Indium Antimonide Detector Cooling using a Miniature Split-Stirling Cycle Cryocooler with Coldfinger Heat Shunt

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ABSTRACT

The optimal operating temperature range for Indium Antimonide detectors is typically near 35 Kelvin. Commercially available miniature Split-Stirling cycle cryocoolers present an attractive approach to detector cooling. These units offer stand-alone operation, small size, light weight, low power input, low vibration, moderate cost, and reasonable lifetime. However, currently available units have inadequate cooling capacity at 35 Kelvin when operated in a normal manner.

We have substantially increased the low temperature cooling capacity of commercial cryocoolers by utilizing the 77 Kelvin intermediate temperature available in liquid nitrogen cooled instruments. We thermally connect the liquid nitrogen cold sink to the middle of the cryocooler coldfinger, shunting heat from the coldfinger to the LN2. The resulting performance improvements and careful thermal design of the detector mount to minimize parasitic heat loads allow miniature Split-Stirling cycle cryocoolers to provide adequate cooling of large format Indium Antimonide focal plane arrays.

Keywords: cryocooler, coldfinger, infrared detector, Indium Antimonide

1.0 INTRODUCTION

Astronomical instruments which use Indium Antimonide(InSb) focal plane arrays require a cooling system which can provide temperatures in the 35K range for optimal detector operation. Several cooling options exist.

A two cryogen dewar with liquid nitrogen (LN2) to cool the instrument and liquid helium to cool the detector could be used. However, the need for liquid helium infrastrucure precludes this option for many applications.

Multi-stage Gifford-McMahon cycle mechanical cryocoolers have the required temperature range and cooling capacity to cool not only the detector but also the entire instrument dewar. However, these refrigerators require powerful external helium compressors and on-telescope helium transfer lines, and have large cold heads mounted to the instrument. The large moving mass of the cold heads can lead to unacceptable instrument vibration levels, so two opposing cold heads with vibration isolating mounts and phase control drive electronics are typically employed to reduce vibration to acceptable levels[1].

The option discussed in this paper uses a LN2 cooled instrument dewar and a commercial Split-Stirling microcooler for detector cooling. This approach offers the advantages of stand-alone operation (no external compressor or helium lines on the telescope), very small size, light weight, low vibration (dual opposed-piston compressor design), tight integration of detector and cryocooler, low power input, simple drive electronics, and moderate cost. The disadvantages are the need for LN2 cryogen, limited cooling capacity, and moderate life (~4000 hours). The simple passive technique of connecting the middle of the cryocooler cold finger to the LN2 dewar with a thermal link enhances the low temperature performance enough to provide a practical detector cooling option.

2.0 DESIGN OF THE DETECTOR COOLING SYSTEM

2.1 Description of the MX8000 Cryocooler

The Split-Stirling cryocooler selected for this application is a model MX8000 originally developed by Magnavox Electro-Optical Systems and now available from Hughes/Magnavox Mahwah Division[2] . A photograph of the MX8000 is shown in **Figure 1** and the internal construction is shown in **Figure 2**. The cryocooler is a hermetic unit (charged with 400 psi helium working fluid) which produces refrigeration using the Stirling cycle. The compressor uses dual opposed pistons which minimizes vibration.

The design goals of the MX8000 program were: small size, light weight, low input power, low vibration, and long life. The cooling capacity of the MX8000 operating in a 23C environment is about 350 milliwatts at 77K with 12 watts of input power. However, the performance data supplied with the MX8000 indicates that the "no load" minimum cold tip temperature is about 40K. Therefore a method is needed to extend the low temperature performance of the cryocooler.

2.2 Description of the Thermal Shunt Technique

A method for reducing input power to a Stirling cryocooler for a fixed cooling load was investigated for a spacecraft detector cooling application[3]. The technique involved shunting some heat from the middle of the coldfinger to a heat sink at an intermediate temperature. The thermal shunt intercepts parasitic conduction from the warm end of the coldfinger and reduces the temperature of the helium in the regenerator. The thermal shunt improves the efficiency and extends the low temperature performance of the cryocooler. The heat removed by the shunt increases LN2 boiloff by a modest amount. This approach is used to extend the low temperature performance of the MX8000 cooler.

