ADVANCES IN THERMAL CONTROL TECHNOLOGIES FOR SMALL SATELLITE SYSTEMS

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Abstract

The miniaturization of cryogenic components plays a significant role in the never ending quest for "smaller, better, faster, cheaper" satellite systems. My advisor and I are developing three separate applicable technologies for the thermal control of small satellite systems. The first of these technologies is called FiST (Fiber Support Technology). FiST serves to thermally isolate and mechanically support cryogenically cooled components from their warm surroundings by utilizing high performance fibers in tension. Use of this technique on a preliminary breadboard model for the SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) cooled focal plane assembly reduced conduction parasitic heat loads through the support structure by two orders of magnitude from nearly 90 mW to less than I mW. The mechanical stiffness of the system has been dramatically enhanced by increasing the first natural resonant frequency of the system from 50 Hz to 700 Hz. The second of these technologies is the development of a solderless flexible thermal link.

Thermal links play a vital role in the thermal management of space based cryogenically cooled instruments by connecting the cold heat sink with a cooled component. Using the "swaging" process, we have developed a fast, simple, and cost effective method for providing a low thermal impedance, highly flexible thermal link. With this process, a link has been developed that has a thermal resistance of 1.8 K/W over a 4. 5" length and weighs only 63 grams. The flexibility of this link is such that a 7 mm deflection in any axis will result in no more than a 2 N load on the opposite end. The third area of advancement in thermal control which we are studying is controlling the reject temperature of cryogenic mechanical refrigerators. By maintaining a stable, lower reject temperature the efficiency of these mechanical refrigerators is greatly enhanced which results in lower power consumption and/or greater cooling capacity for the cooled satellite systems. The weight and power savings make this approach an important part of small satellite thermal control. This paper briefly describes the basic concepts behind these thermal control technologies and their potential benefits to small satellite systems.

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Nomenclature

A	=Cross-sectional heat transfer are
K	=Thermal conductivity
L	=Thermal path length
q	=Heat load
ΔT	=Temperature difference
R	=Thermal resistance
R_c	=Contact resistance
R_i	=Ideal link resistance
R_m	=Measured contact resistance

Introduction

A keyword in "small satellite" technology is small. For satellites carrying infrared sensors the cryogenic subsystem has often been referred to as the "900 lb gorilla on the block". It therefore seems appropriate to look at thermal management in the drive for "smaller, better, faster, cheaper" systems.

As small satellites systems and the instruments of which they are composed become smaller and more efficient, the instrument performance specifications are usually not relaxed. In fact, more often than not, more performance is expected out of less instrument. Issues such as component temperature ranges, temperature drift, reduction of parasitic heat loads to cooled components, and extending mission life of cryogenically cooled components are all examples of requirements which remain unchanged or may have become even more stringent.

Here at Utah State University we have examined ways of reducing power, mass, volume, and cost required to produce satellite systems while maintaining or improving performance. We have looked at (a) reducing heat loads on cooled components which enables utilization of smaller capacity refrigerators or heat sinks, (b) lowering the mass of and temperature drop across thermal links between cooled components and heat sinks, and (c) improving performance of the overall refrigerator heat rejection system by developing methods to maintain stable, low temperature heat rejection platforms on which to operate miniature mechanical refrigerators.

The following sections of this paper will discuss each of the three of these approaches in more detail and our me of solving them.

2.0 Fiber Support Technology

Certain components in optical systems, such as orbiting telescopes, must often be cooled to cryogenic temperatures to enable the optical sensors to function properly and obtain the desired data. These cooled components must be thermally isolated from their much warmer surroundings. Such thermal isolation is complicated by the necessity of supporting these components in a fixed and rigid position with respect to the warm structures to which they are attached. This task proved to be rather challenging as how does one mechanically connect a structure while thermally disconnecting it.

