Initial Test Results for a 35 K Variable Load Cryocooler

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ABSTRACT

Ball Aerospace and Redstone Engineering together have designed, built, and are currently assembling a hybrid cryocooler tailored for cooling infrared imaging systems that have variable loads. The system is a hybrid of complementary Stirling and Joule-Thomson (JT) cycle cryocoolers. It is based on Ball's efficient two stage Stirling cycle cryocooler, the SB235E, which provides the bulk of the refrigeration. It supplies well in excess of 8 W at 80 K for optics cooling in addition to approximately 2 W at 35 K for intercepting parasitic loads associated with the JT cryostat.

The JT system uses a custom "Oxford" style linear compressor equipped with reed valves to circulate neon through a compact cold head. The cold head consists of high efficiency counter flow heat exchangers, heat sinks, and a very special internal thermal storage unit (ITSU) mounted in a rigid support structure. The ITSU, basically a tank for holding liquid neon, provides the system's load leveling capability. During the high load part of the focal plane's operating cycle, the JT compressor speeds up to increase the circulation rate of the coolant to the 35 K interface, drawing down the stored neon in the process. In this way it can provide instantaneous cooling that is several times greater than the precooler's average refrigeration power.

Although the system is just now in assembly, the components have been individually tested. Component test results are given, and the upcoming system tests are described.

INTRODUCTION

When airborne or space systems image a specific object, the view is often brief. Because the thermal load associated with the scene can be substantial, a significant savings in system mass and power can be realized by designing a cryogenic system that takes advantage of the load's transitory nature. Clearly, the cryocooler can be smaller if it can be sized to handle the average instead of the peak load.

To average a heat load, the system has to store thermal energy. The conventional thermal storage approach is to use a phase change material, which has a substantial latent heat at the

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temperature of interest. An example would be a pool of liquid collected by the cryocooler during the low load interval and evaporated away during the high load interval. At low temperatures, though, appropriate phase changes are few and far between.

Conventional phase change systems have an additional problem if they are relied on for temperature regulation. Although in principle the phase change temperature is precise, the load temperature in practice varies because of the temperature drop associated with the large heat flow through the link between the load and the thermal storage device. So the only way to minimize this error is to locate the bulky thermal storage unit close to the detector, potentially intruding on the IR system design.

Our 35 K cooler avoids these problems by using the thermal storage unit in a unique configuration.[1] Instead of attaching the TSU to the load, it is attached instead to the tip of the precooler, as shown in Figure 1. Then, a second, separate, circulating compressor sweeps the refrigerated fluid from the precooler to the load on demand and in the quantity needed. This approach has many advantages. First, because of the averaging provided by the TSU, the precooler can now be sized for the average rather than the peak load. Second, the precooler and its storage unit can be located some distance away from the load. The only footprint in the detector area is a small heat exchanger attached to the load. In addition to disentangling their designs, the approach effectively isolates the detector from the active cryocooler. Finally, the circulator provides active, rather than passive cooling resulting in improved temperature control. The system does require extra hardware, specifically the circulating compressor and its flow cryostat.

The main parts of the 35 K Hybrid cryocooler are shown in Figure 1. The bulk of the refrigeration is provided by the mechanical precooler. In addition to cooling the ITSU, it also provides a significant amount of shield cooling to lower the parasitics on the cold parts of the cryostat. The remainder of the system is dedicated to the circulating fluid, which in our application can be neon. Neon conveniently has a liquid-vapor phase transition in the vicinity of 35 K. It has over 40 times the refrigeration storage capacity of an equivalent volume of helium and more than 3 times the storage capacity of hydrogen. It is inert and inexpensive, and its great refrigerating power storage density results in a compact cooler.

The four main parts of the circulation system are the ITSU, the load tank, the counter flow heat exchanger, and the circulating compressor. The ITSU stores neon in liquid form during the accumulation phase. In the high load phase, when refrigeration is required at the load, liquid

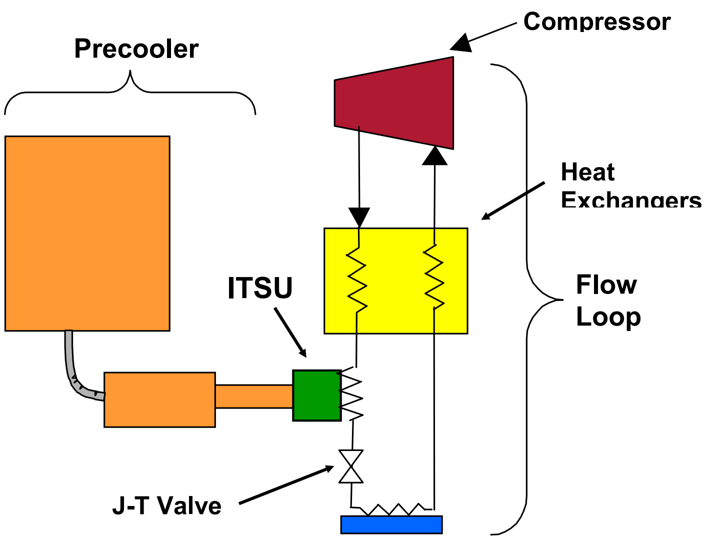

Figure 1. A hybrid cooler with an internal thermal storage unit is well suited for controlling the temperature of a load that has a varying heat load.

