Design and Implementation of a Ground Test Configuration for a Space Infrared Sensor

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ABSTRACT

A Gifford-McMahon type cryocooler was successfully used as a low cost, low risk cryogenic cooling solution for the ground demonstration of a space infrared sensor. The program desired a cryocooler that could provide more than 50 W of cooling at 100 K to collect sensor performance data would not be jeopardized by a lack of cooling capacity. In addition, aggressive cost and schedule constraints were placed on the cryogenic cooling system. Several methods for providing cryogenic cooling were considered. A summary of the trade study is presented herein. The mechanical integration of the G-M type cryocooler is also presented. Because of the sensor's sensitivity to jitter, the rotary valve and its drive motor were removed from the cold head and placed in a remote motor housing, in order to mitigate the amount of vibration imparted to the system by the cryocooler.

Finally, a description of the cryogenic cooling system test setup and performance data for the G-M cryocooler is presented. A conduction bar was calibrated using the G-M cryocooler, and served as a "Q-meter" to determine the sensor's waste heat. Heaters and feedback control temperature sensors were placed on both ends of the conduction bar, and were used to control the temperature at locations of interest inside the sensor.

INTRODUCTION

The focus of the space infrared sensor ground demonstration program was to show that the optical design and focal plane arrays performed as intended. The technical requirements levied on the Cryogenic Cooling System (CCS) were stringent. First and foremost, the CCS had to provide sufficient cooling capacity, such that changes in the sensor thermal design would not impact its ability to cool the sensor adequately. As the sensor thermal design was still somewhat fluid at the time the CCS was designed, a large performance margin was required. In addition, the CCS had to impart very little vibration onto the sensor assembly, as the jitter requirements for the sensor were extremely demanding. Also, the CCS had to have minimal special facility support requirements.

Finally, the CCS had to cost substantially less than a flight design cryocooler system, even if the cryocooler was built to engineering model quality requirements, and had to be available within 6 months of placing the order. This requirement eliminated the possibility of procuring a

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new, long life, space cryocooler, as the lead time for a space cryocooler system is usually on the order of 14-18 months.

CRYOGENIC COOLING SYSTEM TRADE STUDY

Having already eliminated the option of procuring a new, flight design cryocooler system, several other options were considered. The first option was to use a preexisting space cryocooler. The second option was to design and build an LN_2 cooling loop, and the third option was to purchase a laboratory grade cryogenic cooler.

Several preexisting space cryocoolers were considered for the CCS. Using a space cryocooler was desirous, because it would be more representative of an integrated flight sensor design. However, all of the existing cryocoolers available were limited in the amount of heat they could lift. None of them could provide the required performance capacity of 50 W of cooling at 100 K. Also, there were accessibility issues with each existing cryocooler option. The cost of using the hardware were prohibitive. As a result, the use of preexisting hardware was eliminated.

The second option was to design and build an LN_2 cooling loop. This option was not pursued because of the amount of time required to design the system, generate and approve drawings, and then have the parts fabricated would not support the need date for the CCS. In addition, this approach was seen as risky, because it would be a brand new system design. Furthermore, this system would require facility support in the way that the liquid nitrogen plumbing, nitrogen venting systems and oxygen monitors were designed. Not all of the labs under consideration for sensor testing had this infrastructure in place. Liquid nitrogen dewars could be used for supply, but that would result in the need to design a manifold system to enable the dewars to be changed out as the LN_2 was expended, and this approach would still require a venting system and oxygen monitors.

As a result, the program decided to purchase a closed system, laboratory grade cryocooler. After considering several manufacturers, a Cryomech PT-60 cryorefrigerator was selected for the CCS. The Cryomech PT-60 cryorefrigerator is a single-stage pulse tube, with a nominal no-load temperature <30 K and cooling capacity of 60 W at 80 K with an input power of 4.0 kW.[1] The nominal PT-60 cryorefrigerator consists of a pulse tube cold head and rotary vane compressor module. Flexible metal hoses connect the high and low pressure side of the compressor to the pulse tube cold head. A rotary valve directs the helium gas working fluid in and out of the pulse tube.[2]

MECHANICAL INTEGRATION

Thermal Interface

Flexibility was designed into the CCS to enable the insertion of a flight design cryocooler at a later date. The thermal interface and vacuum interface were both sized with that intent in mind.

