# COLD-TIP OFF-STATE CONDUCTION LOSS OF MINIATURE STIRLING CYCLE CRYOCOOLERS

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## ABSTRACT

For redundant miniature Stirling-cycle cryocoolers in space applications, the off-state heat conduction down the coldfinger of one cooler is a parasitic heat load on the other coolers. At JPL, a heat flow transducer specifically designed to measure this load has been developed, and measurements have been performed on the coldfinger of a British Aerospace 80 K Stirling cooler with the tip temperature ranging between 40 and 170 K. Measurements have also been made using a transient warmup technique, where the warmup rates of the coldtip under various applied heat loads are used to determine the static conduction load. There is a difference between the results of these two methods, and these differences are discussed with regard to the applicability of the transient warmup method to a non-operating coldfinger.

## INTRODUCTION

An increasing number of astronomical and earth-observing space detectors have cryogenic cooling requirements, leading to a high demand for miniature space-qualified cryocoolers. These coolers must not only have high reliability and 5 - 10 year lifetimes, but must also be interfaceable to sensitive space instruments. The frontrunner in the technology to provide cooling in the 50 K - 150 K temperature range is a split-Stirling-cycle cryocooler based on a design originated at Oxford University[1,2]. This cooler uses tight tolerance, non-contacting clearance seals on the piston and displacer, linear motors, and spiral diaphragm flexure springs to maintain alignment of the piston and displacer within their clearance seals. The Jet Propulsion Laboratory (JPL) has a comprehensive test and analysis program underway to understand this cryocooler with regard to reliability and integration into space-instrument systems.[3] Among the issues being addressed are output vibration levels[4], EMI[5], thermal performance, life testing, and developing non-obtrusive diagnostic methods for detecting failure mechanisms.

One issue regarding systems integration is the off-state (non-operating) coldtip conduction heat load, where, in systems using redundant coolers without heat switches, the heat conducted down the coldfinger of a non-operating cryocooler is a parasitic load on the operating coolers. For various versions of the Oxford-heritage 80 K cooler, the reported values of this heat load range from 250 mW to 550 mW for coldtip temperatures near 55 K . Because this level of parasitic heat load is a substantial fraction of the available cooling power at these temperatures, accurate data of the heat load is essential for systems design.

A static conductance measurement technique has been developed by JPL to measure the coldfinger conduction load in a test setting that simulates the flight configuration of redundant coolers. In the test configuration, the coldfinger of the test cooler is enclosed in a vacuum housing together with the coldfinger of a second cooler that is used to cool the coldtip of the non-operating test cooler down to typical flight operating temperatures. The heat load of the test cooler is measured using an absolute heat flow transducer specifically designed for this application. This method has been applied to the BAe Oxford-heritage 80 K cooler, and the experimental details and results are presented in the first section of this paper.

A series of experiments have also been performed using the transient warmup technique[6] commonly used in the cooler industry. In this method, the cooler is first operated to cool its coldtip to its base temperature. The cooler is then turned off, and a known heat load is applied to the coldtip. By measuring the warmup rates with several different applied heat loads, the off-state conduction load can be determined. These measurements were made on the same BAe cooler used in the static conductance experiments in order to make a comparison of these two techniques. The second section of this paper presents these measurements, and discusses the differences in the results between this method and the static conduction method.

## STATIC CONDUCTANCE MEASUREMENTS

The static conductance measurements involved the use of a second cryocooler to cool the coldfinger of the non-operating BAe cooler, with the two coldtips thermally linked to each other through the absolute heat flow transducer. The parasitic heat flow down the test coldfinger passes through the transducer enroute to the other cooler, providing a direct measurement under true steady-state conditions.

In the experimental arrangement, shown in Fig. 1, a 10 K Gifford-McMahon (GM) cryocooler, with its temperature regulated using a resistive heater and temperature controller, provided the cooling for the BAe coldtip. Both coldfingers were contained within a vacuum housing and linked through a thermal strap made of parallel strips of copper foil. To minimize the radiation heat leak, the BAe coldfinger was loosely wrapped with several layers of 0.009 mm doubly aluminized embossed Kapton. Because of the cryopumping of the GM cryocooler, the vacuum within the housing was in the $10^{-6}$ - $10^{-7}$ Torr range.