neon flows from the ITSU to the load tank, passing through a flow regulating JT valve. The neon evaporates in the load tank and is pumped away by the circulating compressor. The neon returns to room temperature via the counter flow heat exchanger, where it precools the neon entering the cryostat on the other side. The circulating compressor draws in the neon at a low pressure and sends it out at a high pressure, enabling it to condense back into the storage unit, thereby completing the cycle.

The schematic represents the core thermo-mechanical components. A real system includes a set of cryocooler control electronics and the miscellaneous gas handling components that support the circulator's operation. These components will all be briefly discussed below, and performance data will be given for the two active components, the precooler and the circulating compressor.

STIRLING CYCLE CRYOCOOLER

The precooler provides the bulk of the refrigeration, consumes the most electrical power, and has the most mass and volume. The precooler in our system is the compact, very power efficient SB235E two-stage Stirling refrigerator, shown in Figure 2. It has a twin-opposed-piston 'Oxford'-style linear compressor and a fixed-regenerator-style two-stage displacer with expansion stages optimized for 85 K and 35 K. The fixed-regenerator design insures low vibration and non-contacting operation. The residual vibration of the moving displacer is opposed by the moving mass of a smaller active counterweight moving in opposition.

The precooler performance is shown in Figure 3. It easily meets its nominal design requirements of 8.5 W at 85 K and 1.5 W at 35 K at a reduced stroke. Even higher capacities can be obtained by increasing the charge pressure and shifting operation to higher frequencies. The precooler has been designed for power efficiency. Both cold interfaces have internal heat exchangers for improved thermal contact at these high loads, and both housings have internal heat exchangers for improved heat rejection at ambient.

CIRCULATING SYSTEM

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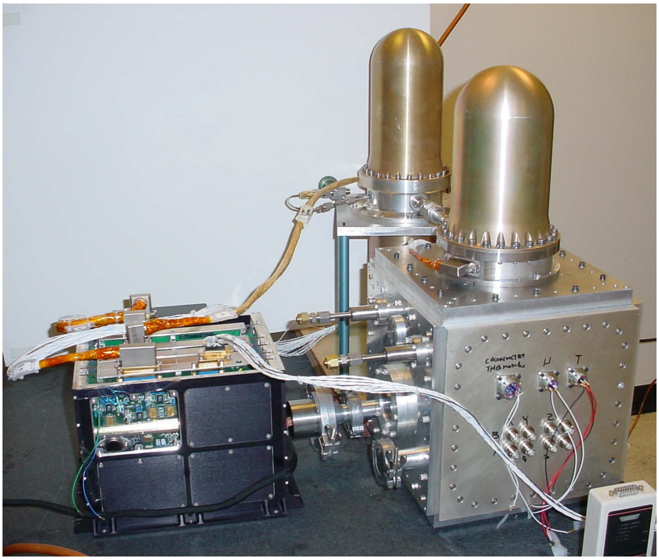

Figure 2. The precooler is a two stage Stirling cycle refrigerator.

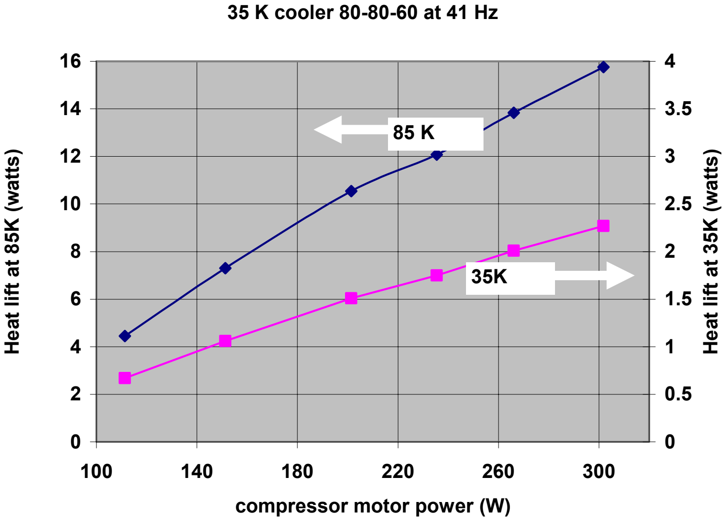

Figure 3. The performance of the precooler at 35 K and 85 K as a function of the compressor motor power.