A woven copper braid (1.2cm wide x 0.6cm thick x 15cm long) is bolted to the 77K LN2 worksurface at one end and soldered to a brass collet at the other end. The collet is lubricated with vacuum grease and carefully slipped onto the coldfinger and placed about 1.0 cm. away from the expander. The collet fingers are flexible enough to provide a good thermal connection without damaging the fragile thin-wall coldfinger tube. The thermal resistance of this braid and connections is estimated to be about 15 C/watt

A second copper braid (0.6cm wide x 0.6cm thick x 6.5cm long) is bolted to a the cold sink of the detector at one end and connected to the cold finger tip of the cryocooler with a brass collet at the other. This flexible braid provides good vibration isolation between the expander and the detector. It also allows for relative motion between the detector (mounted on the LN2 worksurface) and the cryocooler (mounted to the room temperature dewar vacuum shell). The cooling path from the cryocooler to the detector is: cryocooler cold tip, copper braid, copper bar clamped to the 30K PC Board, detector socket contacts soldered into PC Board, electrical contact pads of detector chip.

2.3 Cryocooler Drive Electronics

The cryocooler compressor has two voice coil driven pistons that are run at 60 hz and 180 degrees out of phase to cancel vibration. The drive voltages required range from 8 to 12 volts. A constant voltage source is provided from the line by a ferro-resonant transformer (output voltage nearly independent of line voltage variations), a Variac autotransformer to allow adjustment of the drive voltage, and a final center-tapped 10:1 step down transformer.

2.4 Detector Mount

The detector mount is designed to support a 1024^2 Alladin InSb array (a detector with two working quadrants is currently on loan from NOAO and the Naval Observatory). The total parasitic heat load budget is about 50 milliwatts from conduction and radiation. The mount also allows for easy removal of the detector and cryocooler as a single unit. Details of the detector mount and the integration of the cryocooler and thermal shunt are shown in **Figure 3**.

