(NASA-CR-199743) HIGH T(SUB C) LEADS FOR REMOTE SENSING APPLICATIONS (NASA. Langley Research Center) 4 p

N96-15745

Unclas

G3/35 0083571

NASA-CR-199743

IN-35-CR

NAG1-1242

6436

P-4

High T_c leads for remote sensing applications

M.W. Hooker, S.A. Wise*, R. Selim†, R. Caton† and A.M. Buoncristiani†

Science and Technology Corporation, Hampton, VA 23666, USA
*NASA-Langley Research Center, Hampton, VA 23681, USA
†Department of Physics and Computer Science, Christopher Newport University, Newport News, VA 23606, USA

Received 23 February 1993

Several NASA programmes designed to monitor the earth's atmosphere from space utilize infrared detectors which operate at or below 4.2 K for optimum performance. At present, the detectors are maintained at cryogenic temperatures by a stored volume of liquid helium. These detectors must be electrically linked to amplification electronics and data storage instruments maintained at 80 K. The electrical connections over the temperature gradient account for ≈20% of the total heat load on the Dewar for some systems, accelerating the boil-off of liquid helium cryogen and reducing the operational lifetime of the space-borne instruments. The recent discovery of high temperature superconductors has provided an opportunity to develop electrically conductive, thermally insulating links to bridge this thermal gradient. This paper describes the modelling of the thermal transport properties of thick film, high T_c electrical bridges across a 4.2–80 K temperature gradient and the impact of such devices on a space-borne remote sensing system.

Keywords: high T_c superconductivity; space cryogenics; remote sensing

Several future NASA programmes designed to monitor the upper atmosphere utilize infrared (IR) detectors. These detectors operate at or below 4.2 K for improved signal-to-noise characteristics and are electrically linked to data acquisition and storage electronics at 80 K[1], as shown in *Figure 1*. One of these projects currently under consideration by NASA is the spectroscopy of the atmosphere using the far infrared emissions (SAFIRE)[2] experiment, designed to detect chemical radicals in the upper atmosphere. SAFIRE will employ gallium-doped germanium detectors operating in a liquid helium environment and the signals from these sensors must be linked to data acquisition instruments which are maintained at 80 K by a mechanical cryocooler. The current design utilizes ≈150 manganin (85% Cu, 12% Mn, 3% Ni) wires (40 AWG) as the electrical connections, due to the low thermal conductivity of manganin at cryogenic temperatures[3]. The temperature gradient spans ≈15 cm in length, and each lead carries less than 1 μA of current.

In this design, the heat load due to the electrical leads constitutes ≈20% of the total heat load on the liquid helium Dewar. Furthermore, these connections comprise the only non-parasitic heat load that can be modified to reduce the thermal load on the liquid helium Dewar, and thus increase the operational lifetime of the space-borne instrument.

The discovery[4,5] of high T_c superconductors provides an alternative to the currently employed manganin leads. High T_c materials possess adequate curent transport properties for sensor lead applications, as well as low thermal conductivities[6]. However, fine diameter wires of these materials have not demonstrated the required mechanical durability to withstand operational stresses in space-borne systems. As an alternative, the use of thick film superconductors screen-printed on to low thermal conductivity substrates is currently under investigation. Thick film technology provides the ability to deposit long length superconductive elements with cross-sectional areas similar to the currently used manganin wires on to rigid ceramic substrates[7].

The preparation of $YBa_2Cu_3O_{7-x}$ and $Bi_2Sr_2Ca_2Cu_3O_x$ thick films on ceramic substrates has been demonstrated by several researchers[8–10]. For this particular application, a current density of 0.065 A cm^{-2} is required, assuming a similar cross-sectional area to that of 40 AWG wire. This value is attainable for thick film superconductors, which exhibit critical current densities in excess of this value.