Traditionally, cryogenically cooled components developed by Utah State University/Space Dynamics Laboratory (USU/SDL) have been supported by composite glass-epoxy (G-10) concentric cylinders that provide a compromise between thermal isolation and the necessary rigidity to support typical launch loads (see Figure 1). This approach has two limitations that are particularly serious in small satellites.

First, the parasitic heat loads due to conduction through this type of system,

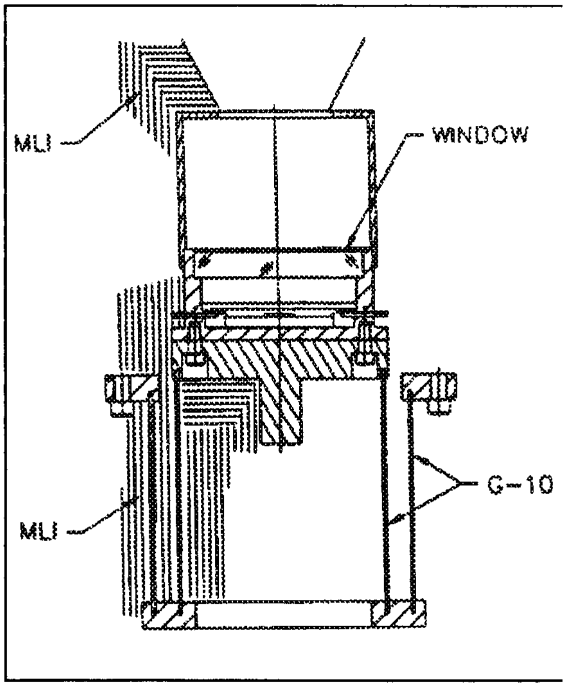

Figure 1. Conventional suppot method.

although small, have a significant thermal impact on systems with reduced cooling capacity. For systems using an expendable cryogen as the heat sink, mission life is limited. In systems using mechanical coolers, refrigerator cooling capacity may be exceeded.

Second, the first natural resonant frequency is typically 50-70 Hz for the concentric G-10 cylinder approach. Higher values are desirable to avoid the risk of resonant response during launch.

Increasing financial limitations, translating to ever more stringent mass and size constraints for satellites, provide motivation to develop alternative ways to support cooled telescope components in order to significantly reduce the parasitic heat load on the low temperature sink. This will make possible the use of smaller, lightweight mechanical coolers or perhaps less cryogen than would otherwise be necessary for systems using expendable cooling methods.

After a short period of research, my advisor and I embarked on my thesis project which was the task of developing what we have affectionately termed FiST (Fiber Support Technology). The concept behind this design approach was to utilize high performance fibers in tension to mechanically support and thermally isolate a cooled component (see Figure 2).

We looked at utilizing the FiST design approach to support the focal plane assembly of a space-based infrared instrument called SABER (Sounding of the Atmosphere using Broadband Emission Radiometry). SABER is the primary instrument on the TIMED satellite sponsored by APL (Applied Physics Laboratory) at John Hopkins University. The Space Dynamics Laboratory, teaming with the National Aeronautics and Space Administration at Langley, Virginia (NASA LaRC), are currently in the process of designing the SABER instrument which will study the earth's limb.

Cooling of the infrared sensors on this instrument is to be provided by a miniature pulse tube refrigerator, which provides roughly 250 mW of cooling at a cold block temperature of 72 K.

If other parasitic heat loads calculated for the SABER Focal Plane Assembly (FPA) are added to the conduction through the G-10 tubing of the conventional support method shown in Figure I (approximately 85 mW), it would preclude the use of this small, lightweight, low input power refrigerator. The SABER instrument would then not be possible under present mass and power constraints (Jensen 1 996a).

FiST consists of four basic components: the outer and inner support structures, strands used to couple these structures and fasteners on each end of the strands to provide attachment points.

The outer support structure is the mechanism that provides an attachment point to the warm surroundings. The inner support structure usually provides a platforrn for the cooled components to be placed. However, this configuration need not be the case. Depending on the application, the inner support structure could serve as the warm support and the outer support structure is the cooled component.