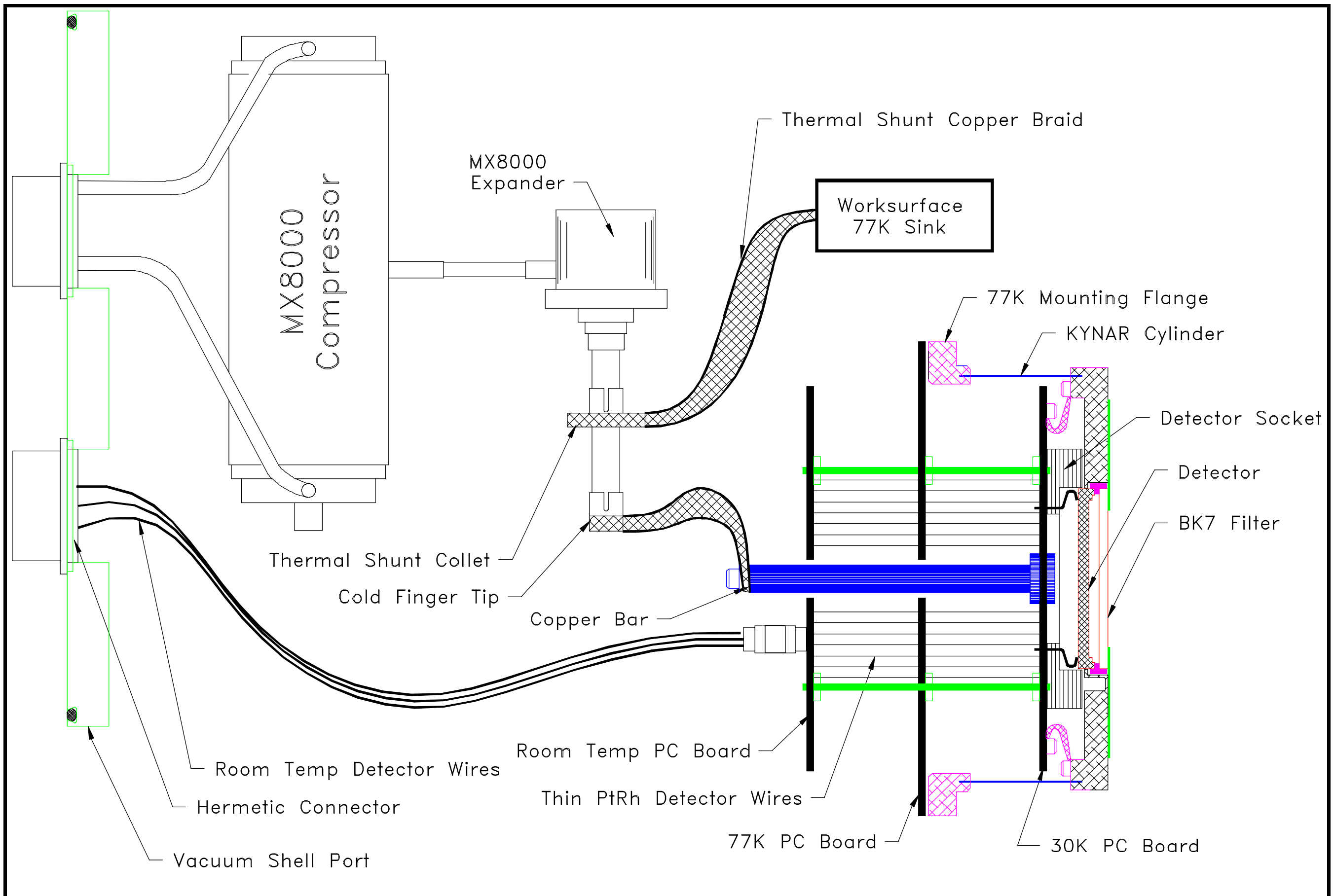

Figure 3: Cryocooler, Detector Mount, and Thermal Shunt

The detector mount consists of a stack of three printed circuit (PC) boards connected by 1.5mm diameter G10 fiberglass rods. The boards are at room temp(293K), 77K, and 35K and provide electrical and thermal connections to the detector. This arrangement provides a situation where the parasitic heat loads to the cryocooler result from a temperature gradient of only 42 degrees instead of the full 258 degree gradient to room temperature. The detector is mounted in a socket on the 35K PC board and the detector chip is cooled through its electrical contacts. The detector electrical leads are brought through the PC board stack with 50 micron platinum-rhodium wires which are thermally connected to each board.

Structural support for the detector is provided by an aluminum disk which is cantilevered from the 77K mounting flange on a 20mm long cylinder of .25mm thick aluminized KYNAR (PVDF polyvinylidene fluoride). KYNAR has a high stiffness/thermal conductivity ratio and is not brittle at cryogenic temperatures. The aluminum disk has kinematic locating features to accurately and repeatably position the chip at room temperature and at 35K without applying high stress to the chip..

The rough detector temperature is established by setting the input voltage to the cryocooler to the desired value. Fine temperature control can be achieved with a closed loop controller which uses a platinum wire-wound RTD as a sensor and a resistor as a heater on the 30K PC board.

2.5 Blocking Long Wavelength Radiation

The long wavelength sensitivity of InSb detectors extends to about 5.6 microns. The thermal emission from the inner radiation shield in a LN2 cooled instrument (the warmest spots are at 85K to 90K) would produce high internal instrumental background. To reduce this to negligible levels a red-blocking filter of 3mm thick anti-reflection coated BK-7 glass is placed in a light tight frame in front of the InSb detector. This approach allows some observing in the astronomical L Band without substantially reducing the throughput in the K Band. The instrument internal background is approximately 0.10 electrons/sec with the detector at 32K and a cold dark slide at the instrument focal plane.

