

Testing of a Two-Stage 10 K Turbo-Brayton Cryocooler for Space Applications

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ABSTRACT

Creare is extending its turbo-Brayton cryocooler technology for space applications that require refrigeration in the 10 to 20 K temperature range. Prior Creare efforts have focused on refrigeration load temperatures primarily in the 30 to 120 K range. These systems provide a strong technology base that is now being applied to lower temperatures with support from the Department of Defense and NASA. Brayton cryocoolers have the potential to achieve unprecedented thermodynamic efficiency at these temperatures due to favorable scaling relationships. Creare recently assembled and tested a two-stage brassboard cryocooler consisting of components developed for other systems. This cryocooler was operated with cold load temperatures between 10 and 20 K and intermediate load temperatures between 57 and 68 K. It produced 236 mW of refrigeration at 10 K and 1.96 W of refrigeration at 57 K with a heat rejection temperature of 305 K and a DC input power of 378 W. This paper presents the brassboard cryocooler test results and provides performance predictions for a fully optimized cryocooler to be built in the future.

INTRODUCTION

Future Department of Defense (DOD) satellites will require efficient, low mass, mechanical cryocoolers to improve capabilities for surveillance, missile detection, and missile tracking. These satellites may utilize infrared detectors that require cooling in the 10 to 20 K temperature range. Cooling loads for these detectors will be 0.25 to 1.0 W, depending on the size of the focal plane. Additional refrigeration loads at higher temperatures (approximately 55 to 75 K) will be required to cool thermal shields, electronics, and/or optical benches. Mission durations may exceed 10 years, making stored cryogenics an unacceptable option due to their high mass. To date, the most efficient cryocoolers developed for 10 K space applications are reciprocating-flow machines based on pulse-tube technology. For example, Nguyen, et. al. [1] reported refrigeration loads of 125 mW, 212 mW, and 255 mW at 10 K with input power of 200 W, 300 W, and 370 W respectively. Similarly, Schaefer et al. [2] reported a refrigeration load of 300 mW with an input power of 450 W. Although pulse-tube technology may continue to improve, the properties of regenerative materials at low temperatures impose fundamental limitations on the performance of reciprocating cryocoolers. Brayton cycle performance is not constrained in this way because Brayton coolers utilize continuous flow in a closed loop, obviating the need for regenerative

materials. In addition, Brayton cryocoolers produce negligible vibration that could create jitter of imaging systems.

Performance predictions indicate that a turbo-Brayton cryocooler can provide 400 mW of refrigeration at 10 K and 2.0 W at 70 K with a heat rejection temperature of 300 K and a DC input power of 266 W. This performance will reduce payload power consumption to help make long-duration 10 K spaceflight systems practical. To demonstrate the potential of this technology, Creare assembled and tested a brassboard cryocooler without optimized components available from other systems. This cooler produced 236 mW of refrigeration at 10 K and 1.96 W of refrigeration at 57 K with a heat rejection temperature of 305 K and a DC input power of 378 W. These results are encouraging and provide confidence that a fully optimized turbo-Brayton cryocooler can achieve significantly better performance. This paper presents the brassboard cryocooler test results and summarizes an approach and performance predictions for a fully optimized cooler.

TECHNOLOGY DESCRIPTION

Figure 1 is a schematic representation of a two-stage turbo-Brayton cryocooler appropriate for refrigeration in the 10 to 20 K temperature range. Helium is the best working fluid for these temperatures to prevent liquefaction and maintain an all-gas cycle. One or more compressors at the warm end of the cooler pressurize the working fluid and force it to flow steadily through the system in a continuous loop. Here, three compressors are shown to provide the desired pressure ratio. The heat of compression and associated inefficiencies are removed from the cooler using a radiator at a temperature near 300 K. The temperature of the high-pressure gas then decreases as it flows through the warm recuperator where it is cooled by a countercurrent flow of low-pressure gas returning from the refrigeration loads. Next, the high-pressure flow bifurcates for the two refrigeration stages. Flow for the warmer refrigeration stage passes through a turboalternator and a load interface heat exchanger before entering the low-pressure side of the warm recuperator. The temperature of the gas decreases as it flows through the turbine, where it is expanded nominally from the compressor discharge pressure to the compressor suction pressure. This expansion creates mechanical shaft power, which is converted to electric power by an