A copper conduction bar served as the thermal interface between the Cryomech PT-60 cold tip and the thermal manifold within the dewar. The conduction bar was sized such that the distance between the sensor thermal manifold and the mounting flange on the dewar could accommodate any number of flight design cryocoolers. It was also designed such that a temperature gradient always exists across the conduction bar, keeping the Cryomech PT-60 cryorefrigerator cold tip temperature colder than the sensor thermal manifold temperature while the PT-60 is running. This enabled the Cryomech PT-60 cold tip to act as a “getter” for contamination control, in addition to providing cooling for the sensor assembly. Figure 1 shows the conduction bar.

The conduction bar also served as a Q-meter during sensor testing. It was calibrated so that measuring the temperature at each end of the conduction bar, and correlating it to the conduction bar calibration curve enables the determination of the sensor’s waste heat.

Mechanical Interface

The mechanical interface also served as the vacuum interface, and was comprised of a customized 5-Way Cross vacuum chamber (Figure 2). One of the flanges on the 5-Way Cross was customized to mate with the Cryomech PT-60 base tube assembly, and one was used to mate with

Figure 1. Copper conduction bar - attaches to the sensor thermal manifold on the left, and Cryomech cold heat exchanger on the right.

the sensor housing. Two of the remaining flanges were used as access ports, and the third was used to mount the penetration plate, which housed the electrical feed-throughs needed for instrumentation and heater control, and the vacuum pump mating flange used during sensor testing. A butterfly valve was also used to isolate the sensor from the vacuum system, if required.

For ambient sensor testing, a 300 liter per second vacuum pump cart consisting of an oil-free scroll pump and magnetically levitated turbo pump was attached to the penetration plate. There was a concern that the Cryomech PT-60 and turbo pump would introduce excessive jitter into the sensor. An ion pump was installed for use when vibration sensitive measurements were taken. A flexible bellows was placed between the CCS and sensor mating flanges to provide further isolation of the sensor from the vibrations emitted from the CCS. In addition, the Cryomech PT-60 rotary valve and its motor were removed from the cold head assembly and put into a remote motor housing. The remote motor assembly was connected to the cold head assembly using another flexible metal line. This also helped to isolate the sensor from cryorefrigerator emitted vibration, as most of the vibration comes from the movement of the rotary valve.

Facility Support Requirements

The Cryomech PT-60 required 208/230 Vac, single phase, 60 Hz input power. Cooling water was also required for cooling the compressor. The initial plan for cooling the compressor was to use a recirculating chiller. However, the compressor created too much heat for the available recirculating chiller. The flow rate and water temperature requirements on the Cryomech specification sheet were met, but the cooling cart reservoir was too small, and its refrigerator could not keep up with the heat output of the compressor. Within a few minutes, both the inlet and outlet lines of the cooling cart were warm. This required the installation of facility chilled water with a 277 – 283 K, ~ 25 psi supply, and an "infinitely large" reservoir.

A cooling circuit was required to remove heat from the warm end of the PT-60 pulse tube. In a nominal, water-cooled PT-60 system, the heat generated by the P-V work at the warm end of the

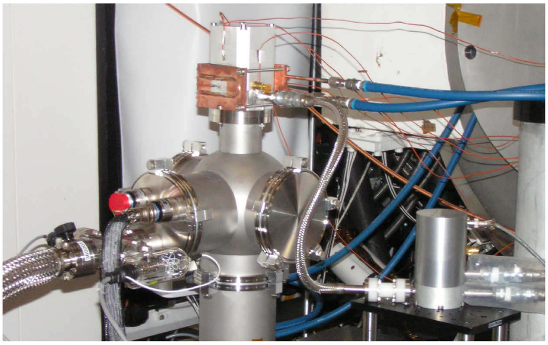

Figure 2. Mechanical Interface (L-R): Butterfly Valve, Penetration Plate, 5-Way Cross. Also shown: Cryomech PT-60 Cold Head (Top Center), and Cryomech Remote Motor Assembly (Bottom Right).

pulse tube is removed when the gas returns to the compressor and is cooled there. No additional cooling is necessary at the cold head assembly. However, when the rotary valve motor assembly was removed and remotely located from the cold head assembly, the expander working gas merely shuttled back and forth at the expander inlet. The temperature at the warm end would rise above the PT-60's maximum operating temperature of 311 K until an additional cooling circuit was installed on the cold head assembly. A cold plate was custom built and installed on the PT-60 cold head, and the cold head assembly temperature was maintained within the Cryomech operating temperature limits of 280 - 311 K.