3.0 DETECTOR COOLING SYSTEM PERFORMANCE

3.1 Thermal Shunt Effectiveness

A test was conducted with a thermal shunt placed on the MX8000 cold finger about 1.0cm. from the expander warm end and connected to an LN2 sink. A heater resistor and a platinum RTD were mounted on the shunt collet so that its temperature could be controlled independently. The compressor was run at a fixed input power. The cold finger tip temperature was then measured as the shunt temperature was reduced. The results shown in **Figure 4** demonstrate a nearly linear relation between shunt temperature and cold tip temperature. This result indicated that the thermal shunt approach should be promising.

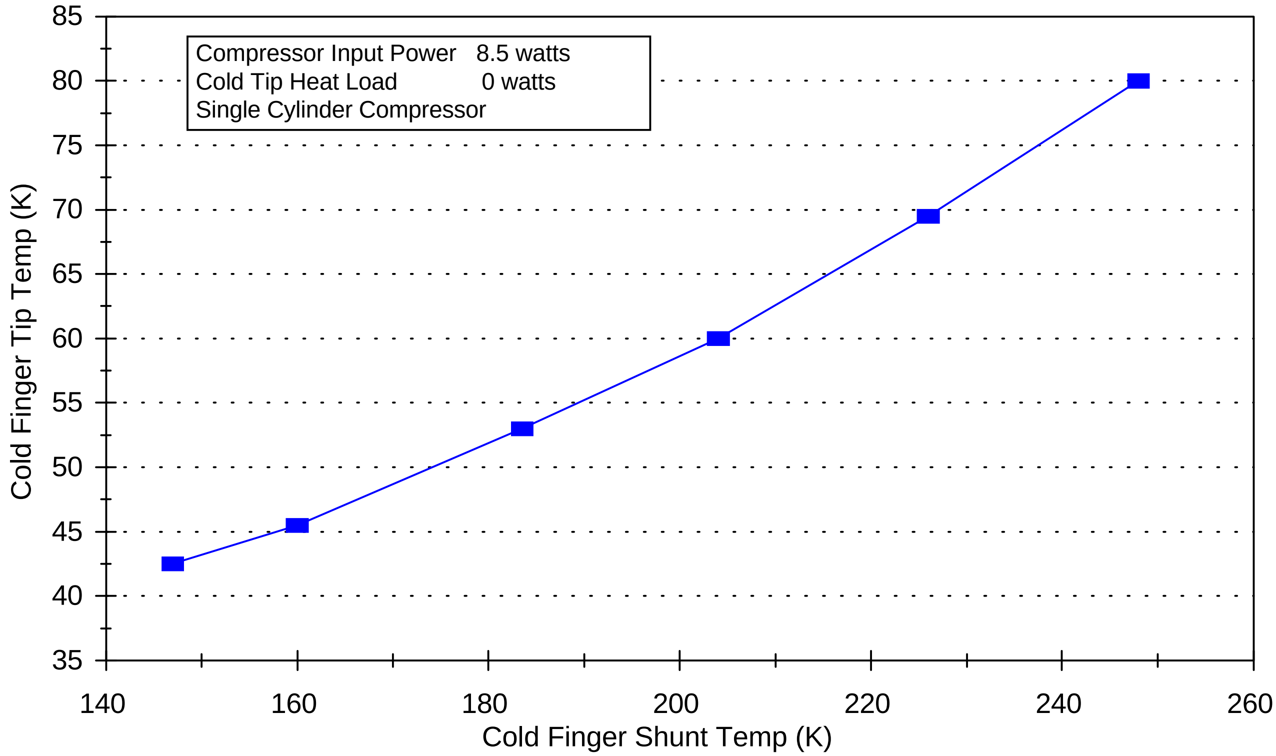

Figure 4: Thermal Shunt Effectiveness

3.2 Cold Tip Temperature vs. Cold Tip Heat Load

The cold finger tip of the MX8000 was fitted with a small heater and RTD so that a controlled heat load could be applied to the cold tip and the resulting temperature increase measured. Three tests were run under different conditions to cover a range of zero heat load tip temperatures. The results plotted in **Figure 5** show a slope of about 1 degree per 10 milliwatts of heat load. This slope is independent of the no load tip temperature over the limited range explored.

