AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

RECEIVED
JUL 26 1993
OSTI

LOW-THERMAL-RESISTANCE, HIGH-ELECTRICAL-ISOLATION HEAT
INTERCEPT CONNECTION*

R. C. Niemann,¹ J. D. Gonczy,¹ and T. H. Nicol²

¹Argonne National Laboratory
Argonne, IL 60439

²Fermi National Accelerator Laboratory
Batavia, IL 60510

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

Submitted to Cryogenic Engineering Conference and International Cryogenic Materials Conference (CEC/ICMC), Albuquerque, July 12-16, 1993.

*Work supported by the U.S. Department of Energy, Conservation and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

LOW-THERMAL-RESISTANCE, HIGH-ELECTRICAL-ISOLATION HEAT INTERCEPT CONNECTION

R. C. Niemann,¹ J. D. Gonczy,¹
T. H. Nicol²

¹Argonne National Laboratory
Argonne, IL 60439

²Fermi National Accelerator Laboratory
Batavia, IL 60510

ABSTRACT

A method for providing a low-thermal-resistance, high-electrical-isolation heat intercept connection is presented. Electrical conductors often require the removal of heat produced from their normal operation. The heat can be removed by mechanical connection to a refrigeration source. Such connections require both effective heat removal (low thermal resistance) and effective electrical isolation (high electrical resistance and high dielectric strength). Such connections should be straightforward to fabricate and provide reliable performance that is independent of operating temperature. The connection method described here involves clamping, by thermal interference fit, an electrically insulating cylinder between an outer metallic ring and an inner metallic disk.

INTRODUCTION

Electrical current carrying conductors and/or surfaces often require the removal of heat as a part of their normal operation. The heat removal can be by the mechanical connection to a heat sink that is cooled by a coolant bath or by a refrigeration source. Such connections require both effective removal of heat (high thermal conductivity) and effective electrical isolation (high electrical resistivity and high dielectric strength). Such connections should be straightforward to affect and provide reliable performance independent of operating temperature for long periods of time.

A method is presented for developing high thermal conductivity connections having high electrical isolation. The method involves clamping, by means of a thermal interference (shrink) fit, a thin electrical insulating cylinder between an outer metallic ring and an inner metallic disk. Such connections have been successfully employed in suspension system components for superconducting magnet cryostats.¹ This method allows connections between the ring and the disk that have high thermal conductivity (low temperature difference) and high electrical isolation (low leakage current and high voltage isolation). The connections, by virtue of the interference fit, have controlled and repeatable performance, are rugged in nature and are suitable for applications at both low and high temperatures. The components due to their circular nature are straightforward to fabricate with precision and readily lend themselves to mass production manufacturing methods.

Representative applications of such connections include the connection of a metallic heat shield to a refrigeration source and the connection of a metallic tube to a refrigeration source are as shown by Figure 1.

Figure 1. Representative connection applications.

DESIGN METHODOLOGY

Geometry

The basic geometry of the connection is shown by Figure 2. An electrical insulating tube 1 is clamped between an inner metallic disk 2 and an outer metallic ring 3. The clamping is by means of a thermal interference (shrink) fit between the disk, tube and ring. The metallic components 2 and 3 can be connected directly to a heat load or heat sink 4 or by an auxiliary conductor 5 to a heat load or heat sink 6.

The specific geometry of a connection is determined by the requirements of the application. These requirements include installation spatial constraints, electrical isolation requirements, allowable temperature differentials across the insulating tube, structural considerations, and fabricability.

The connections to the connection can be by various methods which include mechanical clamping, soldering, welding and brazing.

Materials

The insulating tube can be a plastic film, composite or ceramic. The material selection is based on a number of factors which include electrical resistivity, dielectric strength and suitable mechanical properties over the operating temperature range. The tube thickness is determined by electrical isolation requirements and fabrication considerations.

Figure 2. High thermal conductivity high electrical isolation connection.

