ULTRA LOW POWER CRYO-REFRIGERATOR FOR SPACE. M. V. Zagarola, R. W. Hill, and J. R. Gagne, Creare LLC (P.O. Box 71, Hanover, NH 03755, mvz@creare.com, rwh@creare.com, jrg@creare.com).

Introduction: Future NASA astronomical observatories will require long-life, mechanical cryocoolers for cooling bolometers, detectors, sensors, shields, and telescopes. Many of these missions are expected to explore the outer planets or to orbit the L2 Lagrange point where payload power and mass are even more critical parameters than for earth-orbiting satellites.

The development of current cryocooler technology for space has been driven almost exclusively by satellites in low earth and geosynchronous orbits where spacecraft heat rejection temperatures are typically 300 K to 320 K. The recently launched Planck observatory [1] and the future James Webb Space Telescope [2] will both operate in an L2 orbit, but will utilize cryogenic systems that reject most of their waste heat at temperatures near 300 K. The process of pumping heat from an extremely low to high temperature is thermodynamically inefficient and results in excessive input power and payload mass. Conversely, rejecting heat at cryogenic temperatures requires cryogenic radiators which increase in size inversely with rejection temperature to the fourth power. These competing effects should be considered during payload trade studies, but the lack of an efficient cryocooler that can operate with a cryogenic heat rejection temperature has prevented meaningful mission studies in this area. Creare's circulators and turboalternators have already been demonstrated on prior space programs to operate at cryogenic temperatures. The application of our turbomachine technology to a cryo-compressor is an enabling technology and a natural extension of this prior work. On this program, we are working to develop an innovative type of cryocooler, an Ultra-Low Power (ULP) cryocooler that utilizes a cryogenic heat sink. We recently completed successful Phase II SBIR efforts to design and test a Technology Demonstration Unit (TDU) cryocooler system.

ULP Cryocooler Overview: The cryocooler concept is shown in Figure 1: a single-stage turbo-Brayton cryocooler operates between a cryogenic heat rejection temperature and the primary load temperature. The key cryocooler components are a cryogenic compressor, a recuperative heat exchanger (i.e., recuperator), and a turboalternator. The cryogenic compressor and turboalternator are gas-bearing turbomachines that are extremely reliable and produce no perceptible vibration. The continuous flow nature of the cycle allows the cycle gas (neon) to be transported from the compressor outlet to a heat rejection radiator at the warm end of the cryocooler, and from the turboalternator outlet to the object to be cooled at the cold end of the cryocooler. The unit shown in Figure 1 has been optimized to provide 300 mW of cooling at 35 K and requires 8.9 W of compressor input power at 150 K. The total system mass is 6.2 kg including electronics and cryo-radiator. The cryocooler is designed to operate at cold end temperatures of 30 to 70 K, loads of up to 3 W, and heat rejection temperatures of up to 210 K by changing only the charge pressure and turbomachine operating speeds. The enabling technology for this concept is a cryogenic compressor which has heritage to the NICMOS circulator. The NICMOS circulator is a relatively low-speed cryogenic compressor that operates at a temperature of about 80 K. To obtain the pressure ratio required for the ULP cryocooler, an increase in the circulator operating speed by a factor of 2.8 is required. Recent advances in gas bearing technology at Creare have demonstrated the feasibility of a high-speed cryogenic compressor. The program utilizes the results of these advances to pursue an innovative cryocooler configuration that is extremely valuable for future space science missions.

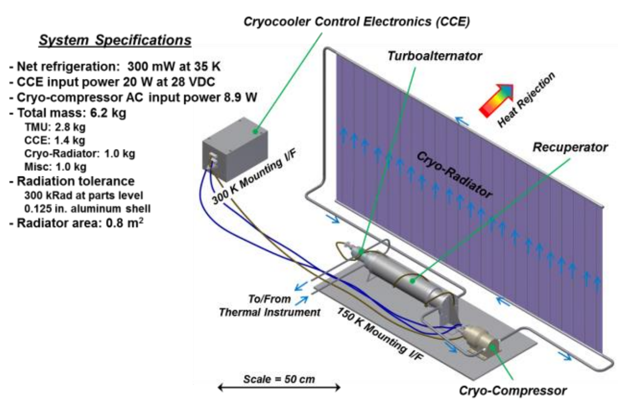

Figure 1. Ultra Low Power Cryo-Refrigerator

The cryocooler components are based on space-qualified technology and have low development risk. The efficiency of the cryocooler is about 11% of the Carnot cycle, an extremely high value for a low capacity refrigerator. The total mass of the flight system is 6.2 kg comprising 2.8 kg for the mechanical cryocooler, 1.0 kg for the cryo-radiator, 1.0 kg for integration hardware, and 1.4 kg for the control electronics.