The heat flow transducer, shown in Fig. 2, is a thermal shunt made of a short section of german silver, a high thermal resistivity material. By measuring the temperature drop ($\Delta T$) across the shunt, the heat flow $Q_p$ can be determined from:

$$Q_p = \kappa \Delta T$$

where $\kappa$ is the thermal conductance of the resistive element. Two copper end-pieces were silver soldered to the ends of the german silver, insuring isothermal

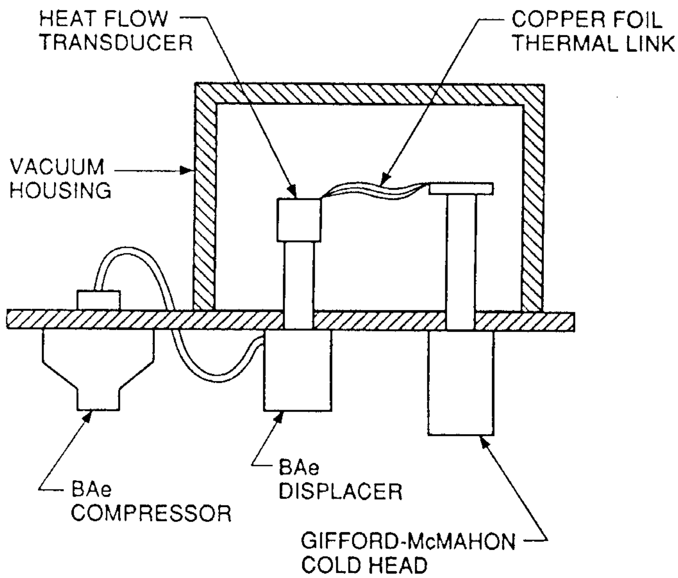


Fig. 1. Schematic of the static conduction test apparatus.

boundaries to create uniform heat flows across the resistive element. Diode temperature sensors (Lakeshore DT-470) were epoxied into each end cap, and an aluminum radiation shield enclosed the transducer. The radiation shield was heat sunk to the side of the transducer thermally anchored to the GM cryocooler so that the radiation heat load did not pass through the german silver shunt. The transducer was calibrated by thermally anchoring only one end to the GM cryocooler, applying measured heat loads with a resistive heater to the other end, and recording the resulting temperature differences.

Data were taken by regulating the GM cooler at a particular temperature, waiting several minutes for the BAe coldtip temperature to stabilize, and then re-

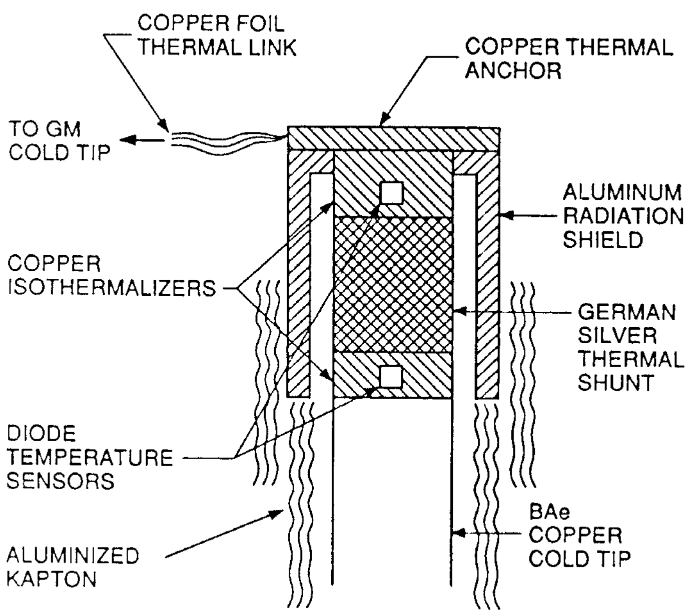


Fig. 2. Schematic of the absolute heat flow transducer as mounted on the BAe coldtip.

cording the temperature drop across the transducer. Fig. 3 shows the static conduction loads as a function of temperature; the results range from about 340 mW at 40 K to about 210 mW at 170 K. The data on this plot were taken both stepping up and stepping down in temperature, and a few of the points were taken after allowing the system to remain at the same temperature overnight. The repeatability indicates that temperature gradients within the coldfinger were well stabilized.

## TRANSIENT WARMUP MEASUREMENTS

To perform the transient warmup measurements, a resistive heater, imbedded in a copper block, was mounted to the cooler coldtip, and several layers of aluminized Kapton were wrapped around the entire assembly with the edges sealed with aluminized Kapton tape. The Kapton shielding near the BAe coldtip was heat sunk to the GM coldtip, whose temperature was regulated at 50 K.