While there is no one design for the outer and inner support structure, there are several things that must be considered when designing these components: First, the supported weight and conducted parasitic heat load allowed must be known. This is critical in determining the number of strands needed in the design. The number af strands then drives the geometry of the outer and inner support structures. Second, the space available for the FiST system to occupy must be known. Small or large spaces drive the design to the size of strand and strand fastener that can be used. Third, the inner, or possibly the outer, support structure typically will be in the middle of some thermal path. It is critical to make the length of this part as short as possible while maximizing the cross-sectional area to reduce the overall temperature gradient in the thermal path. Material selection here will be critical from both a mechanical standpoint as well as a thermal standpoint. And Fourth, the outer support structure and inner support structure must be designed to mechanically handle the harsh dynamic environment of launch. Figures 3 and 4 show possible configurations for the outer and
inner

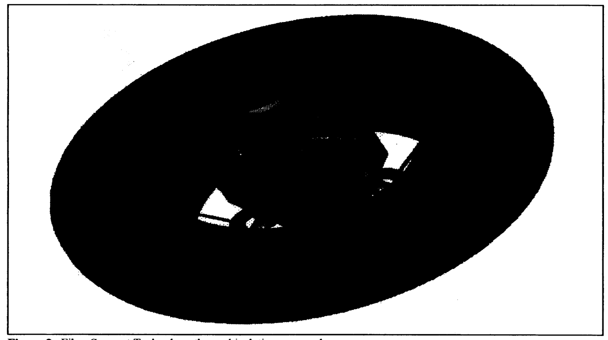

Figure 2. Fiber Support Technology thermal isolation approach.

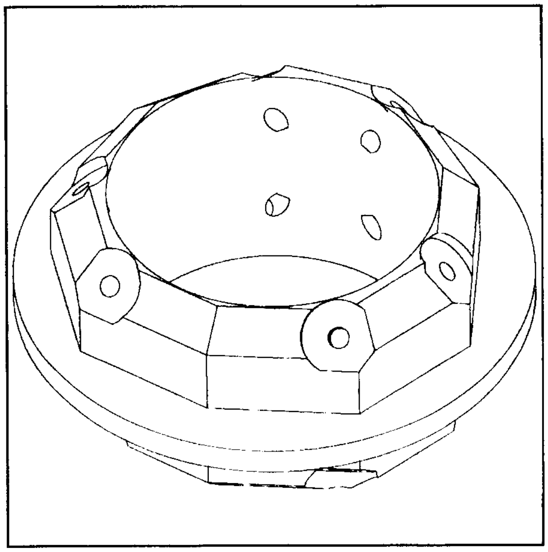

Figure 3. Possible outer support structure configuration.

support structures.

The central component of the FiST system is the fiber. It provides the necessary thermal isolation for the cold components as well as the mechanical rigidity for the system. In determining the fiber to be used for the SABER FPA, many factors had to be considered. First, the thermal conductivity

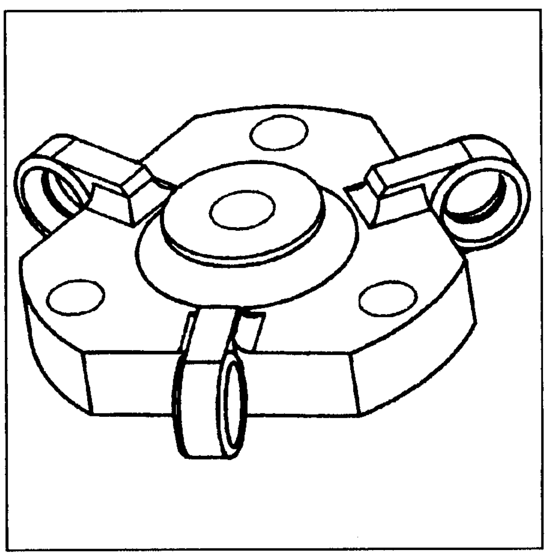

Figure 4. Possible inner support structure configuration.

of the fiber selected must be low enough to limit the conducted heat loads incident upon the FPA to values less than approximately 10 mW. Second, the fiber selected must be sufficiently strong to withstand the rigorous loads incurred during launch. Third7 molecular breakdown in certain environments and out-gassing of the material is critical due to the sensitive nature of the instrument. Optical systems must be virtually contamination free and high outgassing materials are unacceptable. And Fourth, the fiber is unmanageable in its raw form, so a braiding scheme had to be determined.