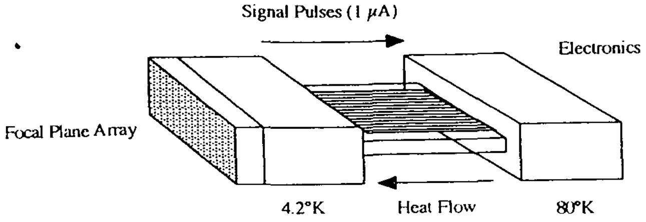

Figure 1 Schematic representation of remote sensing instrument for space flight

This paper demonstrates the feasibility of using a thick film superconductive lead assembly as an alternative to manganin wires. The thermal characteristics of various superconductor/substrate combinations are compared to those of the existing manganin leads and the potential impact on mission lifetimes is discussed.

Thermal modelling

Heat transfer calculations

To calculate the heat flow through both manganin wires and superconductive thick film lead assemblies, a thermal model was developed[11] using the design criteria for SAFIRE[2]. In this design, two isolated thermal reservoirs are linked by an element with thermal conductivity k and electrical resistivity ρ_{elect}, as shown in *Figure 1*. According to conventional thermal transport theory, the heat flow will proceed from the higher temperature reservoir to the lower temperature reservoir. Additionally, when an electric current is passed along this link, heat is generated due to I^2R losses. The steady state behaviour for such a system is governed by the following ordinary differential equation[12]

$$\frac{\mathrm{d}}{\mathrm{d}x}\left[\frac{k(T)\,\mathrm{d}T}{\mathrm{d}x}\right] = -J^2\rho_{\text{elect}}(T) \qquad (1)$$

where x is the position along the link. Because the thermal conductivity and electrical resistance vary with temperature, numerical methods must be employed to determine the temperature distribution over the thermal gradient. The numerical calculations for the one-dimensional heat transfer across the thermal gradient were performed using a Runge–Kutta method with MathCAD™.

Design criteria

The above calculations were performed for both $YBa_2Cu_3O_{7-x}$ ($T_c = 93$ K) and $Bi_2Sr_2Ca_2Cu_3O_x$ ($T_c = 110$ K) films on Al_2O_3, MgO, 8 mol% Y_2O_3-stablized ZrO_2 (cubic YSZ) and fused silica (SiO_2) substrates. Printed superconducting elements with dimensions 0.076 mm × 0.020 mm, with 0.076 mm spacing between each printed lead were employed. A substrate thickness of 0.152 mm was assumed for each case. The calculations were performed on a per lead basis to determine the heat load of each superconductive element and the corresponding substrate.

A similar calculation was also performed assuming that superconductive elements were printed on both sides of the ceramic substrate. Such a design should reduce the heat loss due to the ceramic substrate by a factor of two. The high T_c device with superconductive leads on one side of the substrate is referred to as model 1, while the case in which superconductors are printed on both sides of the substrate is referred to as model 2. Schematic illustrations of the two designs are shown in *Figure 2*. In each instance, the calculated values were compared to those for 40 AWG manganin wires. The thermal and electrical conductivity values for the various materials addressed in this work were obtained from the technical literature[3,6,13–17].

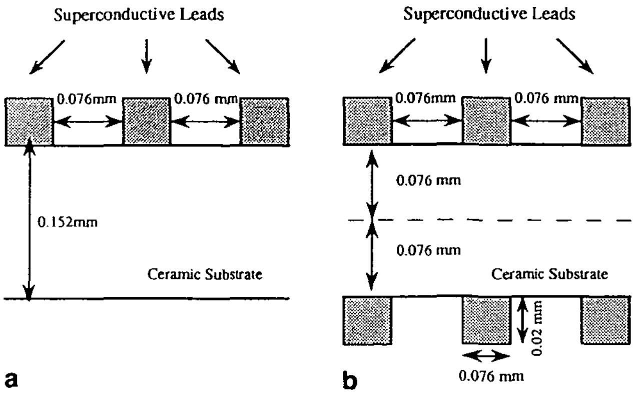

Figure 2 Printing configurations for superconductive leads printed on (a) single side of substrate and (b) both sides of substrate

Calculation of thermal savings

Once the heat flow through the various candidate lead assemblies was determined, the expected lifetime of the SAFIRE experiment was calculated for each of the high T_c sensor lead designs. To translate the heat flow calculations into lifetime savings, the SAFIRE experiment was again used as a basis. In the current design of the SAFIRE experiment, 158 leads bridge the thermal gradient. Thermal analyses of the system design indicate that the manganin connections will comprise 33% of the instrument heat load on the Dewar, or 17% of the total heat load. The proposed mission duration for the SAFIRE experiment is five to seven years, requiring that a minimum of 125 dm^3 of liquid helium be launched into orbit.

