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PERFORMANCE EVALUATION OF HIGH-TEMPERATURE SUPERCONDUCTING CURRENT LEADS FOR MICRO-SMES SYSTEMS*

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Performance Evaluation of High-Temperature Superconducting Current Leads for Micro-SMES Systems

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***Abstract*—As part of the U.S. Department of Energy's Superconductivity Technology Program, Argonne National Laboratory and Superconductivity, Inc., are developing high-temperature superconductor (HTS) current leads for application to micro-SMES systems. Two 1500-A HTS leads have been designed and constructed. A component performance evaluation program was conducted to confirm performance predictions and/or to qualify the design features for construction. The evaluations included HTS characteristics, demountable electrical connections, and heat intercept effectiveness. The performance of current lead assemblies is being evaluated in a zero-magnetic-field test program that included assembly procedures, tooling, and quality assurance; thermal and electrical performance; and flow and mechanical characteristics. The leads were installed in a liquid helium test cryostat and connected at their cold ends by a current jumper. The leads were heat intercepted with a cryocooler.**

I. Introduction

Use of HTSs for current leads to deliver power to devices at liquid helium temperature, now near commercial realization, has the potential to reduce refrigeration requirements to values significantly below the theoretically best values achievable with conventional leads [1]. Such leads are particularly advantageous for micro-superconducting magnetic energy storage (SMES) devices [2]. The micro-SMES system stores electrical energy to provide ride-through power during voltage sags and momentary power losses that last several seconds. Energy is stored in a magnet by the flow of current in a coil made of superconducting material.

As part of the U.S. Department of Energy's Superconductivity Technology Program, Argonne National Laboratory and Superconductivity, Inc., are developing HTS current leads suitable for application to micro-SMES systems [3,4].

II. Current Lead Details

A. Installation Geometry

The geometry of the current lead installation is shown in Fig. 1.

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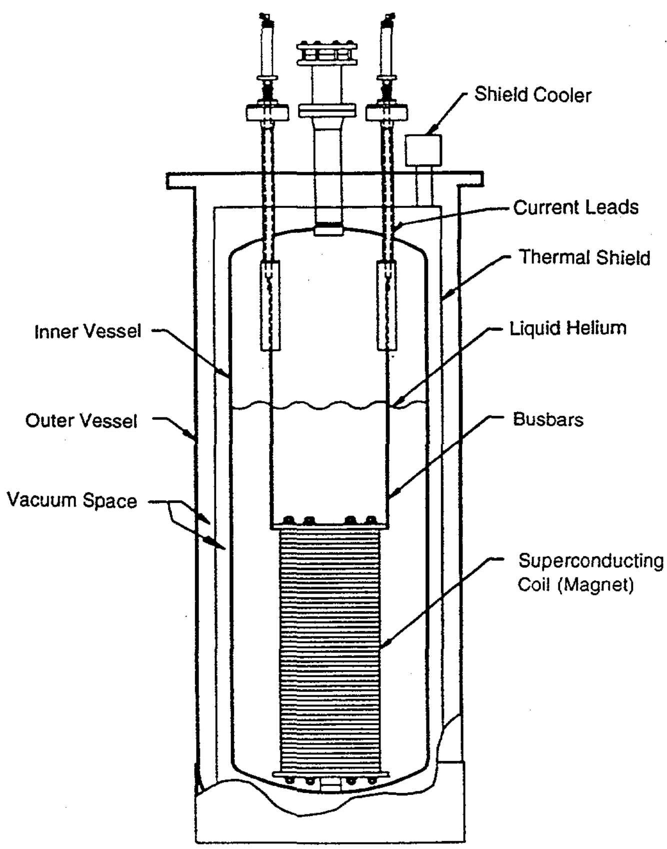

Fig. 1. Geometry of current lead installation.

B. General Arrangement

The general arrangement of the current lead is shown in Fig. 2. The major subassemblies of the current lead are the conventional upper stage, the transition assembly, and the HTS lower stage.

C. Conventional Upper Stage

The design parameters of the upper stage include a 1500-A operating current; warm- and cold-end temperatures of 300 and 60 K, respectively; and helium-vapor flow equivalent to 1.2 L/hr per lead. The estimated heat leak to 60 K is 47 W per lead. The upper stage was designed and constructed by a commercial vendor.