Several different fibers were considered and a decision based on overall properties of the fiber. Table I and Figure 5 are a summary of some of the critical properties of these fibers. Based on a compromise between mechanical and thermal performance, Kevlar 49 fiber was selected for use on the SABER instrument and proves to provide superior thermal isolation while maintaining sufficient mechanical strength. Once the fiber selection was finished, an approach to taking hold of the strand, without inducing sufficient shear loading to weaken the strand, was needed. When designing a strand fastener7 there were several things that had to be considered: First7 shear loading must be minimized. Shear strength testing of the fiber showed that shear loads considerably weaken the strength of the fiber. Second, the SABER FPA sits in a very confined space so the strand fasteners must be very small. Room is not available for large radius fasteners such as eyebolts. Third, the strand fastener strength must be comparable to the strength of the strand. The current design of the strand fasteners shown in Figure 6 meets all of the requirements previously specified.

Table 1.--Material Properties of Selected Fibers

Fiber Description	Thermal Conductivity (W/m-K)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Tendency to Creep
T-300 Carbon	13.0	231	3240	Small
E-Glass (G-10)	1.0	72	3100	Small
Spectra 900	0.30	174	3128	Large
Nomex	0.13	13	614	Large
Vectran HS	0.20	65	2841	Very Small
Kevlar 49	0.04	124	2800	Small