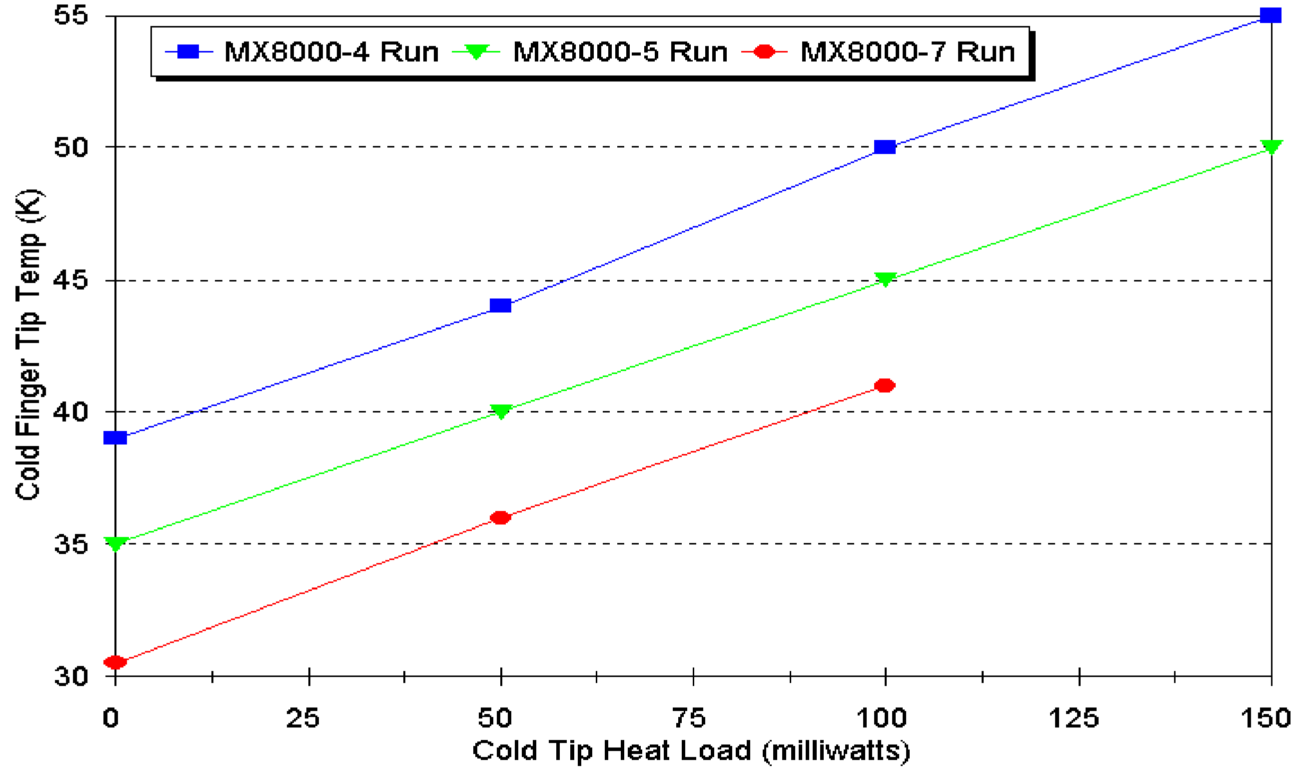

Figure 5: Cold Tip Temp vs. Heat Load

3.3 Cold Tip Temperature vs. Compressor Input Power

Several experiments produced data showing the dependence of cold finger tip temperature as a function of electrical input power to the compressor. The electrical power is computed from the measured rms voltage and current and assumes a power factor of unity.