Technology Demonstration Overview: We built and tested a TDU on a recent NASA-funded project. The TDU consists of prototypical cryocooler components, rack-mounted cryocooler electronics, and a cryo-radiator. The TDU compressor and turbo-alternator were existing units to allow a comprehensive cryocooler demonstration within a standard SBIR Phase II budget. A new high performance silicon recuperator was designed, fabricated, and integrated with the existing turboalternator (Figure 2). A cryo-radiator was also designed and fabricated to prototypical size and a custom configuration to allow integration in an existing vacuum chamber test facility. Schematics of the cryocooler TDU cryocooler assembly are provided in Figures 3 and 4. The testing included performance testing as well as launch vibration testing of the recuperator.

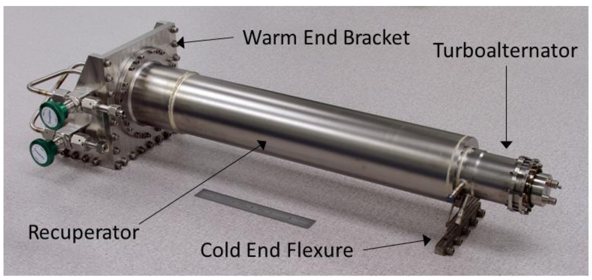

Figure 2. Silicon Recuperator Assembly with Integrated Turboalternator

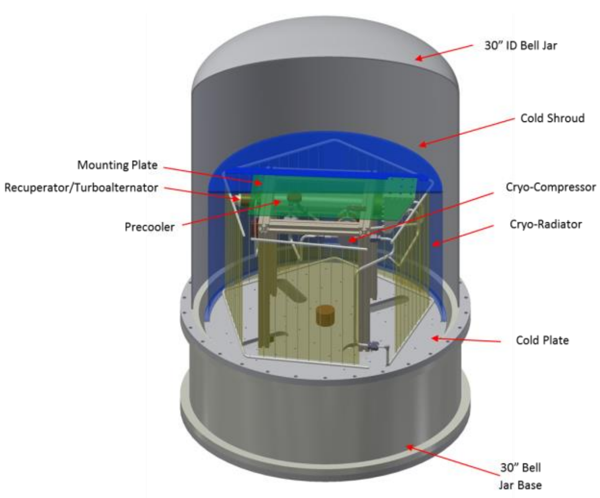

Figure 3. Schematic of TDU Test Configuration

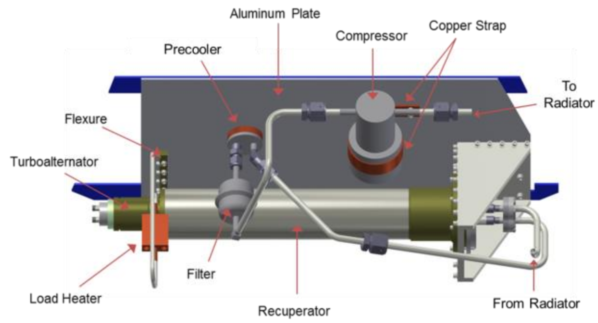

Figure 4. Schematic of Installed TDU Cryocooler

TDU Thermal Performance: System thermal performance testing was performed for cold load temperatures down to 35 K, mount plate and warm end temperature of 150 to 160 K, and a radiative heat sink vacuum chamber cold shroud) temperature of 100 to 140 K. The net turbine refrigeration (available cooling) as a function of the load temperature is shown in Figure 5 for conditions of fixed input power, radiator temperature, and heat sink temperature. The cryo-cooler performance is quite good and slightly below a design target refrigeration level of 300 mW at 35 K due to higher than expected parasitics. The target refrigeration could be met with a 10% reduction in parasitics through improved insulation or a 3% increase in input power.

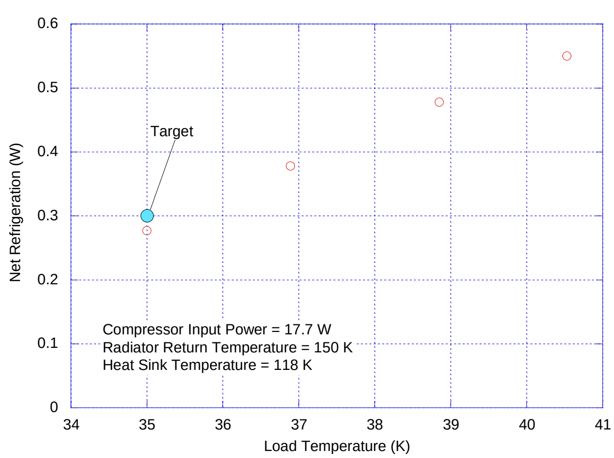

Figure 5. Net Refrigeration vs Load Temperature for Fixed Input Power, Rejection Temperature, and Heat Sink Temperature

The figure of merit for a cryocooler is the Carnot efficiency (η_{Carnot}) which is the coefficient of performance (COP) for the cryocooler (cooling capacity divided by input power) divided by the COP of an ideal Carnot cycle operating at the same temperatures:

$$\eta_{Carnot} = \frac{Q_{load}}{W_{AC,c} - W_{AC,t}} \left(\frac{T_{reject}}{T_{load}} - 1 \right)$$

where T_{reject} is the heat rejection temperature taken to be the radiator outlet temperature, and T_{load} is the cooling load temperature taken to be the load outlet temperature. The COP of the cryocooler relative to the Carnot cycle is shown in Figure 6. Also shown in Figure 6 is the Carnot efficiency if we are able to reduce thermal parasitics by 70% through improved insulation or operation at a lower heat sink (shroud) temperature. The measured efficiency of this cryocooler compares favorably to existing cryocoolers at 35 to 40 K as shown in Table 1, even at lower refrigeration values, but our cryocooler is lighter and requires less input power. In addition, this level of performance was achieved on a non-optimized version (TDU) that utilized mostly existing components. Further optimization for a flight unit should further improve performance.