The per cent reduction in thermal loss for each of the superconductive lead assemblies was calculated by dividing the heat flow through each lead assembly by the heat flow through the manganin wires and subtracting this value from one. Determination of the thermal savings for the system was then performed by substituting the various lead assemblies for the manganin wires. The heat load due to each lead assembly was calculated, added to the baseline, and divided by the current heat load value. Lifetime extensions were then calculated based on these savings for both five year (60 month) and seven year (84 month) missions.

Results and discussion

Heat loss through high T_c leads

The heat transfer calculations show that the lowest heat flows are obtained when $Bi_2Sr_2Ca_2Cu_3O_x$ elements

Table 1 Calculated heat flows through candidate high T_c superconductive lead assemblies (calculated on a per lead basis)

Lead assembly	Heat flow (μW): model 1	Heat flow (μW): model 2
123/fused silica	4.9	3.2
2223/fused silica	3.7	2.0
123/cubic YSZ	14	7.8
2223/cubic YSZ	12.8	6.6
Manganin	**16.6**	**16.6**
123/alumina	884	443
2223/alumina	882	441
123/magnesia	8020	4012
2223/magnesia	8019	4010

are printed on to both sides of a fused silica substrate. Similar printing configurations using either $YBa_2Cu_3O_{7-x}$ or $Bi_2Sr_2Ca_2Cu_3O_x$ on YSZ substrates also possess heat flows that compare favourably to manganin wires. The heat flows through thick film leads printed on fused silica or YSZ range from 2.0 to 7.8μW per lead as compared to 16.6μW per manganin wire.

Similar lead assemblies printed onto Al_2O_3 and MgO substrates exhibited significantly higher heat flows (i.e. >440μW per lead) than the manganin wires, which would result in a significant decrease in the operational lifetime of the experiment in space. In these instances, the substrate is the major contributor to the thermal losses over the 4.2–80 K temperature gradient, with no discernible differences attributable to the superconductive compound employed. A summary of the heat flows through each of the candidate lead assemblies is given in *Table 1*.

These results show that substrate selection is the most critical parameter in the design of a high T_c thermal bridge. While superconductor selection is important (e.g. bismuth cuprate superconductors possess lower thermal conductivities than $YBa_2Cu_3O_{7-x}$)[6,13], the superconductor's contribution to the heat load is minor due to the small cross-sectional area of the conductor as compared to the substrate material.

Thermal savings due to high T_c *leads*

The overall impact on the mission lifetime was found to be dependent upon the superconductive compound, substrate material and printing pattern (i.e. printing on one or two sides of the substrate) employed in the production of the device. Replacement of the manganin wires in the SAFIRE system with printed superconductive elements on either YSZ or fused silica substrates would result in mission lifetime extensions up to almost 10% based on the choice of substrate, superconductor and printing configuration. This reduction in thermal losses translates into an additional two to twelve months of operation for a seven year mission depending on the lead assembly design used.

The per cent reduction in thermal loss and the percentage of lifetime increase for the entire system for each superconductor–substrate printing combination are shown in *Table 2*. The calculated lifetime extensions for the SAFIRE instrument (in months) for both five and seven year missions are also shown in *Table 2*.

Electrical considerations

In each of the candidate lead assemblies modelled, including manganin wires, Joule heating was not found to contribute significantly to the heat load on the liquid helium Dewar. The negligible heat loads due to I^2R losses may be attributed to the low electric currents passed through the leads. For applications with high current transport requirements, the use of manganin leads may result in higher thermal loads on the liquid helium Dewar due to resistive heating. However, resistive heating would not affect the thermal properties of a superconductive lead assembly, as electrical resistance would be non-existent in this instance[18].