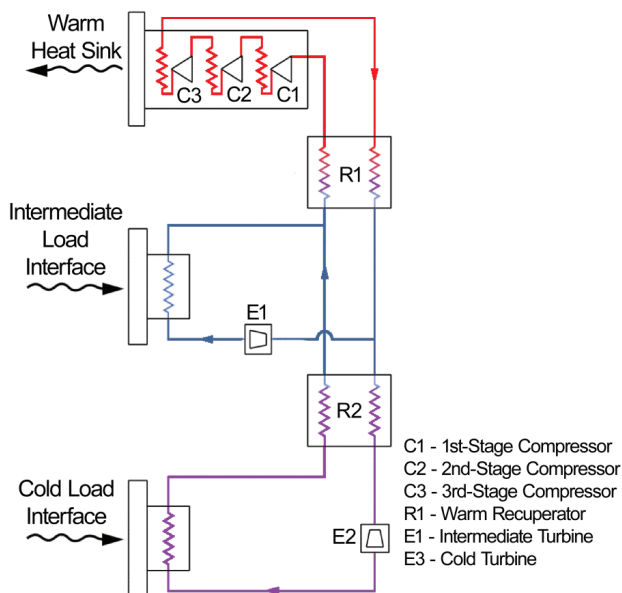


Figure 1. Two-stage turbo-Brayton cryocooler.

integral alternator. The electric power is then either dissipated by electrical resistors at the warm end of the system, or it can be conditioned and fed back to the spacecraft electrical bus. The colder refrigeration stage is analogous to the warmer refrigeration stage, with the addition of a second recuperator and a second turboalternator.

Creare turbo-Brayton cryocoolers build upon proven technology for miniature, high-performance turbomachines and heat exchangers Creare has developed over the last 35 years for long-duration space missions and other applications. These systems have satisfied rigorous NASA and DOD requirements for reliability, endurance, vibration emittance, launch tolerance, electromagnetic interference and susceptibility, and environmental cycling [3,4]. One such system is a turbo-Brayton cryocooler that operated on the Hubble Space Telescope for over 6.5 years while meeting all mission requirements [5]. More recently, Creare made significant improvements in manufacturing readiness level [6], and is continuing advanced component and system development work under several current programs [7, 8]. These projects along with several others have demonstrated fundamental technologies required at relevant sizes, power levels, temperatures, and rotational speeds.

Hydrodynamic gas bearings and clearance seals are key features. Gas bearings support the turbomachine rotors with no mechanical contact between moving surfaces. This lack of contact enables extremely high rotational speeds, which is important for high efficiency and low mass. In addition, gas bearings eliminate wear and the need for lubricants, which enables extremely long maintenance-free lifetimes and makes the resulting systems ideal for space applications. Similarly, clearance seals limit internal bypass leakage without mechanical contact. Key reliability and endurance demonstrations include a 14-year turbomachine test with no maintenance or performance degradation, over 10,000 start/stop cycles with no maintenance or performance degradation, and over 6.5 years of in-space operation.

BRASSBOARD CRYOCOOLER DESCRIPTION

Figures 2 and 3 are photographs of the assembled brassboard cryocooler. It is comprised of components developed previously for the Air Force, MDA, and NASA. The underlying technologies are derived from or are identical to those developed by Creare for the NICMOS Cryogenic Cooler (NCC) on the Hubble Space Telescope. The following paragraphs describe the primary components.

Compressors. High performance compressors have been developed by Creare at power levels from about 1 W to 3 kW [9, 10, 11]. These compressors include a 350-W induction-motor compressor and a 1-W permanent-magnet-motor circulator that were space qualified for the NCC. The current brassboard cryocooler has two 100-W permanent-magnet-motor compressors and one 350-W induction-motor compressor.

Recuperators. Creare has developed compact heat exchangers with high thermal effectiveness for a broad array of applications. In particular, the Creare slotted-plate configuration is ideal for the high thermal effectiveness desired for recuperators in spaceflight coolers. The embodiment of this technology that was space qualified for the NCC has copper and stainless steel components, while Creare is also developing a more advanced version that uses silicon components to reduce mass. The recuperators in the brassboard cooler have the space-qualified configuration with copper and stainless steel components.

Turboalternators. Creare has developed cryogenic turboalternators for many different systems with a wide range of requirements. The space-qualified turboalternator in the NCC enables 7 W of net cryocooler refrigeration at 70 K. The impeller diameter for this turboalternator is 7.6 mm (0.30 inch), which is too large for efficient refrigeration at the temperatures and power levels envisioned for 10–20 K spaceflight applications. The brassboard cryocooler assembly has smaller turbine rotors for this reason. Specifically, the diameter of the intermediate-temperature turbine impeller is 5.8 mm (0.23 inch), and the diameter of the cold-temperature turbine impeller is 3.0 mm (0.12 inch). Performance measurements for the intermediate-temperature turbine are provided by Zagarola et al. [12].