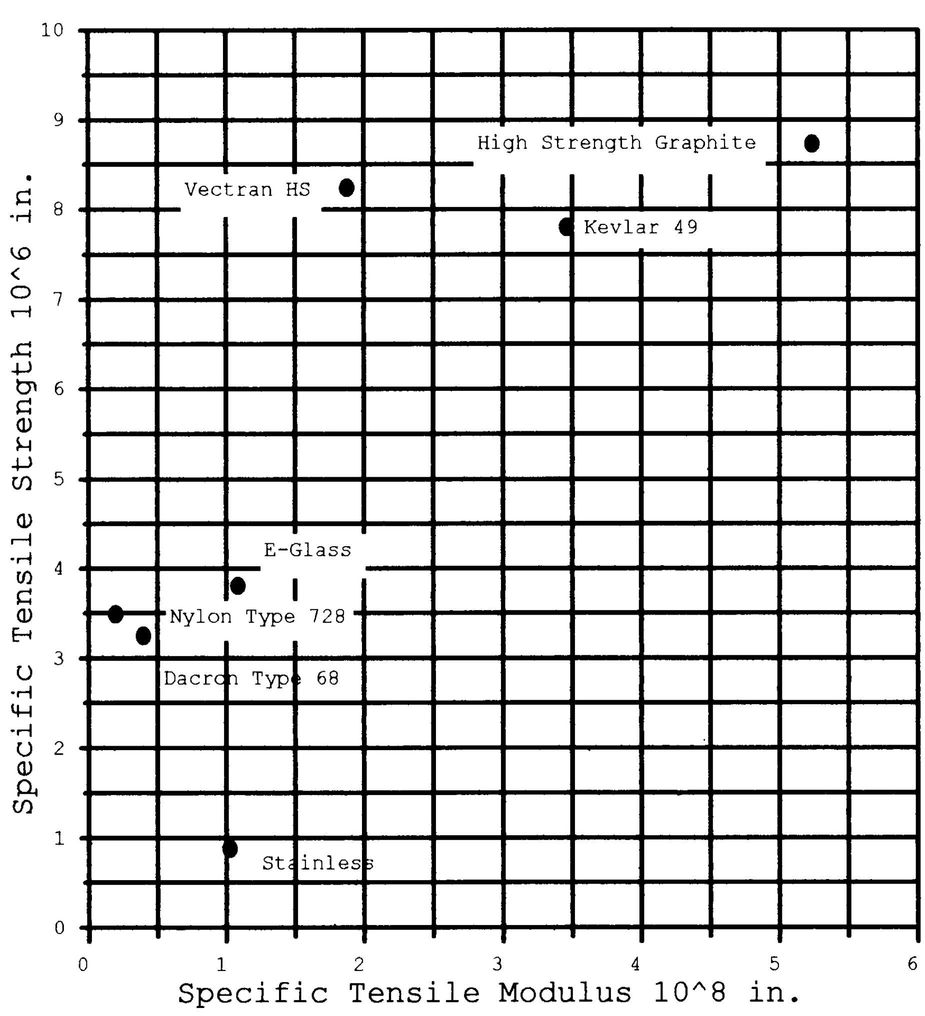

Figure 5. Specific tensile strength and specific tensile modulus of various materials.

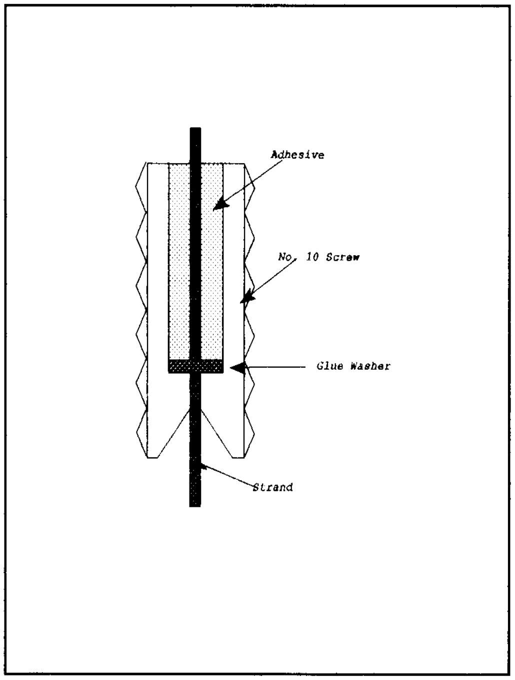

Figure 6. Strand fastener design.

The assembled FPA support system, as is shown in Figure 2, is mechanically robust. The predicted first natural resonant frequency of this system is approximately 700 Hz. This is an order of magnitude larger than needed to avoid the risk of resonant response during launch.

Thermally the FPA support system is very effective. A total of no more than 4 mW is expected to come through 12-.035" Kevlar 49 strands .5" long. When compared to 85 mW conducted through the supports of the conventional &- l O tube approach, this is a major advance in thermal control technology. The added bonus comes in that there are no known negative impacts on the mechanical properties of the system.

3.0 Solderless Flexible Thermal Links

Flexible therrnal links play an important role in the thermal management of cryogenically cooled components . Their uses range from linking space based sensors to cryogenic mechanical refrigerators to connecting massive storable cryogen tanks to optical components for terrestrial based applications. The purpose of the thermal links is to provide a means of transferring heat from a cooled component to a cooler reservoir while minimizing mass and temperature drop.

When a thermal link is attached to the cold block of a mechanical cryogenic mechanical refrigerator, extreme care must be utilized due to the very fragile nature of the thermally isolating cold block support. For space based applications, the thermal link must be extremely light to ensure that large inertial forces are not imposed on the cooler during launch. Some systems have the added requirement of vibration suppression between the sensor and cold sink, hence the need for a flexible thermal link to dampen out vibrational effects which may affect proper operation of the sensor. Flexibility is also advantageous because it allows for relative motion between the sensor and the cold block during assembly and operation.