Test Setup

The CCS was required to provide cryogenic cooling and maintain a high vacuum environment inside the sensor housing during ambient laboratory testing, as well as provide cryogenic cooling during thermal vacuum testing. The PT-60 system had flex lines that were 3 m between the compressor and remote motor assembly, and 0.6 m between the remote motor assembly and cold head assembly for ambient testing. For thermal vacuum testing, a customized penetration plate with flex line attachments was purchased along with a set of 6 m flex lines to go from the penetration plate to the remote motor assembly inside the vacuum chamber.

In addition, the CCS was required to monitor and record temperature and heater power data as a stand-alone system, as well as interface with an external database, which would collect the telemetry and integrate it with the rest of the sensor data. All of the vacuum system monitoring and control was done manually.

The data acquisition and control system was comprised of a computer workstation, a National Instruments GPIB-ENET/100 box, 4 Lakeshore 340 Temperature controllers, six calibrated Lakeshore Diodes, 4 Lakeshore 100 W cartridge heaters, and 2 temperature alarm boxes. The heaters were used to maintain the temperature of the sensor assembly while the Cryomech was running. The data acquisition and control system provided the capability to manually control the heaters, as well as to use the Lakeshore 340 PID control for heater control. The temperature sensors on the conduction bar served as feedback sensors. It also monitored and recorded telemetry, including temperature set point, measured temperature, heater command, heater output power, temperature ramp rate command, and actual temperature ramp rate. The temperature alarms were triggered by either the primary or redundant feedback temperature sensors.

Thermal interface material was used between the conduction bar and Cryomech cold tip to minimize thermal resistance across the interface. After mating the Cryomech cold heat exchanger to the conduction bar, the temperature diodes were bonded to different locations along the cold heat exchanger and conduction bar, in order to provide a thermal map of the system. Figure 3 shows the CCS instrumentation map.

CONDUCTION BAR CALIBRATION TEST

Methodology

For the conduction bar calibration test, the CCS was placed into a vacuum chamber. Figure 4 shows the assembly just before it was mounted in the vacuum chamber. All of the access ports were

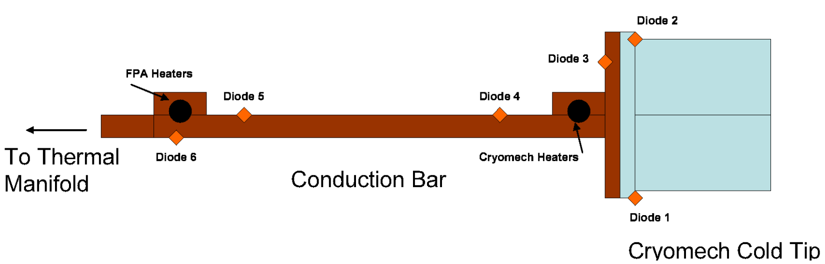

Figure 3. CCS instrumentation map (not to scale).

left open, and the electrical feed-throughs were installed in the vacuum chamber penetration plate. The CCS was mounted on an extension flange, with the conduction bar protruding into the extension flange.

For the first set of data points, no multilayer insulation (MLI) was used to shield the conduction bar or Cryomech cold tip from radiation from the 5-Way Cross, extender and vacuum chamber walls. This was done to expedite the initial system checkout and provide cursory data for initial thermal model correlation.

The conduction bar was calibrated by applying a known heat load to the thermal manifold end of the conduction bar, allowing the temperature to stabilize, and then leaving the system to dwell at steady state for a prescribed amount of time. The actual heat load vs. temperature data from the conduction bar calibration test was compared with the thermal model predictions for correlation purposes.