Manufacture of high T_c *lead assemblies*

While the use of screen-printing has been successfully demonstrated for both $YBa_2Cu_3O_{7-x}$ and $Bi_2Sr_2Ca_2Cu_3O_x$ on YSZ substrates[8–10], the use of fused silica substrates has resulted in delamination of the superconductive element due to thermal expansion

Table 2 Estimated thermal savings for space-based system, such as SAFIRE, using various superconductive lead assemblies (data based on 158 leads, with leads comprising 17% of total heat load)

Lead assembly	% Reduction in thermal loss of lead wires	%Thermal savings for system	Lifetime extension for 5 year mission (months)	Lifetime extension for 7 year mission (months)
123/fused silica				
Model 1	70.5	11.4	6.9	9.6
Model 1	80.7	13.2	7.9	11.1
2223/fused silica				
Model 1	77.7	12.7	7.6	10.6
Model 2	87.9	14.4	8.6	12.1
123/cubic YSZ				
Model 1	15.8	2.1	1.3	1.8
Model 2	53.4	8.5	5.1	7.2
2223/cubic YSZ				
Model 1	23.0	3.4	2.0	2.8
Model 2	60.6	9.8	5.9	8.2

mismatches[19]. Additionally, a chemical reaction between $YBa_2Cu_3O_{7-x}$ and SiO_2 has been reported, resulting in the formation of an intermediate compound and degradation of the superconductive properties[20].

At present, YSZ appears to be the most viable candidate material for use as the substrate in the fabrication of the thermal isolator. However, other alternative printing schemes such as the use of multilayer printing of $YBa_2Cu_3O_{7-x}$, with the electrically insulating Y_2BaCuO_5 compound serving as a dielectric layer[21], and the use of sputter deposited ZrO_2 buffer layers[22] on fused silica substrates are currently under investigation at NASA-Langley Research Center.

Conclusions

Modelling of the heat transfer characteristics of high T_c lead assemblies over a 4.2–80 K temperature gradient has shown that the replacement of the manganin leads with thick films of a ceramic superconductor printed on a low thermal conductivity substrate can significantly decrease the thermal loads on liquid helium Dewars. The critical parameter in designing a thermal isolator was found to be the selection of a low thermal conductivity substrate, as the substrate contribution to the heat load is larger than that of the superconductive elements.

This study was designed to determine the feasibility of employing superconductive lead assemblies for cryogenic detector systems. While cryogenic thermal conductivity data are limited for ceramic compounds, other materials may offer further benefits for thermal savings. In general, materials with random (i.e. glasses) or complex crystal structures, high atomic weight constituents and/or defect structures exhibit low thermal conductivities at cryogenic temperatures[23]. However, the primary concern in selecting a substrate for this application must be chemical compatibility with $YBa_2Cu_3O_{7-x}$ or $Bi_2Sr_2Ca_2Cu_3O_x$ at high temperatures in order to successfully co-fire the two materials to produce a useful device.

Beyond SAFIRE, NASA has several other planned missions with similar designs and cryogenic requirements[1]. Some of these experiments will require several hundred electrical connections to span a similar thermal gradient. As the number of electrical leads increases, the thermal load on the liquid helium Dewar will also increase, making low thermal loss, high T_c sensor leads even more beneficial to these programmes.

Acknowledgements

The authors wish to thank I. Nolt of NASA-Langley Research Center and J. Lee of Ball Aerospace for providing system parameters for the SAFIRE experiment. Additionally, R. Selim, R. Caton and A.M. Buoncristiani wish to acknowledge the support of NASA grant no. NAG-1-1242.

References

1 **Sherman, A** National aeronautics and space administration needs and trends in cryogenic cooling *Cryogenics* (1983) **23** 348–352

2 **Lee, J.H., Payne, D.A. and Averill, R.D.** Design of the cryogenic system for the SAFIRE instrument *Adv Cryog Eng* (1992) **37** (Pt B) 1211–1219

3 **Zavaritskii, N.V. and Zeldovich, A.G.** Thermal conductivity of some technical materials at low temperatures *Zhur Tekh Fiz* (1956) **26** 2032–2036

4 **Wu, M.K., Ashburn, J.R., Torng, C.J., Hor, P.H. *et al.*** Superconductivity at 93 K in a new mixed-phase Y-Ba-Cu-O compound system at ambient pressure *Phys Rev Lett* (1987) **58** 908–910