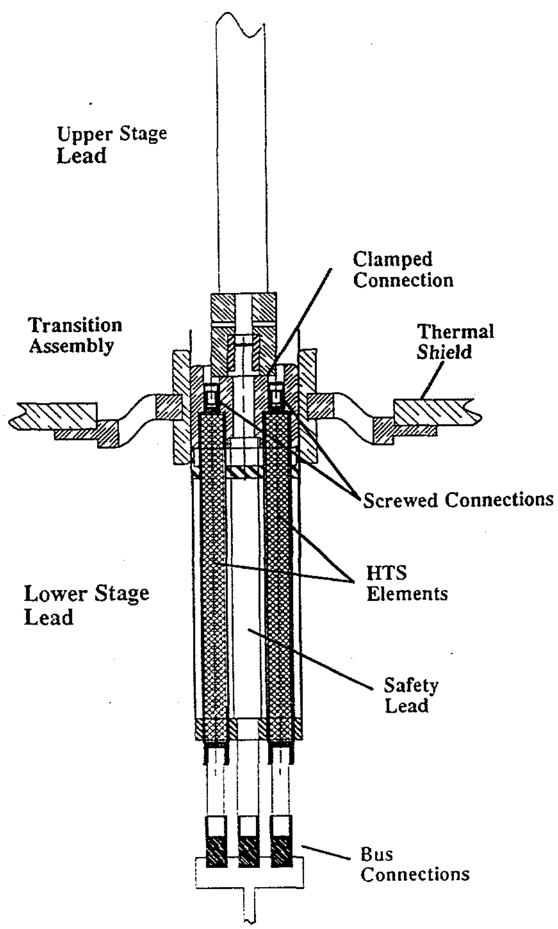

Fig. 2. General arrangement of current lead.

D. Transition Assembly

The transition assembly provides electrical and mechanical connections between the lower and upper stages, flow paths for the helium-vapor cooling stream, a heat intercept connection to a cryocooler, electrical isolation between the lead and the adjacent cryostat components, and pressure vessel continuity within the cryostat.

The geometry, materials, and methods of fabricating the transition assembly are selected to minimize the temperature difference between the warm end of the HTS element and the cryocooler intercept. The transition assembly must also provide effective and reliable electrical isolation, i.e., very low leakage current and high voltage standoff [5].

E. HTS Lower Stage

The lower stage consists of six parallel current-carrying YBCO with 15 vol.% silver HTS rods. The rods, 1.3 cm in diameter and 20 cm long, are connected to the transition assembly at their warm ends and to the bus collector assembly at their cold ends. Each rod is contained in an epoxy/fiberglass tube that channels the helium-vapor coolant and provides structural support for the rod. A safety lead is in the center of the HTS rod array. The estimated heat leak to 4 K is 0.9 W per lead.

Lateral loads to the conductor rods are controlled by supporting each conductor rod with a composite tube shroud and then configuring the conductor rods, composite tubes, and safety lead as cantilever beams acting in parallel. Axial loads to the conductor rods are controlled by loading the conductor rods in compression at assembly and then loading the lower-stage assembly in compression at final assembly.

A safety lead is incorporated in the lower-stage assembly as an alternate current path in the event of HTS malfunction. The safety lead consists of a stainless steel tube connected in parallel with the conductor elements.

The lower ends of the six HTS elements are connected to a bus collector by six low-temperature superconductor (LTS) composite elements. The two bus collectors are connected to the terminals of the magnet coil by LTS buswork. Voltage isolation along the length of the lead is provided by epoxy/fiberglass composite tubing that surrounds the lead elements.

III. Evaluation of Component Performance

A component performance evaluation program was conducted to confirm the performance predictions and/or qualify the design features for construction.

A. HTS Elements

The individual HTS rods were electrically tested before and after attachment of the end caps and support tubes. The testing was performed at 77 K in liquid nitrogen. Differences in rod-to-rod critical current were observed. Groups of rods were selected to give balanced performance between the two lead assemblies. This was accomplished by comparing the current-vs.-voltage drop profiles of all available rods. The groups were made up by selecting pairs of rods with nearly equal current-carrying capacity and assigning each pair to a lead assembly. Selection progressed from pairs with the highest current capacity to those with the lowest capacity. Flow characteristics of individual rod assemblies were measured at room temperature.

B. Demountable Electrical Connections

The electrical connections to the transition are demountable. The connection to the upper stage is a clamped surface-to-surface joint with an indium gasket. The connections to the lower stage are screw joints that incorporate male and female machine-thread components with indium tinning. The connections have been evaluated experimentally in liquid nitrogen [6]. Experimental variables included clamped-joint and thread-surface treatment and assembly methods. Resistivities were independent of current and reached a minimum value at moderate assembly torques. The allowable assembly torques were determined by the structural strength of the connection. The apparent resistivity of the clamped joint was 0.35 $\mu\Omega$-cm at 77 K. The apparent resistivity of the screwed joint was 0.40 $\mu\Omega$-cm at 77 K. The results of the evaluations confirm that low-resistance, demountable electrical connections can readily be made with clamped- and screwed-joint geometries.

C. *Transition Assembly*

The performance of prototype transition assemblies has been evaluated. The transition assembly was instrumented to provide a temperature profile throughout the assembly and its connections. The heat load of the upper-stage current lead is electrically simulated. Evaluation parameters included heater power and heat intercept temperature.

The results of the initial evaluations, made in vacuum [5], indicated good agreement between measured and predicted performance, i.e., temperature gradient-vs.-heater power, for the metallic components and connections. However, the measured temperature gradient across the isolating composite tube was several times that predicted, i.e., 6 K at 45 W heater power. The predicted value was based on the thermal resistance of the composite tube alone and did not include contact resistances at both tube surfaces [8]. Inspection of the disassembled transition assembly indicated nonuniform surface contact and the presence of oxide layers on the metallic surfaces. Both conditions increase the contact resistance and thus the temperature gradient.