After the first test run, the assembly was taken out of the vacuum chamber and a 5-layer MLI blanket was installed on the conduction bar and the Cryomech cold tip. Figure 5 shows the assembly with the MLI blankets. Another set of data points was taken with the MLI blankets installed for comparison. The comparison between test cases with no MLI, and MLI installed helped to verify the accuracy of the thermal model prediction of the radiative heat load on the conduction bar and Cryomech cold head.

After the completion of the last test point for the conduction bar calibration, the Cryomech PT-60 was allowed to reach no-load temperature, and the cold head and conduction bar were allowed to come to thermal equilibrium. Then the PT-60 was shut off, and the warm-up rate of the cold head and conduction bar was measured and recorded. The warm end of the pulse tube remained approximately isothermal at ambient temperature. The cold head temperature rate of change and OFE copper specific heat over the linear portion of the warm-up curve in the temperature range of interest were used to calculate the parasitic heat load through the Cryomech cold finger.

Test Results

For the first test run, smaller heat loads were used. For the second test run, after the MLI was installed, the cold tip temperature was increased to ambient temperature. Figure 6 shows the comparison between the two test runs.

Figure 7 shows smaller heat loads, and the small radiative parasitic heat load from the ambient temperature vacuum chamber walls without the MLI installed. However, the Cryomech PT-60 was sufficiently oversized that this radiative heat load would not impact its ability to provide adequate cooling for the sensor. Note that these load curves will not match the Cryomech test data, as they

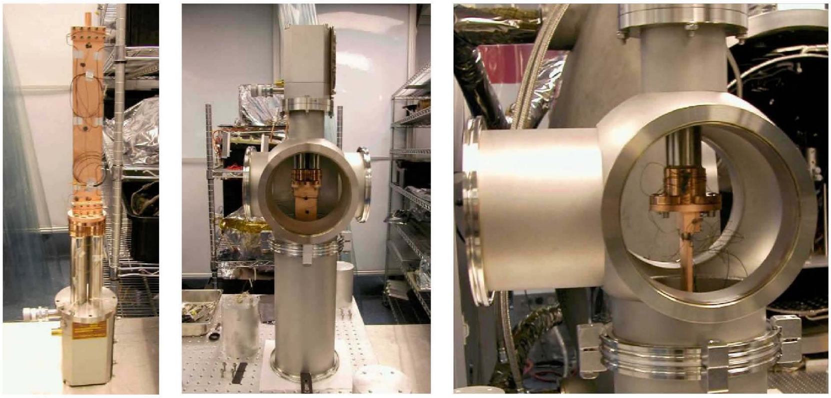

Figure 4. Instrumented Cryomech PT-60 cold head and conduction bar (Left), PT-60 cold head installed on 5-Way Cross with extension flange (Center, Right).

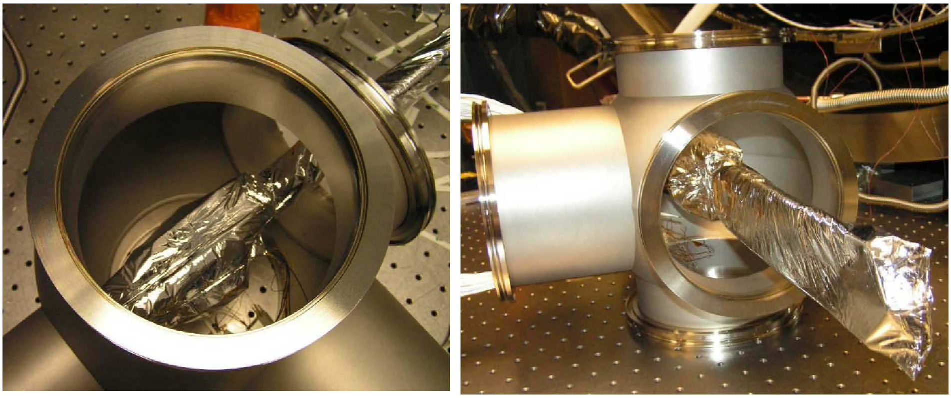

Figure 5. 5-layer MLI blanket installed on PT-60 cold tip (Left) and conduction bar (Right).

