal conductivity will be performed where necessary to ensure model validity. Based on this analysis, quench detection and protection methods will be breadboarded and tested on model coils. It is anticipated that this task will provide input to the high field HTS magnet currently under construction for NRL as well as providing a basis for the construction of coils for minesweeping and propulsion applications.

A one-dimensional quench model was developed to predict the voltage development and peak temperature during a quench event. This model represents adjacent thermally coupled turns.

A coil quench analysis was performed for a coil in an 8 tesla field. The quench was artificially initiated by forcing a turn on the coil ID above 40 K. The quench slowly propagates into adjacent turns. The model predicts that a detection of 10 millivolts per coil is an adequate warning for initiation of the protection unit. After this 10 millivolt threshold, the coil can withstand 5 seconds at full current before reaching 140 K. Experimental data from both the NRL high field magnet and DoE funded motor programs have verified that this model is a conservative estimate of the quench development and that a time constant, $L/R = 5$ seconds is adequate to protect magnets built with the current generation of HTS wire.

Task 3. Coil reinforcement: In high power shipboard applications such as electric propulsion, minesweeping, and SMES, the combined magnetic, thermal, and externally applied stress on a coil can exceed the design limits for an unreinforced HTS coil. Simplistic methods of reinforcement, such as those applied in the early coils for the homopolar motor by another vendor, are not easily applicable to HTS coils because they create excessive thermal strain in the coil and lead to conductor degradation. In this task we will model analytically more sophisticated methods of coil reinforcement, demonstrate them in model coils which will be loaded to failure,

and deliver selected ring coils to NRL for evaluation. It is anticipated that this task will involve the measurement of anisotropic properties such as thermal contraction, compressive stress-strain, and tensile stress-strain on conductor samples and representative coil sections.

The elastic moduli, tensile and compressive strengths, and thermal expansions in the temperature range 300K to 4.2K were measured on representative HTS coil samples in the radial and hoop directions. The data so gathered are now routinely used in Finite Element analyses of HTS coils.

Task 4. Cyclic loading: *In applications such as SMES, minesweeping under AC excitation, and rotating machinery, HTS coils can be subjected to cyclic loading. Little is known about the high cycle fatigue properties of these ceramic composite conductors or devices fabricated from them. In this task we will analyze the cyclic fatigue requirements imposed by credible designs for these devices and measure the fatigue properties of conductor and coil sections.*

Cyclic hoop strain up to 0.16% was applied to HTS coil samples for 1000 cycles. Unreinforced as well as stainless-steel-cowound coils were tested. No significant signs of degradation were observed in any of the coils. Cyclic axial compressive loading was also applied on HTS coil samples for 1000 cycles. No significant degradation was observed up to 2100 psi.

Task 5. Insulation development: *Conduction cooled magnets requiring AC operation or fast ramps can generate significant heating inside the winding packs. This heat must be removed in an efficient manner. The AC operation also imposes larger voltages across the coil. It is, therefore, important to develop insulation solutions which permit efficient heat transfer from the interior of winding packs to the outside coil surfaces from which it could be removed via a conduction mechanism. At the same time, the selected insulation solutions must withstand high voltages between pancakes as well as between the coil and ground plane. We propose to study a class of materials that act as electrical insulators and have approximately 10 times the thermal conductivity of conventional polyamide and glass-epoxy systems.*

In the layer winding process being developed for the ALISS program, three strands of HTS wire cowound with copper were wrapped with fiberglass overlapped 50%. This cable is then layer-wound onto a G10 mandrel, again using fiberglass for interlayer insulation. The voltage tolerance of the cured coil is estimated at ~400V. A higher voltage tolerance may be obtained by using different insulation and/or thickness.

Task 6. Advanced cooling techniques: *In this task we will address advanced methods for transferring heat from coil surfaces to cryocoolers and for electrically insulating cryocoolers from operating devices. In addition to extensions of the methods previously developed at NSWC, we will investigate a class of heat pipes which can simultaneously provide high power density and high voltage standoff capability and integration of magnet systems with a new class of single stage cryocoolers which have the potential for providing in excess of 50 watts of refrigeration at 30K.*

The NRL magnet thermal bus-work was designed to support over 1 watt per pancake coil. Each coil in the high field magnet was individually tested to 1 watt heat load in a vacuum 30 K transport current measurement. Most coils had a measured dT/dQ of 1 K per watt. Completed magnet achieved a peak magnetic field of 7.25 T at a temperature of 25 K which is a world record – this was made feasible by the excellent coil pancake cooling technology developed at ASC under this program.

Task 9. Coil fabrication and delivery: *BSCCO conductor with improved performance will be produced continuously during the course of this contract. Short samples of high performance experimental conductor will be provided to NRL on a mutually acceptable schedule to facilitate*

NRL collaboration in evaluation of the emerging material. In addition, pre-production lengths of continuously improving conductor will be fabricated into ring coils for test at NRL and by NRL designated collaborators within DoD and the national laboratories. The number and delivery schedule for these coils will be determined by agreement with NRL.

ASC has delivered 3 ring coils (6-in diameter, 0.5 x 0.5 in approximately in cross-section) to NRL with increasing performance as measured by the current density of the wire. Three coils with their performance are listed below:

Coil# P98-1403 31,884 A/cm² at 4.2 K

Coil# P98-1454 34,362 A/cm² at 4.2 K

Coil# P98-1455 34,585 A/cm² at 4.2 K

C. Plans for Next Years Research and Development

None

D. List of Publications/Reports/Presentations

G. Snitchler, S. S. Kalsi, M. Manlief, R. E. Schwall, A. Sidi-Yekhlef, S. Ige and R. Medeiros, "High Field Warm-bore HTS Conduction Cooled Magnet Design and Test Results", an invited paper under preparation for presentation at the 1998 Applied Superconductivity Conference, Palm Springs, California in September, 1998