The disk and ring are metals with suitable thermal and electrical conductivity, having material compatibility with the object to be cooled and with the heat sink, and having suitable mechanical properties over the operating temperature range. The disk and tube dimensions are determined by the nature of the specific application and by the requirements of the thermal interference fit.

Thermal Interference Fit

The thermal interference fit is determined by the materials and geometry of the connection and the required clamping force on the insulating tube.

DESIGN PROCEDURE

The design procedure is as follows:

- Specify the application specific geometry. Included are insulating tube diameter, ring outer diameter, and connection length.
- Specify the electrical isolation requirements. Included are electrical resistance and dielectric strength.
- Specify the heat flux across the connection.
- Specify the temperature range. Included are assembly, and maximum and minimum operating temperatures.
- Determine the insulating tube parameters. These are initially based on electrical isolation requirements. The tube material and thickness must provide the required isolation with a margin of safety. The tube parameters are then reviewed mechanically. Included in the mechanical review are fabricability; electrical insulation integrity; i.e., voids, punch-through resistance, compressive strength, etc.
- Verify the acceptability of the temperature drop across the tube for the design heat flux through the tube.
- Determine the ring and disk materials. These materials are normally selected to yield high thermal and electrical conductivities, and appropriate mechanical strength.
- Determine the thermal interference fit parameters. A typical joint configuration is shown in Figure. 3. The fit, i.e., diametral interference, is normally designed to yield a high clamping force between ring-tube-disk without exceeding the compressive strength of the tube and the tensile yield strength of the ring. The equations that determine the clamping force on the tube² are as follow:

P_i, P_o = inner and outer interface pressures respectively and are given by

$$P_i = \frac{P_o(k_4 + k_5) - \delta_o}{k_6} \quad (1)$$

$$P_o = \frac{\delta_i k_6 + \delta_o(k_1 + k_2)}{(k_4 + k_5)(k_1 + k_2) - k_3 k_6} \quad (2)$$

where δ_i, δ_o = inner and outer interface radial interference fits respectively,
 $k_1 - k_6$ = constant parameters determined by the joint geometry and material properties and are given by

Figure 3. Thermal interference joint notation.

$$k_1 = \frac{b}{E_1} \left(\frac{b^2 + a^2}{b^2 - a^2} \right) - \nu_1; \quad k_2 = \frac{b}{E_2} \left(\frac{c^2 + b^2}{c^2 - b^2} \right) + \nu_2; \quad k_3 = \frac{b}{E_2} \left(\frac{2c^2}{c^2 - b^2} \right);$$

$$k_4 = \frac{c}{E_3} \left(\frac{d^2 + c^2}{d^2 - c^2} \right) + \nu_3; \quad k_5 = \frac{c}{E_2} \left(\frac{c^2 + b^2}{c^2 - b^2} \right) - \nu_2; \quad k_6 = \frac{c}{E_2} \left(\frac{2b^2}{c^2 - b^2} \right);$$

where E_1, E_2, E_3 = Young's modulus for the disk, tube, and ring respectively,
 ν_1, ν_2, ν_3 = Poisson's ratio for the disk, tube, and ring respectively.

- Develop detailed fabrication design.

The design procedure must consider the component materials' properties at assembly to operational temperatures.

The successful application of the design requires precision component machining and measurement, assembly tooling, and care to preserve electrical isolation of the ring-tube-disk interface.

REPRESENTATIVE APPLICATIONS

The connection method is being applied by the Argonne National Laboratory for the purpose of heat intercepting high temperature superconductor HTS current leads.³

Current Lead Measurement Facility

The application⁴ is as shown by Figure 4. The heat flux down the lead's conventional upper stage is intercepted at the transition to the lead's HTS lower stage. The intercepted heat is carried by copper cable to the cold head heat exchanger of a mechanical refrigerator. A connection of the thermal interference type is the interface between the cable and the heat exchanger. The design requirements are given by Table 1.

The connection details are as shown by Figure 5.

Type EL Mylar was selected as the insulating tube material. Selection was based on the material's high dielectric strength, high resistivity, and availability. The tube consisted of a single wrap of 0.0025 cm (0.001 in.) film applied to the disk.