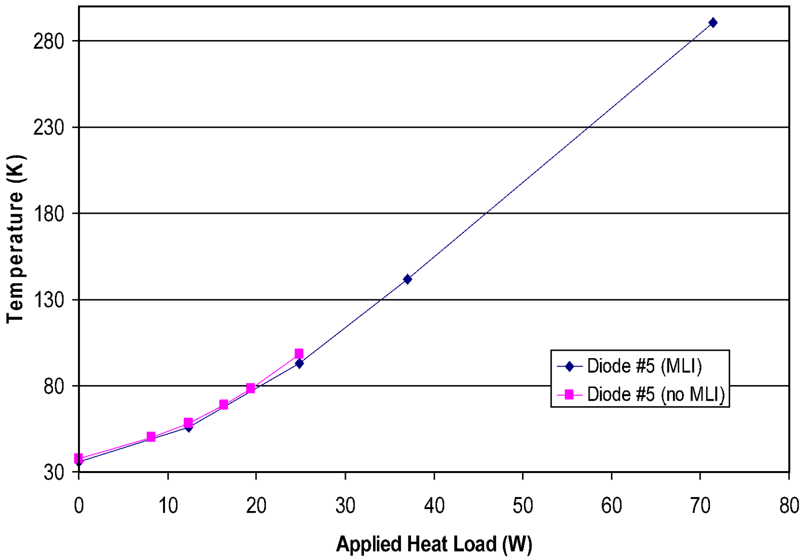

Figure 6. Load curve comparison for test configurations with and without MLI

include the extra parasitic heat load from the conduction bar. In any case no MLI was used for sensor testing because the PT-60 cold head was also used as a contamination control getter.

After the dwell period for the last conduction bar calibration test point was completed, the heat load was removed, and the system was allowed to stabilize again at the no-load temperature. At this point, the Cryomech PT-60 was shut off, and temperature data was taken for the warm-up curve. The parasitic heat load through the cold finger can be determined by using the time rate of change of the conduction bar during warm-up, and solving the Eq (1):

$$\frac{dE}{dt} = \frac{d(mc_pT)}{dt} = m\frac{d(c_pT)}{dt} \approx m\overline{c_p}\frac{dT}{dt} = Q_{load} \quad (1)$$

where

$$\overline{c_p} = \frac{c_p(T1) + c_p(T2)}{2} \quad (2)$$

The cold mass was calculated to be 1200 g. The average c_p was determined by interpolating between the following known c_p values shown in Table 1, over the temperature range of interest.

For this calculation, the temperature range of interest was defined as 60-100 K. This is the temperature range that will most likely encompass the Cryomech operating temperature for sensor testing. For this temperature range of interest, the specific heat was plotted and a logarithmic trend

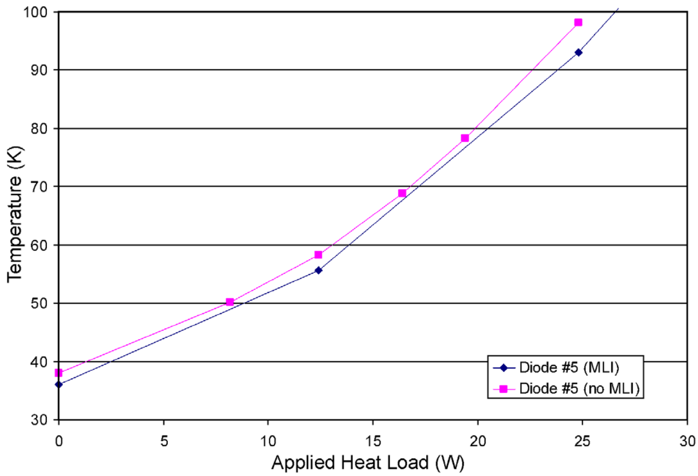

Figure 7. Comparison for test configurations with and without MLI

line used to calculate the "instantaneous" c_p within that temperature range. Using the trend line equation to calculate the average specific heat, the parasitic heat load was calculated in an Excel spreadsheet, using the warm-up temperature rate of change data collected. Figure 8 shows the calculated parasitic heat load along the Cryomech cold finger over a cold finger/conduction bar temperature range of 60-100 K. Cryomech provided a parasitic heat load estimate of 3.8 W when the warm end of the pulse tube is at 300 K, and the cold tip is at 100 K.[3] For this warm-up test, the warm end of the pulse tube was at approximately 295 K. When Cryo Diode B reads 100.3 K, the parasitic heat load at that location is calculated as 3.2 W.

