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ENGINEERING DESIGN OF A HIGH-TEMPERATURE SUPERCONDUCTOR CURRENT LEAD*

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INTRODUCTION

As part of the U.S. Department of Energy's Superconductivity Pilot Center Program, Argonne National Laboratory and Superconductivity, Inc., are developing high-temperature superconductor (HTS) current leads suitable for application to superconducting magnetic energy storage systems.

The principal objective of the development program is to design, construct, and evaluate the performance of HTS current leads suitable for near-term applications. Supporting objectives are to (1) develop performance criteria; (2) develop a detailed design; (3) analyze performance; (4) gain manufacturing experience in the areas of materials and components procurement, fabrication and assembly, quality assurance, and cost; (5) measure performance of critical components and the overall assembly; (6) identify design uncertainties and develop a program for their study; and (7) develop application-acceptance criteria.

DESIGN CRITERIA

A current-lead design was generated for a near-term energy storage system. Significant elements of the criteria are given by Table 1.

HTS LOWER STAGE

Geometry

Based on the current-carrying characteristics of available, well-characterized HTS conductors and the geometrical requirements of the magnet cryostat, the lower stage was designed to consist of six parallel current-carrying HTS conductor rods. The rods are connected to the transition 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 located central to the HTS rod array. The geometry offers flexibility that can readily accommodate conductors of different materials and/or geometries.

Conductor

YBCO with 15 vol.% silver was selected as the baseline HTS rod material. Conductor selection was based on near-term material availability, balanced electrical and mechanical properties, and existence of an extensive data base on this material's performance characterization. Significant elements of the HTS conductor specifications are given in Table 2.

Table 1. HTS current–lead design criteria.

Parameter	Design value
Current (A)	1500
SSD background field (T) at HTS conductor	
* Radial	≥ 0.050
* Axial	≥ 0.100
Temperature (K)	
* Upper–stage warm end	300
* Transition	$50 \leq T \leq 70$
* Lower–stage cold end	≤ 10
Heat leak per lead to 4 K (W/lead at current)	≤ 0.7

Table 2. Outline specifications for HTS current–lead conductor.

Material	YBCO w/15 vol.% Ag
Critical current	$J_c \geq 200 \text{ A/cm}^2 @ 77 \text{ K} @ 5 \text{ mT}$
Thermal conductivity	$\lambda \leq 12 \text{ W/mK} @ T \leq 77 \text{ K}$
Mechanical integrity	Flexural strength $\geq 180 \text{ MPa} @ 300\text{K}$ Fracture toughness $\geq 3.2 \text{ MPa} \sqrt{\text{m}} @ 300 \text{ K}$
Geometry	Cylindrical rod (O.D.) = $1.3 \text{ cm} \pm 0.03 \text{ cm}$ Length = $20 \text{ cm} \pm 0.15 \text{ cm}$ Straightness = $\pm 0.04 \text{ cm}$ about a centerline joining the centers of the two ends

Thermal Performance

The thermal performance estimate of the overall lower stage assembly is shown in Table 3.

Structural Performance

The objective of the structural design and performance analyses was to ensure the long-term effective and reliable performance of the lower stage assembly. The loading included (1) static (gravity and fabrication), (2) dynamic (handling, transportation, seismic, and magnet charge and discharge), and (3) thermal cycles. Lateral and axial loading of the conductor rods is controlled by assembly geometry and materials.

Magnetic Shielding

The conductor rods are in the presence of applied magnetic fields from the magnet solenoid and the other five rods in the lower stage assembly. The resulting applied radial field of approximately 0.03 T at the cold end of a conductor. Magnetic shielding employing conventional material and geometry is employed to attenuate the field.

Safety Lead

A safety lead is incorporated in the lower stage assembly as an alternate current path in the event of HTS conductor malfunction. The safety lead consists of a stainless steel tube connected in parallel to the conductor elements. The safety lead contributes 0.11 W to the lead assembly's 0.87 W cold–end heat leak. Lead temperature rises to 500 K.

Table 3. Thermal performance estimate of lower stage assembly.