The predicted temperature drop across the tube is 1.5 K for 12 W heat transfer at 77 K with thermal conductivity of 0.01 W/cm K.

ETP copper was selected as the ring and disk material. Selection was based on the material's high thermal conductivity, relatively high strength, and availability.

The thermal interference fit design required that the ring did not yield. This results in a 0.0051 cm (0.002 in.) diametral interference and develops a 20.8 MPa (6000 lb/in.²) clamping pressure on the tube.

Figure 4. Current lead heat leak measurement facility connection application.

Table 1. Current lead measurement facility connection design requirements.

Geometry	
• Insulating tube diameter [cm (in.)]	3.81 (1.50)
• Outer ring diameter [cm (in.)]	6.35 (2.50)
• Connection length [cm (in.)]	5.08 (2.00)
Electrical Isolation	
• Resistance [Ω]	300 ¹
• Dielectric strength [V]	125
Temperature	
• Assembly [K]	300 K
• Operating [K]	60 $\leq T \leq$ 80
Heat Transfer [W]	12 ²

Notes: 1 Corresponds to a leakage current < 0.1 A @ 30 V

2 6 W per lead

The assembly procedure involved cooling the disk with Mylar overwrap to 77 K with liquid nitrogen, heating the rings to 525 K (482°F), and then inserting the disk-tube into the rings. Following assembly, the electrical isolation was verified at 300 K in air. The completed prototype connection is as shown by Figure 6.

The performance of the prototype connection was evaluated at 77 K in vacuum. The disk was clamped with an indium gasket to the surface of a liquid nitrogen reservoir. The rings were wrapped with electrical heaters to simulate the current lead heat load. At steady state with a combined heater power input of 2 W, the average (of both rings) temperature difference across the tube was 0.67 K. The predicted temperature difference is 0.25 K.

The prototype connection has been installed in the current lead heat leak facility and will be employed in the heat leak measurement program.

Element	Detail
• Refrigeration Source	Cryocooler Cold Head
• Insulating Tube	Type EL Mylar
• Ring	ETP Copper
• CL Connection	Bolted to OD of Ring
• Separating Washer	Micarta
• Disk	ETP Copper
• Environment	Vacuum or Helium Gas
• Assembly	Ring-Tube-Disk Shrink Fit

Figure 5. Current lead measurement facility connection details.

Figure 6. Current lead heat leak measurement facility prototype connection.

SMES Current Leads

Current leads for superconducting magnetic energy storage (SMES)⁵ are being co-developed with Superconductivity, Inc., of Madison, WI.⁶ The application is as shown by Figure 7. The heat flux down the lead's conventional upper stage is intercepted at the transition to the lead's HTS lower stage. The intercepted heat is transferred through a thermal shield assembly to the cold head heat exchanger of a mechanical refrigerator. The design requirements are given by Table 2.

The connection details are as shown by Figure 8.

A composite equivalent to G10 CR epoxy fiberglass was selected as the insulating tube material. The selection was based on the material's high dielectric strength, high resistivity, and mechanical durability. The tube was fabricated as a wet lay-up on a mandrel and machined to final outside diameter. The nominal tube thickness of 0.043 cm (0.017 in.) was determined by the 8500 V breakdown requirement and fabrication consideration; i.e., minimum tube thickness.

Table 2. SMES current lead connection design requirements.

Geometry	
• Insulating tube diameter [cm (in.)]	6.35 (2.50)
• Outer ring diameter [cm (in.)]	8.89 (3.50)
• Connection length [cm (in.)]	5.08 (2.00)
Electrical Isolation	
• Resistance [Ω]	850,000 ¹
• Dielectric strength [V]	8500
Temperature	
• Assembly [K]	300 K
• Operating [K]	$60 \leq T \leq 80$
Heat Transfer [W]	45

Notes: 1 Corresponds to a leakage current < 0.1 A @ 8500 V

Figure 7. SI dewar installation.

Figure 8. SMES current lead connection details.