RESULTS AND CONCLUSIONS

The Cryomech PT-60 successfully supported the ground demonstration of a space infrared sensor by providing cryogenic cooling during both ambient laboratory testing, and thermal vacuum testing. The flexibility in line length proved to be crucial in enabling the CCS to support both test environments. More than 20 feet in additional line length was added to the system between the compressor and remote motor assembly for thermal vacuum testing, and the cryorefrigerator was still able to cool the sensor. In addition, the oversized performance provided a lot of flexibility to the sensor test team in that they were able to test the sensor at temperatures colder than initially desired to get more performance data than initially intended. Furthermore, the oversized system enabled relatively fast sensor cool-down times, saving days of schedule time and labor charges. The faster cool-down time also enabled the sensor team to perform multiple extra cool-down and warm-up cycles in order to get more sensor performance data.

Moreover, the ease in starting up and shutting down the PT-60 system saved a lot of schedule time, as it was shut down for minutes at a time for ultra vibration sensitive measurements, and restarted quickly afterwards, before the sensor warmed up significantly. This enabled testing to continue quickly afterwards, since there was no complicated start-up sequence to deal with. Inci-

Table 1. Specific heat of copper vs. temperature

Temperature (K)	c_p (w-min/lb-K)
30	0.20454
40	0.45454
60	1.13409
100	2.64621
180	2.64621
300	2.87424

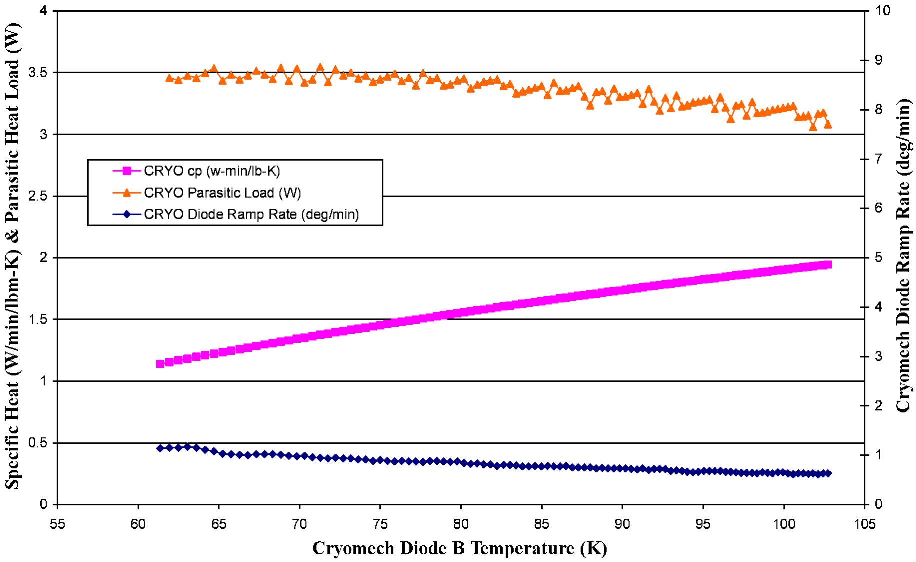

Figure 8. Parasitic heat load along Cryomech cold finger, with corresponding temperature, specific heat and temperature rate of change

dentally, shutting down the PT-60 was only required for a few measurements. It was able to remain running for the majority of the sensor testing, while imparting small enough levels of vibration to the sensor assembly that data acquisition was not precluded.

The sensor data taken to date was reduced, and performance goals so far have been successfully demonstrated. The thermal data and thermal model correlation are ongoing as of this writing.

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