The ITSU is shown mounted atop its support structure in Figure 4. Although thermally connected to the precooler (which fits up inside the structure), the structure supports the tank during launch. The load tank is shown in Figure 5. This complex structure provides the thermal interface between the flowing neon and the customer's load. Its internal structure affords a tight, uniform temperature across its extended surface and operation in any orientation in gravity.

The counter flow heat exchanger is shown in Figure 6. It is comprised of multiple foils diffusion bonded together in a stack. Compact and effective, it is much smaller than the tube-in-tube heat exchanger it replaces. It nestles within the support structure under the ITSU.

Finally, the circulating compressor is shown in Figure 7. It is also a twin opposed linear compressor, although much smaller than the compressor used for precooling. The armatures drive a common compression space for large flow rates at a modest pressure ratio. Reed valves rectify the pressure wave into a DC pressure head, and the pressure drives the neon flow through

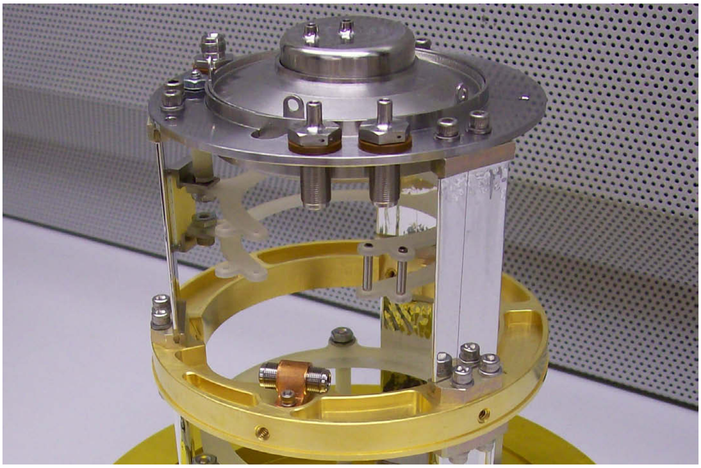

Figure 4. The TSU mounted atop its support structure.

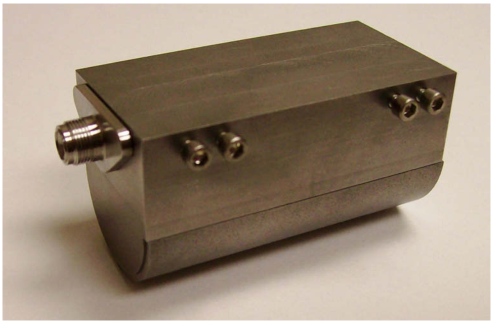

Figure 5. The load tank is the thermal interface to the customer.

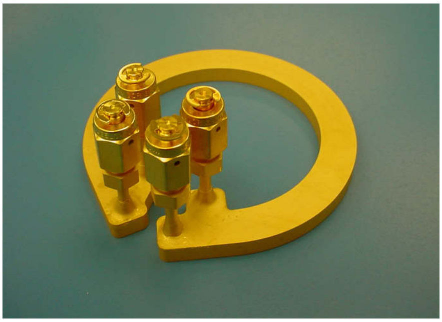

Figure 6. Microplate counter flow heat exchangers used in the 35 K cooler.

the system. The circulating compressor's key pressure-flow characteristics and the motor power required are shown in Figure 8.

CRYOCOOLER CONTROL ELECTRONICS

Both active coolers are controlled by a single set of electronics, which are shown along with the precooler in Figure 2. The architecture of our proven Stirling cooler control electronics was expanded to allow the microprocessor to control both active coolers sequentially. The electronics have the customary space attributes: efficient operation from 28 VDC power, RS-422 serial interface to the spacecraft host computer, robust construction to withstand launch loads, and low noise for compatibility with sensitive space sensors.

The microprocessor controls both coolers as well as a number of other auxiliary components. Both mechanisms operate at the same frequency and have waveforms tailored by the microprocessor to control stroke, centering, and balance. The electronics are in a modular form with a power board, a digital board, dedicated boards for driving each compressor, and an analog board for operating various sensors. Although the set developed for our testing uses commercial parts, radiation-hard parts are available.