The predicted temperature drop across the tube is 5.8 K for 45 W heat transfer with a thermal conductivity of 0.0028 W/cm K at 77 K.

ETP copper was selected as the ring and disk material. Selection was based on the material's high thermal conductivity, relatively high strength, and availability.

The thermal interference design required that the ring does not yield. This results in a 0.0064 cm (0.0025 in.) diametral interference and develops a 22.9 MPa (3200 lb/in.²) clamping pressure on the tube.

The assembly procedure involved preassembly of the tube into the ring with a snug fit; i.e., 0.0013 cm (0.0005 in.) interference. The disk was then cooled to 77 K with liquid nitrogen and inserted into the ring-tube subassembly. Following assembly, the electrical isolation was verified at 300 K in air. The completed prototype connection is as shown by Figure 9.

Prototype connection performance evaluations are in progress. Upper stage current lead heater power is simulated by an electrically heated current lead end. The connection is instrumented to provide a temperature profile throughout the assembly and its connections. Evaluation parameters include heater power and heat intercept temperature. The evaluations are made in a vacuum.

CONCLUSIONS

- Low thermal resistance, high electrical isolation heat intercept connections can be provided by a thermal interference fit between a metallic disk, insulating tube, and metallic ring.
- Connection attributes are high thermal conductivity with high electrical isolation, performance effective over a wide operating temperature range, performance effective for a long period of time, connection which is mechanically rugged, connection that is straightforward to construct and capable of being manufactured at a reasonable cost.
- The connections can be applied at both low and high temperatures.
- The connections employ readily available materials, common machining operations, and modest assembly tooling, and can be assembled on either a laboratory or mass production scale.
- Two prototype connections corresponding to HTS current lead applications have been designed and fabricated. A connection for a current lead heat leak measurement facility incorporates a Mylar tube clamped between an ETP copper ring and disk. The measured and predicted performance are in good agreement. A connection for a SMES current lead incorporates a G-10 CR equivalent tube clamped between an ETP copper ring and disk. Performance evaluations of this connection are in progress.
- Follow-on activities include the application of suitable ceramic insulating tubes. Ceramics are excellent electrical insulators, have higher thermal conductivities than plastics and composites, and have high compressive strengths.

Figure 9. SMES prototype connection.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the engineering contributions of W. E. Buckles, Y. S. Cha, and M. A. Daugherty; the technical expertise of M. Bordson and A. S. Wantroba; and the manuscript preparation skills of J. A. Stephens and the editorial contributions of C. A. Malefyt. Work at ANL was supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38.

REFERENCES

1. R.C. Niemann, J.D. Gonczy, T.H. Nicol, J.G. Otavka, and M.W. Roman. Design, construction and performance of a post type cryogenic support, "Proc. 1985 Cryogenic Engineering Conf.," August 12-16, 1985, Cambridge, MA, Plenum Press, New York (1986).
2. T.H. Nicol, R.C. Niemann, and J.D. Gonczy, Design and analysis of the SSC dipole magnet suspension system, "Proc. Int. Industrial Symp. on the Supercollider, February 8-10, 1989, New Orleans, LA, Plenum Press, New York (1989).
3. J.R. Hull, High-temperature superconducting current leads, *IEEE Trans. Appl. Supercond.* **3**(1), 869-875 (1993).
4. R.C. Niemann, Y.S. Cha, and J.R. Hull, Performance measurements of superconducting current leads with low helium boil-off rates, *IEEE Trans. Appl. Supercond.* **3**(1), 392-395 (1993).
5. W.E. Buckles, M.A. Daugherty, B.R. Weber, and E.L. Kostecki, The SSD: a commercial application of magnetic energy storage, *IEEE Trans. Appl. Supercond.* **3**(1), 328-331 (1993).
6. R.C. Niemann, Y.S. Cha, J.R. Hull, M.A. Daugherty, and W.E. Buckles, Engineering design of a high-temperature superconductor current lead, Presented at Fifth Annual IJSSC, San Francisco, May 6-8, 1993.

**DATE
FILMED**

9 / 3 / 93

END