The design was modified to reduce contact resistance. Changes include increased contact pressure, reduced roughness of the metallic component, plating of metallic component surfaces, and inclusion of deformable, thermally conductive materials between the tube and the adjacent metallic surfaces. The modified transition assembly was also evaluated in vacuum [7]. The measured temperature gradient across the isolating composite tube was 12 K at 45 W heater power at 70 K. The apparent thermal conductivities of the isolating tube for the tube material and the original and modified transition assembly designs are shown in Fig. 3.

The final design increased the contact area between the composite tube and its mating metallic parts. A transition assembly of this design has been fabricated and is being thermally evaluated. Evaluations will include operation in helium gas as well as in vacuum. The helium gas is predicted to increase the thermal contact conductance to several times that of the value for vacuum operation [9].

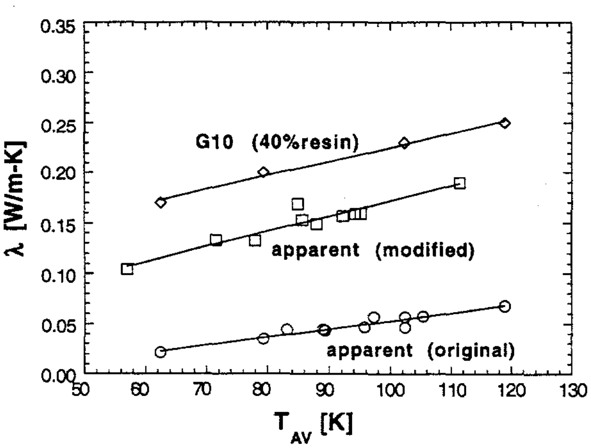

Fig. 3. Apparent thermal conductivity vs. average tube temperature of tube material and original and modified transition assemblies.

IV. Evaluation of System Performance

A system performance evaluation program has been developed to evaluate the performance of the current lead assemblies. The test program objectives include evaluation of assembly procedures, including tooling and quality assurance; thermal performance, including heat leak, temperature distribution, steady-state and upset response, and shield cooler performance effects; electrical performance, including voltage drops, voltage isolation, upset conditions, safety lead, and lead-to-lead differences; flow characteristics, including pressure drop vs. mass flow rate, voltage drop vs. mass flow rate, voltage drop vs. inlet temperature, and lead-to-lead differences; and mechanical characteristics, including thermal contraction, HTS rod strain, upset conditions, and stiffness of upper- and lower-end connections.

A. *Test Program*

Evaluations are performed in a liquid-helium test cryostat. Upper-stage (heat meter) and lower-stage (boil-off) heat leak values are calculated from test data. Measured electrical values include upper-stage, transition assembly, rod, and collector assembly voltage drops. Tests will be run for several steady-state and upset conditions, as shown in Table I. The test program includes runs at reduced cryocooler capacity and elevated cooling-gas inlet temperature. After all thermal and electrical tests are completed, the test apparatus will be disassembled and the radial and axial stiffness of the lower stage assembly will be measured.

B. *Initial Operation*

The integrated performance measurement system has been initially operated to evaluate operational readiness. The liquid helium and liquid nitrogen vessels and piping area leak tight during cryogenic operations. The cryocooler is functional and provides effective shield and intercept cooling. Cryostat external insulating vacuum feedthrough were found to be temperature sensitive and require corrective measures. The instrumentation and data acquisition system are functional. The power supply system is functional.

The integrated system has been operated at lead currents to 1150 A.

TABLE I

Steady State and Upset Thermal and Electrical Tests

Measured Quantity	Current	Lead Gas Flow	Cryocooler Status
Zero current heat leak	0	Unrestricted	On
Nonzero current heat leak	25-100% of design	Unrestricted	On
Zero flow current	50-100% of design	Off	On
Zero current, zero cryocooler heat leak	0	Unrestricted	Off
Nonzero current, zero cryocooler heat leak	75-100% of design	Unrestricted	Off
Loss of flow upset	25-100% of design	Unrestricted to off	On
Loss of cryocooler upset	25-100% of design	Unrestricted	On to off

V. Conclusions

• A pair of 1500-A HTS current leads for micro-SMES application have been constructed.

• Each lead employs a parallel cylindrical array of six (6) 1.3 cm OD x 20 cm long YBCO w/15 vol.% Ag sintered HTS conductor elements. The average measured $I_C = 234$ A @ 77 K @ 0.005 T applied field.

• Demountable connections join the conventional upper stage lead to the HTS lower stage lead. Both clamped and screwed connections are employed and result in an apparent joint resistivity of ≤1.8 that of the base material (ETP copper) at modest assembly torques.

• Heat intercepting is via a transition assembly which provides an electrically isolating and thermally effective connection. The measured ΔT for a prototype assembly across the insulator is ≈12 K @ 45 W heat flow @ 70 K operating temperature.

• The transition assembly cables have been calibrated as heat meters to allow measurement of the heat load to the transition intercept.

• The lead pair is undergoing electrical, thermal, and structural evaluations under simulated operating conditions. The integrated measurement system has been operated to evaluate functional readiness. The leads have been initially operated at currents to 1150 A.

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