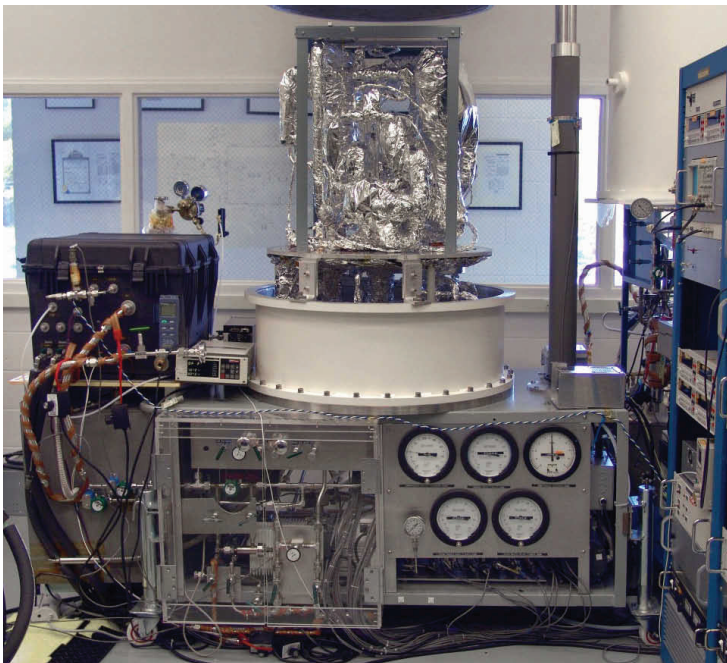


Figure 2. Brassboard cryocooler system



Figure 3. Cryogenic components in brassboard cryocooler.

BRASSBOARD CRYOCOOLER TEST RESULTS

Successive tests were conducted to characterize and refine the performance of the brassboard cryocooler. An initial 30-day test is described by Breedlove et al.[13]. During this test, the cryocooler had a no-load temperature of 8.9 K, it provided 122 mW of refrigeration at 10.0 K, and it provided 500 mW of refrigeration at 18.5 K. Additionally, the intermediate-temperature refrigeration load varied between 62 and 68 K with a thermal load of 1.6–3.5 W, the heat rejection temperature was 303–304 K, and the DC input power was 309–322 W. These preliminary results led to relatively minor changes that improved performance significantly. Specifically, one of the three compressors was replaced with a more advanced version that provides a higher pressure ratio and greater efficiency. The performance characteristics of the replacement compressor were well-established from prior component-level and system-level tests for other cryocooler development programs. A second change involved refinements to reduce the parasitic heat transfer rate. Most notably, a significant thermal short was identified in the system where a 300 K tube contacted another tube attached to the cold refrigeration stage plumbing. The tubing was rerouted to eliminate the thermal short. Detailed inspection of the multi-layer insulation (MLI) throughout the system also identified several areas where improvements were made to reduce parasitic heat gain further. A subsequent round of testing was then completed to quantify the impacts of these changes. Figure 4 shows the measured refrigeration load temperatures throughout the duration of the test.

Cryocooler performance improved greatly from initial testing. Table 1 presents key steady-state measurements for the two tests. As shown, refrigeration at 10 K increased by nearly 50% as a result of the system changes detailed in the preceding paragraph. Furthermore, by operating the Stage 1 turboalternator at 57 K instead of 62 K, the refrigeration increased by another 30%. The net result is nearly two times the refrigeration capacity at 10 K. The final test point in the table shows gains are also significant at greater cold-load temperatures. These improvements highlight the benefits achievable with test and refinement iterations.

Brassboard cryocooler testing was extremely successful and valuable. Foremost, these tests demonstrated the ability of turbo-Brayton technology to provide refrigeration for 10–20 K space applications. The tests also validated design models, which reduces performance uncertainty for optimized cryocoolers with greater efficiency. Consequently, future programs can develop Engineering Model and Flight Model cryocooler designs with greater confidence. Finally, the tests served as a useful shakedown of the test facility, identifying improvements for future testing.

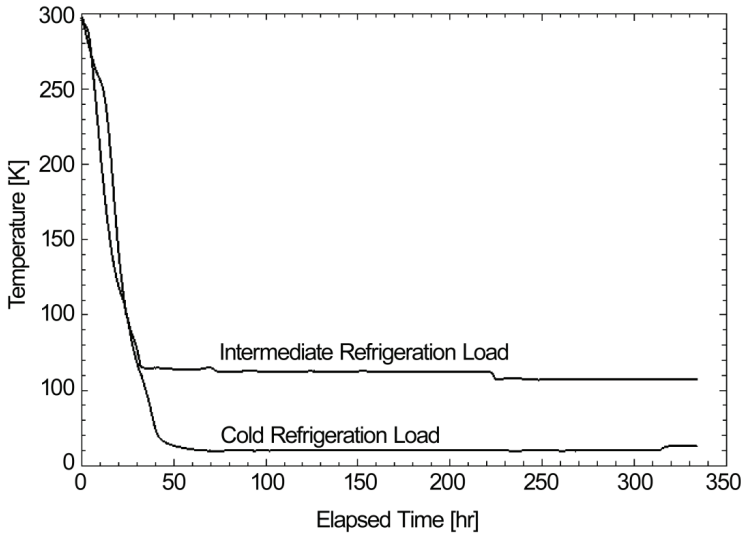


Figure 4. Measured refrigeration load temperatures throughout duration of test.