5 **Maeda, H., Tanaka, Y., Fukutomi, M. and Asano, T.** A new high T_c oxide superconductor without a rare earth element *Jpn J Appl Phys* (1988) **29** L209–L210

6 **Uher, C.** Thermal conductivity of high T_c superconductors *J Supercond* (1990) **3** 337–389

7 **Vest, R.W.** Materials science of thick film technology *Am Cer Soc Bull* (1986) **65** 631–636

8 **Taffin, A., Brousse, T., Mercey, B., Hervieu, M. *et al.*** Superconducting printed $YBa_2Cu_3O_{7-x}$ thick films prepared with an argon/oxygen annealing treatment *Physica C* (1990) **170** 59–64

9 **Matsuoka, Y., Ban, E. and Ogawa, H.** Properties of high-T_c screen printed Y-Ba-Cu-O films prepared under flowing helium *Supercond Sci Technol* (1989) **2** 300–303

10 **Hashimoto, T., Kosaka, T., Yoshida, Y., Fueki, K. *et al.*** Superconductivity and substrate interaction of screen-printed Bi-Sr-Ca-Cu-O films *Jpn J Appl Phys* (1988) **27** L384–386

11 **Caton, R., Selim, R. and Buoncristiani, A.M.** A comparison of superconductor and manganin technology for electronic links used in space mission applications, NASA Document Number CR-4477 (December 1992)

12 **Hull, J.R.** High temperature superconducting current leads for cryogenic apparatus *Cryogenics* (1989) **29** 1116–1123

13 **Peacor, S.D. and Uher, C.** Thermal conductivity of Bi-Sr-Ca-Cu-O superconductors: correlation with the low-temperature specific heat behavior *Phys Rev B* (1989) **39** 11559–11562

14 **Ackerman, D.A., Moy, D., Potter, R.C., Anderson, A.C. *et al.*** Glassy behavior of crystalline solids at low temperature *Phys Rev* (1981) **23** 3886–3893

15 **Berman, R.** Thermal conductivities of some dielectric solids at low temperatures *Proc Roy Soc (London)* (1951) **A208** 90–108

16 **Nemoto, T., Sasaki, S. and Hakuraku, Y.** Thermal conductivity of alumina and silicon carbide ceramics at low temperatures *Cryogenics* (1985) **25** 531–532

17 **Slack, G.A.** Thermal conductivity of MgO, Al_2O_3, $MgAl_2O_4$ and Fe_3O_4 crystals from 3 K to 300 K *Phys Rev* (1962) **126** 427–441

18 **Matrone, A., Rosatelli, G. and Vaccarone, R.** Current leads with high T_c superconductor bus bars *IEEE Trans Magn* (1989) **MAG-25** 1742–1745

19 **Ginley, D.S., Mitchell, M.A., Fu, W., Kwak, J.F. *et al.*** Freestanding films of $YBa_2Cu_3O_{6.9}$, in *High Temperature Superconductors* (Eds Brodsky, M.B., Dynes, R.C., Kitazawa, K. and Tuller, H.L.) Materials Research Society, Pittsburgh, PA, USA (1988) 673–676

20 **Koinuma, H., Fukuda, K., Hashimoto, T. and Fueki, K.** Chemical interation between $YBa_2Cu_3O_{7-x}$ and substrate materials in the solid state *Jpn J Appl Phys* (1988) **27** L1216–L1218

21 **Yoshiara, K., Kagata, K., Hiroki, T. and Nakahigashi, K.** Multilayered superconducting $YBa_2Cu_3O_y$ thick films on Y_2BaCuO_5 substrate, in *Advances in Superconductivity* (Eds Kitazawa, K. and Ishiguro, T.) Springer–Verlag, Tokyo, Japan (1989) 319–324

22 **Myoren, H., Nishiyama, Y., Nasu, H., Imura, T. *et al.*** Epitaxial growth of $Ba_2YCu_3O_x$ thin film on epitaxial ZrO_2/Si (110) *Jpn J Appl Phys* (1988) **27** L1067–L1070

23 **Kingery, W.D., Bowen, H.K. and Uhlmann, D.R.** *Introduction to Ceramics* 2nd Edn, John Wiley and Sons, New York, USA (1976)