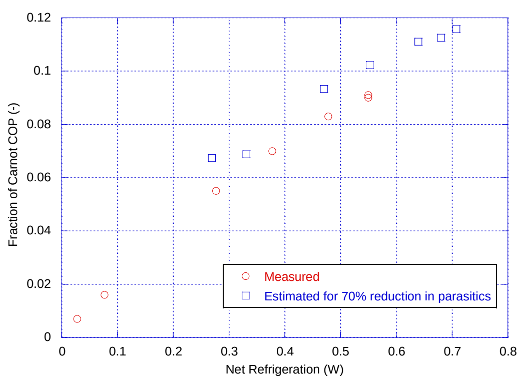

Figure 6. Cryocooler Performance Relative to the Carnot Cycle

Recuperator Random Vibration Testing: Another goal of the project was to increase the TRL of the mechanical cryocooler to 5/6 by testing in an operational environment. This maturity level is achieved through performance testing in a thermal vacuum chamber and launch vibration testing using a shaker table (Figure 7). For our Phase II TDU cryocooler, the cryo-compressor was previously flight qualified during the NICMOS program, the turboalternator is a 2/3-scale version of the unit qualified on the NICMOS program, and were not vibration tested on the Phase II. The recuperator and cryo-radiator are new technologies and are structurally sensitive. The radiator is designed for mounting on the outer surface of a spacecraft and not intended to endure vibration as a stand-alone component. In addition, the cryo-radiator for the TDU was configured in five panels to fit within the thermal shroud of the test chamber precluding vibration testing on this unit. Therefore, our vibration testing focused on the recuperator assembly.

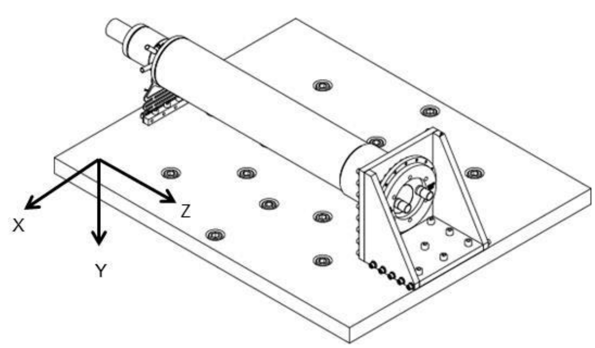

Figure 7. Recuperator on Vibration Test Fixture

Table 1. Comparison of Low Capacity Single-Stage Cryocoolers [3]					
Vendor	Technology	Cryocooler Mass	Comp. Input Power/ Heat Rej. Temp.	Refrigeration	% Carnot
Northrop Grumman	Pulse Tube	7.4 kg	88 W at 300 K	750 mW at 40 K	5.5%
BATC	Stirling	14.6 kg	74 W at 300 K	590 mW at 35 K	6.8%
Raytheon	Stirling	20.1 kg	133 W at 300 K	1300 mW at 35 K	7.4%

The vibration testing consisted of characterization tests to determine the structural response of the recuperator and random vibration tests to verify that the recuperator meets typical random vibration requirements for space flight. The characterization tests were performed in all three axes. The random vibration tests were performed in the X- and Z-axes at -6 dB, -3 dB, and -1 dB relative to the NASA GEVS qualification spectrum (14.1 Grms). The recuperator was not tested at 0 dB relative to the spectrum due to limitations of the shaker table and test fixtures. In addition, a notch to the spectrum was applied at the lowest resonant frequency of nominally 100 Hz due to the measured damping was lower than used for predictions and concerns with failure of the cold-end flexure. The recuperator assembly was successfully tested up to 12.4 Grms without failure.

Conclusions: A TDU for a ULP cryocooler has been designed, built, and tested to demonstrate thermal performance and to increase the TRL level to 5/6. The thermal performance and vibration test results were excellent, and all components met or exceeded expectations. The next step for the technology would be to build and test an optimized engineering model cryocooler for a particular mission or mission class.

References: [1] Bernard, C., et al. (2002) *Proc. of 19th Inter. Cryogenic Engr. Conf.*, pp. 1-11. [2] Durand, D., et al. (2007) *ICC*, pp. 7-12. [3] Curran, D. G., et al. (2008) TOR-2008(1033)-7691, The Aerospace Corporation.