The first experiment ran an MX8000 compressor in a test dewar with no heat load on the cold tip and a shunt temperature of 144K. The results are show in **Figure 6**.

A second experiment ran an MX8000 in an instrument dewar with an Aladdin 1024^2 InSb array in its detector mount. The initial copper shunt braid (1.2cm. wide x 0.35cm. thick x 15cm. long) produced a shunt temperature of 148K and a resulting detector temperature of 40K at 12 watts input power.

Several changes were made to decrease detector temperature. The copper shunt braid size was increased to 1.2cm.wide x 0.6cm.thick x 15cm.long which reduced the shunt temperature to 132K. Also, a small LN2 temperature radiation shield was placed around the cold finger of the MX8000 to reduce parasitic radiation heat loads. These changes resulted in a detector temperature of about 35K with 12 watts input power as shown in Figure 6. This configuration is currently in use on the TIFKAM instrument in the field. There has been very little opportunity to pursue further optimization and there is a reasonably chance that additional performance improvements could be gained by optimizing the shunt location and shunt operating temperature.

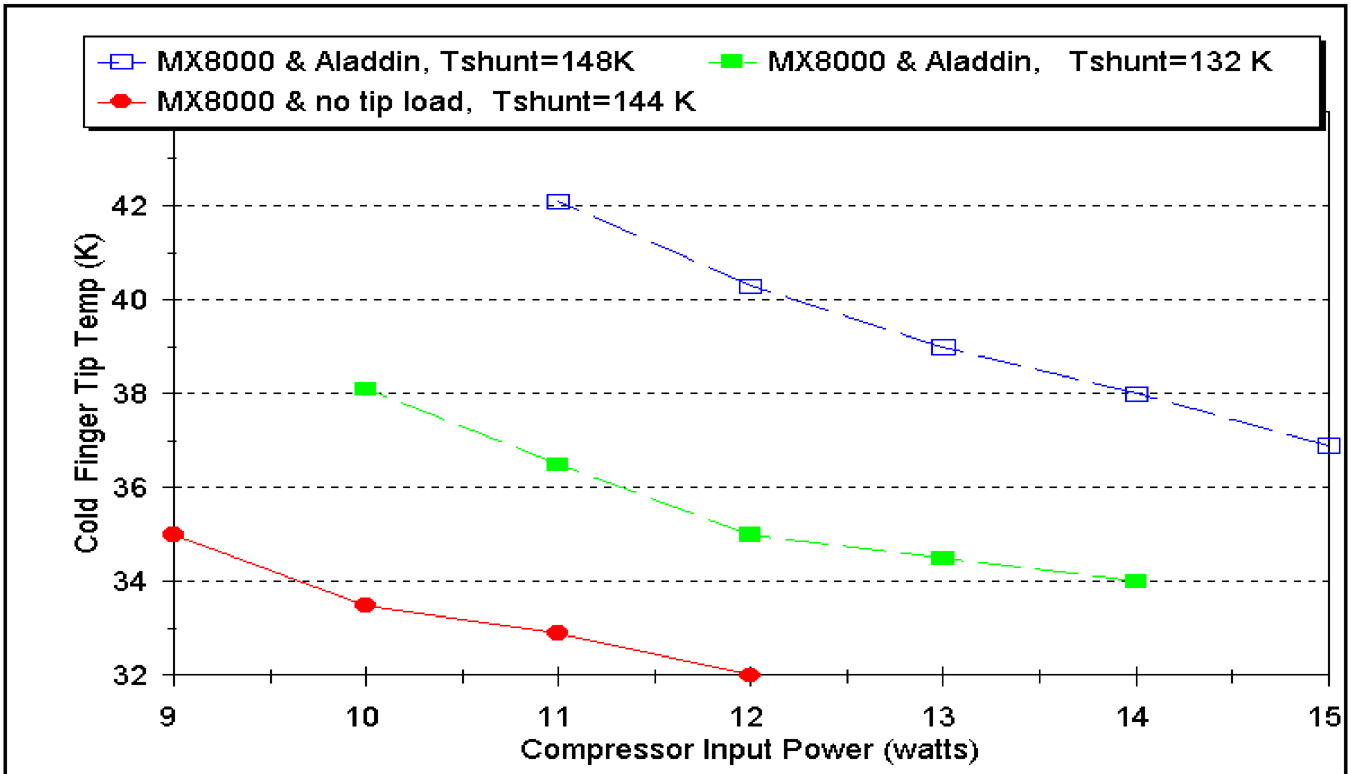

Figure 6: Cold Tip Temp vs Input Power

3.4 Cold Tip Temperature vs. Ambient Temperature Changes

The cold tip temperature is dependent on the ambient temperature in which the instrument is operating because the compressor is mounted to an ambient temperature surface. The manufacturer tests the cryocooler over a wide range of ambient temperatures (49C to -32C). The data indicate that the cold finger tip temperature drops about 1 degree Kelvin for every 5 degree drop in ambient temperature. The implication of this is that for precise detector temperature regulation in the presence of large ambient temperature changes an active control system is required.