The data were taken by first running the cooler until the coldtip reached 50 K, stopping the cooler, then timing the warmup over set temperature intervals with a measured heat load applied to the coldtip as it warmed up to 95 K. The results, heat load vs. $1/\Delta t$, are shown in Fig. 4, where $\Delta t$ is the time required to warm the tip over a 10 K temperature range centered about the temperature of interest. For example, for the 80 K curve, $\Delta t$ corresponds to warming from 75 K to 85 K. Extrapolating to $1/\Delta t = 0$ gives the off-state conduction load, and the results are plotted in Fig. 3. The loads ranged from 390 mW at 60 K to 320 mW at 90 K, and are significantly higher than that using the static conductance technique.

To understand the difference between these two results, a simple model of the warmup technique can be made. The warmup time, $\Delta t$, for a given coldtip tempera-

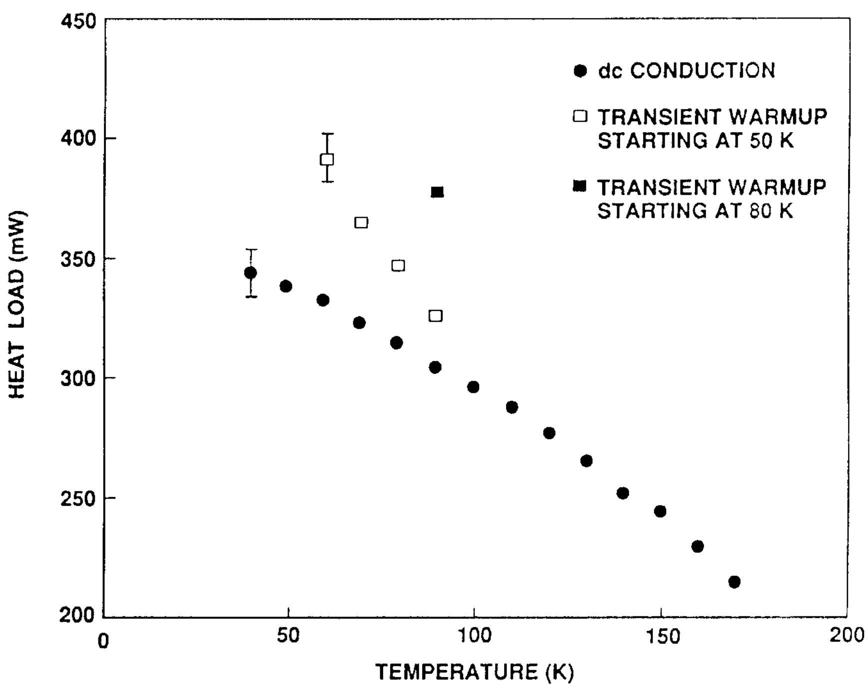


Fig. 3. Coldfinger off-state conduction loss as measured by the static conduction method and the transient warmup method.

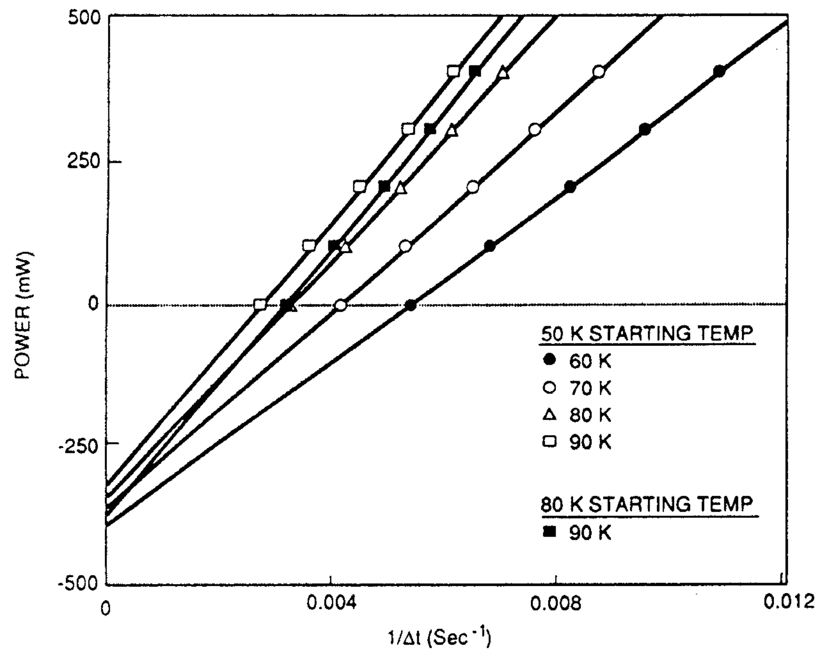


Fig. 4. Results of the transient warmup measurements.