Flexible thermal links are typically made of braided wire or foil strips. A standard approach to making a link is to solder flexible foil or braid between two solid end blocks machined to the proper size and shape. This approach has a few limitations: First, the solder adds a thermal impedance to the link. Solder is a poor conductor compared to typical link materials such as copper and aluminum; for systems with little margin for added temperature gradients, this can be prohibitive. Second, for highly sensitive optical systems, the outgasing of the solder could pose a potential problem by contaminating optical surfaces. Third, the solder could wick into the braid making it stiffunless special precautions are taken when soldering the link.

The soldering technique required to eliminate wicking, and to minimize the solders' effect on impedance, is very time consuming and requires the skill of a well practiced technician.

Seeing the need for better, simpler thermal links, a team of engineers at Utah State University, Brian Williams, Scott Jensen, and Dr. J. Clair Batty, have developed a simple solderless process for securely attaching flexible foil or braid into solid end blocks. This process called "swaging" dramatically reduces the thermal impedance at the interface between the foil/braid and block while maintaining original flexibility. Copper has long been the material of choice for these links due to its relatively high thermal conductivity. However, for this research we did not limit ourselves to copper and investigated other materials such as aluminum and the advantages and disadvantages for using them.

A soldered link, fabricated by a well known aerospace firrn, and a swaged link, developed and built by USU, were tested. Both links used the same braid, having identical construction (same cross-sectional heat transfer area).

Figure 7 shows results from the thermal comparison test of these two links. Included on the plot are thermal resistance's of the soldered link? the swaged link, and the theoretical value for a link based on the analytic solution calculated with Equation 1, as a function of electrical heater power. The swaged link exhibits a decrease in thermal resistance as compared to the standard soldered link and approaches the theoretical limit which assumes no contact or joint resistance.

$$R = \frac{L}{KA} = \Delta\frac{T}{Q} \qquad (1)$$

The thermal resistance caused by the joint can also be derived from these data. It was assumed that the contact resistance may be calculated as shown in Equation 2 (Incropera 1981).

$$R_c = R_m - R_t \qquad (2$$

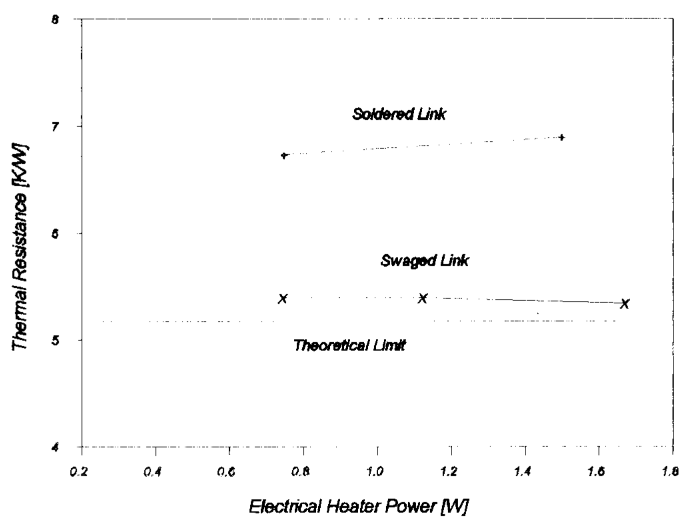

Figure 7. Results of thermal conductivity tests for swaged and soldered thermal links.

The ideal case, with no contact resistance, was calculated to have a thermal resistance of 5.17 K/W. For the soldered link, the measured resistance was found to be 6.81 K/W and for the swaged link7 the thermal resistance was found to be 5.37 K/W. Using Equation 2 results in a contact resistance of 1.64 K/W for the soldered link and 0.20 K/W for the swaged link. Therefore, for this example, the swaging reduced the contact resistance by almost 90% (Jensen 96b). If one takes into consideration that the thermal conductivity of a material could differ slightly from published values, the difference between the swaged and theoretical values may disappear entirely.

A flexible thermal link recently fabricated and tested at USU had the following requirements specified:

I . A thermal resistance of 2.2 K/W at liquid nitrogen temperatures.