3.5 Cooldown Time

The time required to cool the detector to its operating temperature with this mount design is about 20 hours. The thermal background of the instrument reaches its minimum in about 30 hours

3.6 Additional LN2 Boiloff

The heat shunted from the coldfinger to the LN2 sink was calculated to be approximately 4 watts. The calculation is based on the known endpoint temperatures of the copper shunt braid and its thermal resistance. The boiloff of the dewar also increases by about 2 liters per day which corresponds to a 4 watt added heat load. This is not a substantial factor as the instrument has a 24 watt baseline heat load and still has a hold time of about 36 hours even with the added heat load form the cryocooler shunt.

3.7 Reliability

3.7.1 Passive Operational Safety of Cryocooler

It is important that the cryocooler be protected from extremes of temperature during a variety of abnormal operating conditions. The compressor and expander are both rated for service temperatures of -40C to +70C. A copper braid (1.2cm wide x 0.2cm thick x 6cm long) connects the expander to the room temperature vacuum shell to help limit extreme expander temperatures. The cooling system was tested to insure that these limits are never exceeded.

In normal operation with 12 watts input power to the compressor, the compressor temperature is about 27C and the expander is 42C.

In the event of a power failure with a full LN2 instrument dewar the expander is cooled by conduction from the thermal shunt. The minimum expander temperature recorded in this case was -5C.

If the cryocooler is set to full power (16 watts) before the LN2 dewar is filled or if the LN2 dewar is allowed to run dry and warm up while the cryocooler is still running, the expander warms up to about 45C and the compressor warms up to 30C.