Operating conditions	<ul style="list-style-type: none"> • $I = 1500\text{ A}$ • $T_{\text{WARM}} = 60\text{ K}$ • $T_{\text{COLD}} = 10\text{ K}$ 														
Heat leak per lead															
	<table> <tr> <th>Component</th><th>Heat leak to 10 K (W)</th></tr> <tr> <td>HTS elements</td><td>0.70</td></tr> <tr> <td>Element shroud tubes</td><td>0.01</td></tr> <tr> <td>Safety lead</td><td>0.11</td></tr> <tr> <td>Voltage isolation tubes</td><td>0.01</td></tr> <tr> <td>Helium gas</td><td>0.04</td></tr> <tr> <td>Total</td><td>0.87</td></tr> </table>	Component	Heat leak to 10 K (W)	HTS elements	0.70	Element shroud tubes	0.01	Safety lead	0.11	Voltage isolation tubes	0.01	Helium gas	0.04	Total	0.87
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TRANSITION

The transition's functions are to (1) provide electrical and mechanical connections between the lower and upper stages, (2) provide flow paths for the helium-vapor cooling stream, (3) provide a heat-intercept connection to a cryocooler, (4) provide electrical isolation between the lead and the adjacent cryostat components, and (5) provide pressure-vessel continuity within the cryostat.

The transition consists of (1) a central copper disk, (2) an insulating tube, (3) an outer copper ring, (4) twelve copper cables connecting the ring and the cryocooler heat intercept, and (5) stainless steel tubular sections for welding to the cryostat's helium vessel lead-penetration tubes. The lower and upper stages are connected to the disk by screw-joint connections. The connections provide low electrical resistance, low thermal resistance, structural integrity, and long-term reliability.

The transition is configured to minimize the temperature difference between the disk and the cryocooler intercept; this is achieved through geometry, materials selection, and fabrication methods. The transition must also provide effective and reliable electrical isolation.

CONVENTIONAL UPPER STAGE

Configuration

The upper stage requirements are to (1) provide an efficient and reliable electrical connection between the ambient environment and the transition, (2) provide a low heat load to the transition, and (3) be compatible with the magnet cryostat geometry.

Thermal Performance

The thermal performance estimate for the overall upper stage assembly is given in Table 4.

PERFORMANCE EVALUATIONS

Component

A component performance evaluation program has been developed to confirm the analytical performance predictions and/or qualifying the design features for construction.

Table 4. Thermal performance estimate of upper stage assembly.

Operating conditions	<ul style="list-style-type: none"> • $I = 1500$ A • $T_{\text{WARM}} = 300$ K • $T_{\text{COLD}} = 60$ K
Heat leak per lead	
<u>Component</u>	<u>Heat leak to 60 K (W)</u>
Conventional current lead	45.00
Helium vessel pressure tube	1.85
Voltage isolation tubes	0.09
Helium gas	<u>0.13</u>
Total	47.07

Components and/or design features considered by the program include (1) HTS conductor characterization, (2) lower stage element and assembly structure, (3) screwed-joint connections, (4) transition heat transfer, (5) magnetic shield attenuation, and (6) voltage isolation.

System

A system performance evaluation program has been developed to evaluate the performance of current lead assemblies. This program consists of three separate phases: the zero-field test, energy storage operations test, and life-cycle test.

CONCLUSIONS

The engineering design of a HTS current lead assembly suitable for SSD applications has been completed. The general current-lead design approach is applicable to superconducting magnets for the SSC and other applications. Readily adaptable design features include (1) modular lower stage, transition, and upper stage; (2) lower stage structure and connections; (3) transition heat intercept-voltage isolation configuration; and (4) upper stage structure and connections. The design lends itself readily to alternate HTS conductor materials and geometries, system-specific installation geometries, and system-specific operational modes.

A component performance evaluation program is underway.

Lead assemblies are being constructed for system performance evaluations that include zero-field operation, energy storage operation, and life-cycle simulations. The knowledge gained by the performance evaluations will further the understanding of the application of HTS current leads in a true engineering sense to actual superconducting magnetic systems. The resulting information will contribute to the design data base and will identify areas for further development.

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