ture rise $\Delta T$ is given by:

$$C \frac{\Delta T}{\Delta t} = Q_h + Q_p$$

where $Q_h$ is the applied heat load, and $Q_p$ is the parasitic heat load given by:

$$Q_p = K_{eff} \frac{dT}{dx}$$

Here $K_{eff}$ and $dT/dx$ are the thermal conductance and temperature gradient of the coldfinger near the coldtip. The heat capacity of the coldtip, C, is provided by the copper heater block and a copper mass soldered onto the end of the coldfinger. Because of the cold-finger MLI, the radiation heat load is assumed to be small. If $dT/dx$ is constant within the 10 K timing intervals, independent of the applied heat load, then $1/\Delta t$ should be linear in $Q_h$. This linearity is apparent in Fig. 4. As a further consistency check, the slopes of the lines, which should be equal to $C\Delta T$, agree with estimates of the heat capacity of the copper masses and have the same temperature dependence as the specific heat of copper. These arguments suggest that $dT/dx$ is being measured correctly with this method, and that $dT/dx$ is higher in the coldfinger of a running cooler than in a non-operating cooler.

To investigate this, two different data sets were taken, timing the warmup between 85 K and 95 K, but with one set starting with the coldtip cooled to 50 K, and the other cooled to 80 K. These two sets of data are shown as the ■ and □ in Fig. 4, and the resulting measured heat loads are shown in Fig. 3. The run starting with the tip initially cooled to 80 K gave the higher load, while the run starting with the tip cooled to 50 K approached the static conductance values. This suggests that in warming up from 50 K to the 85 K - 95 K timing interval, the coldtip has relaxed into a temperature profile more similar to that of a non-operating cooler.

The steeper temperature gradient in a running cooler may be due in part to the higher temperature of the ambient end of the coldfinger. Measurements of the displacer body temperature near the base of the coldfinger indicate that it is 10 K 15 K above the ambient temperature of 295 K, and the temperature of the warm end of the regenerator may be even higher. Orlowska and Davey[6] estimate that the average gas temperature within the compressor is 320 K, so if this is also the regenerator warm end temperature, the running cooler would have temperature gradients that are 10% steeper corresponding to a 10% increase in the parasitic heat load. This would account for a significant fraction of the difference between the results of the transient warmup and static conductance methods.

A running cooler is also likely to have a different coldfinger temperature profile than a non-operating cooler due to the heat transported by the moving gas and by shuttle heat transfer. However, an analysis of the resulting temperature profiles and the effects on these measurements is beyond the scope of this work.

In making the transient warmup measurements, the GM cooler was used to cool the aluminized Kapton shielding near the tip of the BAe cooler to 50 K. If the GM cooler coldtip was left at the ambient temperature of 295 K, the measured heat loads were about 30 mW higher than the above results. Other preliminary tests with differing radiation shielding arrangements also suggest an uncertainty in the amount of residual radiative heat leak, conservatively estimated on the order of 30 mW, in the experimental configurations used in these experiments.

## SUMMARY

The integration of miniature split-Stirling-cycle cryocoolers into space-instrument systems requires accurate data on the off-state parasitic conduction load of the coldfinger, particularly for systems using redundant coolers without heat switches. This load has been measured for the British Aerospace version of the Oxford University 80 K cooler using a static conduction method with an absolute heat flow transducer developed at JPL. The values obtained ranged from 340 mW at 40 K to about 210 mW at 170 K.

Measurements were also performed using a transient warmup technique. This method was shown not to measure the off-state conduction load accurately, as the results were consistently higher than those from the JPL static conductance measurements. The disagreement is likely due to the steeper temperature gradient in the coldfinger of a running cooler as compared with a non-operating cooler, due in part to the higher warm end temperature of a running cooler.

## ACKNOWLEDGEMENTS

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