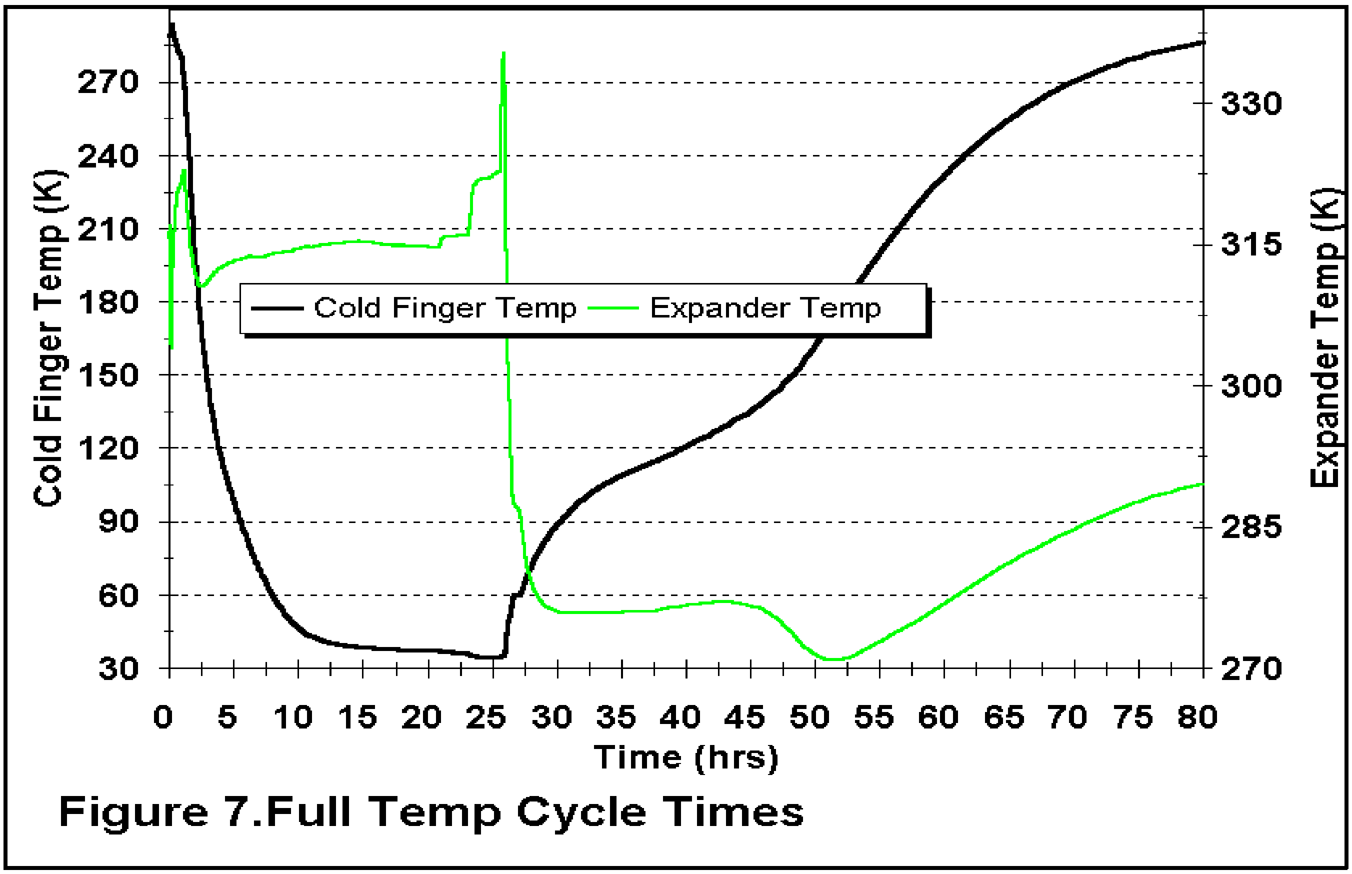

Figure 7.Full Temp Cycle Times

3.7.2 Cryocooler Reliability

The 4000 hour rated life of the MX8000 represents the culmination of efforts in the industry to greatly increase the life of microcoolers[4]. The OSU TIFKAM instrument has used this cooling system in the field for about 150 nights on several telescopes with outstanding reliability.

There has been a single "infant mortality" failure caused by a broken internal voice coil lead. The manufacturer promptly made an in-warranty repair and returned the unit which has subsequently performed without failure. This voice-coil lead failure did not result in any lost observing time because the MX8000 was run with a single piston and provided enough cooling capacity to keep the detector at about 40K.

4.0 CONCLUSIONS

The system described in this paper offers a practical and cost effective detector cooling option for LN2 cooled instruments utilizing InSb detectors. The system has provided very reliable and effective detector cooling in a heavily used facility class astronomical instrument.

5.0 REFERENCES

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MX8000
P/N 4006424 Split Stirling micro cooler with standard 2" transfer line

Approximate price 6/97	$8000.00
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