2. A total link mass of less than 100 grams.

3. Must fit in volume available:
   a. Diameter less than 50.8 mm
   b. Cold block to sensor length of 86 mm
   c. Maximum end block width of 31.8 mm

4. Flexibility of each of the 3 axes taken individually < 3 Newton's for a displacement of 7 mm.

5. Link to be flight qualified by a shaker test at specified shake levels of 32 g rms.

A link was then constructed which met the geometrical configurations specified previously. The performance parameters of the link were then measured and shown to be 1. Total mass = 63 grams. 2. Thermal Resistance = 1.9 K/W. 3. Flexibility

x-axis =1.85 Newtons/7mm
y-axis =.80 Newtons/7mm
z-axis =.75 Newtons/7mm

A picture of this completed link is shown in Figure 8 in a holding jig.

4.0 Control Refrigerator Reject Temperatures

With superior thermal isolation from the FiST system supporting the SABER FPA7 and an enhanced high efficiency thermal link connecting the cooled components of the FPA to a mechanical refrigerator, it was time to focus our attention on reducing the power needed to drive the TRW miniature pulse tube refrigerator cooling the optical sensors. The reject temperature of these coolers strongly influences the cooling capacity available. Effectively controlling the reject temperature of this mechanical refrigerator could result in mass and power savings on the small satellite system. Currently we are working on a radiator/cooler mount configuration which would cool the TRW pulse tube refrigerator to approximately 273 K. Because thermal stability of the sensors is very critical for proper operation of the SABER FPA, a stable mount coupling the cooler and refrigerator must be developed. A mount which very efficiently conducts the heat out of the cooler and into the radiator would be very susceptible to fluctuations caused by albedo and other external heat loads. On the other hand, a mount which is highly insulated from the baseplate would be extremely difficult to control due to the lag time between environmental heat loading and the control heater inputs. A heater must then be placed on the properly designed mount and controlled using a controller. A properly isolated