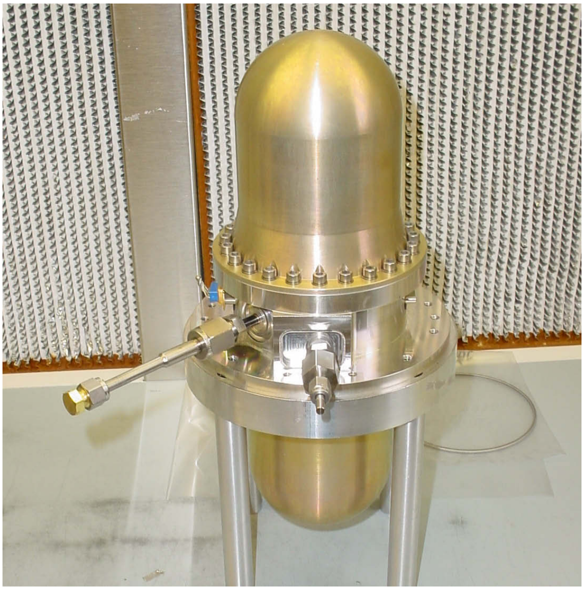

Figure 7. The circulating compressor is a twin opposed linear compressor with reed valves .

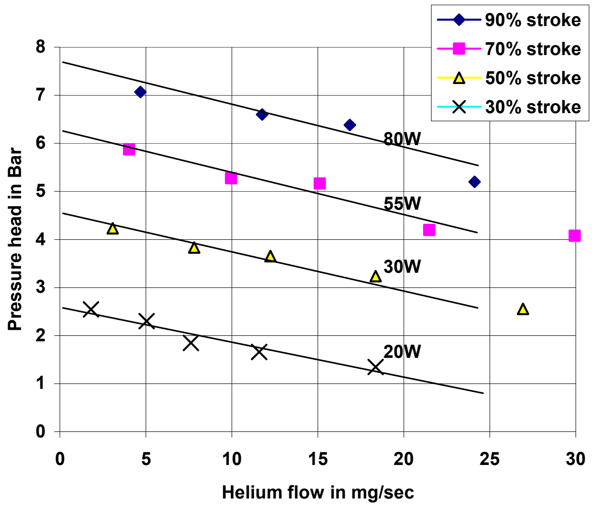

Figure 8. The pressure-flow characteristics of the 35 K JT compressor using helium as its working fluid.

SYSTEM TESTING

A full testing program is planned for the near future. The key tests are vibration export, launch vibration, thermal performance in a vacuum, and extended operation.

Vibration export testing will focus on two interfaces: the base of the active cooler suite, and the isolated customer interface. The active components will be mounted orthogonally in a common housing as shown in our breadboard version in Figure 9. Because all components in the suite are synchronous, active vibration control can be used to reduce the vibration along each principal axis of the system. The load tank will be located remotely. Cold accelerometers will be used to measure the residual vibration transmitted to the tank by the fluid and the lines.

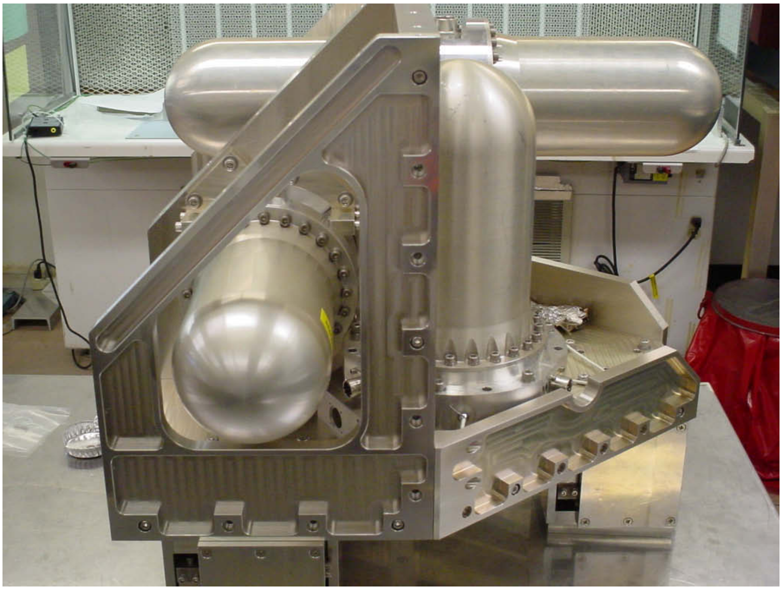

Figure 9. The hybrid cooler components are mounted orthogonally in a compact support structure remotely located from the sensitive detector system.

Plans are underway for the thermal testing. The cryocooler suite will be mounted in a vacuum chamber and cooled by a circulating chiller. The system will be cycled between low and high operating temperatures, and the load will vary periodically between low and high levels to exercise the variable load capability of the system.

REFERENCES

1. Gully, W., Glaister, D.S., Hendershott, P., Kotsubo, V., Lock, J.S., and Marquardt, E., "Ball Aerospace Hybrid Space Cryocoolers," *Adv. in Cryogenic Engineering*, Vol. 53A, Amer. Institute of Physics, Melville, NY (2008), pp. 522-529.