Table 1. Steady-State Performance Measurements for Initial and Final Cryocooler Configurations.

Heat Rejection Temperature	DC Input Power	Intermediate Load Temperature	Intermediate Refrigeration Load	Cold Load Temperature	Cold Refrigeration Load
Initial Cryocooler Configuration					
303.3 K	313 W	62.1 K	1.59 W	8.89 K	0 mW
303.6 K	322 W	62.3 K	2.04 W	10.02 K	122 mW
303.4 K	316 W	62.5 K	2.74 W	12.71 K	300 mW
303.1 K	309 W	63.1 K	3.53 W	18.47 K	500 mW
Final Cryocooler Configuration					
304.6 K	371 W	62.4 K	2.59 W	10.02 K	182 mW
304.8 K	377 W	57.4 K	1.96 W	10.02 K	236 mW
304.5 K	366 W	57.3 K	2.57 W	13.10 K	400 mW

OPTIMIZED CRYOCOOLER

A preliminary design for an optimized cryocooler has been created based on the brassboard system test results. Figure 5 is a solid model design that shows one potential assembly configuration, and Table 2 lists performance predictions for a range of refrigeration capacities and intermediate refrigeration load temperatures. The three design options in the table have minor differences in stationary components within the turbomachines that control the flow split between the two refrigeration stages. These components can be changed with little effort. The predicted mass of the mechanical assembly is 18 kg, and the predicted mass of the electronics is 4 kg. As indicated, the optimized cooler is expected to have significantly better thermodynamic performance than the brassboard unit. One fundamental reason for the improvement is that the brassboard cooler is comprised of components developed for disparate systems, while the components for the optimized cooler are designed specifically for the intended system. In this way, component mismatches that prevent peak system performance will be eliminated. Inclusion of an advanced cold-stage turboalternator is another important feature for the optimized cryocooler. Here, significant design work has been completed to increase net turboalternator efficiency.

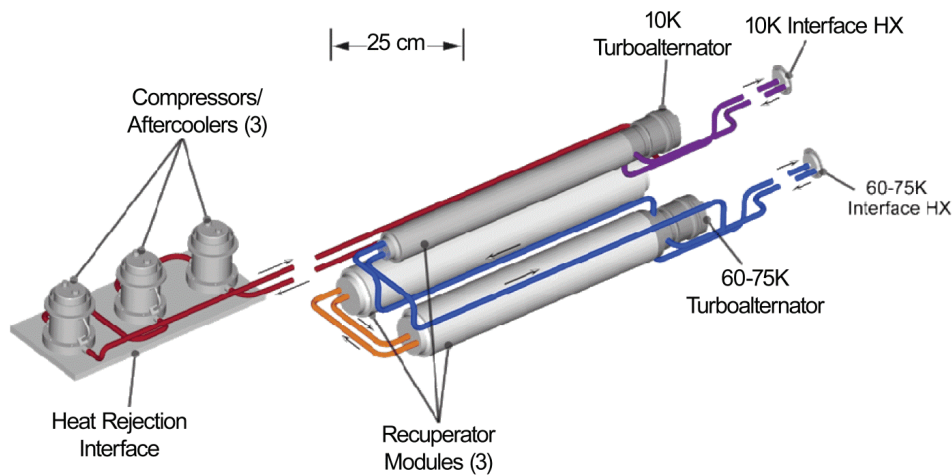


Figure 5. Potential assembly configuration for optimized cryocooler.

Table 2. Performance Predictions for Optimized Cryocooler.

Option	1	2	3
Temperatures			
Heat Sink Temperature	300 K	300 K	300 K
Stage 1 Load Temperature	60 K	75 K	70 K
Stage 2 Load Temperature	10 K	10 K	10 K
Input Power and Refrigeration			
DC Input Power	380 W	408 W	266 W
Stage 1 Cooling Capacity	5.0 W	8.0 W	2.0 W
Stage 2 Cooling Capacity	0.30 W	0.30 W	0.40 W

CONCLUSION

Creare assembled and tested a brassboard cryocooler to demonstrate the potential of turbo-Brayton technology for 10–20 K spaceflight applications. This demonstration was extremely successful in creating a strong foundation for future development of fully optimized 10–20 K cryocoolers. Design projections indicate that the resulting cryocoolers will be extremely valuable for future DOD and NASA missions.

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