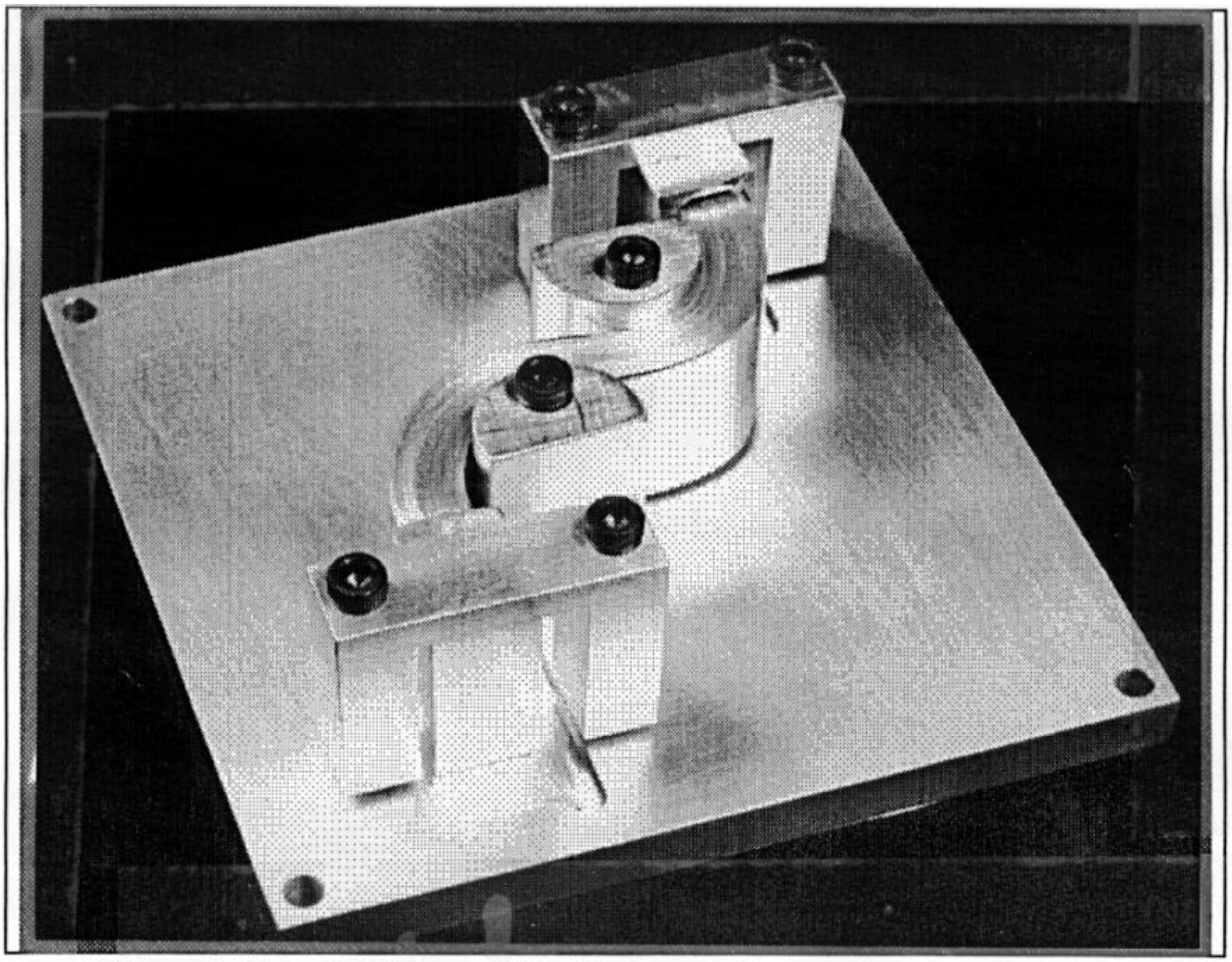

Figure 8. Advanced solderless flexible thermal link in shipping support jig.

cooler mount, coupled with a heater connected to a control system will adequately dampen out the oscillatory affects of environmental and operational heat loading. This will provide a stable platform from which the cooler can maintain precise temperature control of the cooled component while preventing temperature excursions below the recommended operating temperature of the refrigerator.

By reducing the reject temperature from 300 K to 273 K and providing a stable temperature platform for the refrigerator to operate, the cooling capacity is nearly doubled from 250 mW to 500 mW while maintaining the same input power. If the added cooling capacity is not needed, the input power could be reduced by nearly 5 watts and yield the same heat lifting capacit~ as would be achievable at a reject temperature of 300 K and 20 watts inpul the system. By controlling the reject temperature of these refrigerators the ma~, power, and size demands on the SABEn instrument have been reduced.

Summarv and Conclusions

r~ very rigid support structure, zing Kevlar 49 strands in a tension support scheme, has been successfully designed and tested. The instrument being supported has a first natural resonant frequency and order of magnitude above the maximum 70 Hz expected during launch. This was verified theoretically as well as with testing. The heat loads of the system due to conduction have also been reduced nearly an order of magnitude from 85 mW down to less than 5 mW.

We feel that this new technology, FiST, meets all of the conductive heat load and mechanical sti~ness requirements and that this will prove to be a valuable technology in the future.

A new method has been developed to fabricate reliable, efficient, solderless flexible thermal links using the swaging process. The swaging process essentially cold welds braid/foil and end blocks into one integral piece in which the contact resistance is dramatically reduced. Compared to the standard soldering approach, this process has proven to be relatively fast, simple, and low cost. As an added benefit, preliminary tests indicate that the swaged link has lowered contact resistance by nearly 90% or more.

Thermal control of cryogenic mechanical refrigerators reject temperature is a cheap and practical way of improving the performance of miniature mechanical refrigerators while reducing the demands on power, mass, and volume of the small satellite system. Much work is yet to be done on this area, however, the preliminary results look very promising.

We believe that these three advancements in thermal control technologies will indeed further the objective of producing satellites which are "smaller, better, faster, and cheaper".

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