Progress Towards a High-Capacity 90 K Turbo-Brayton Cryocooler

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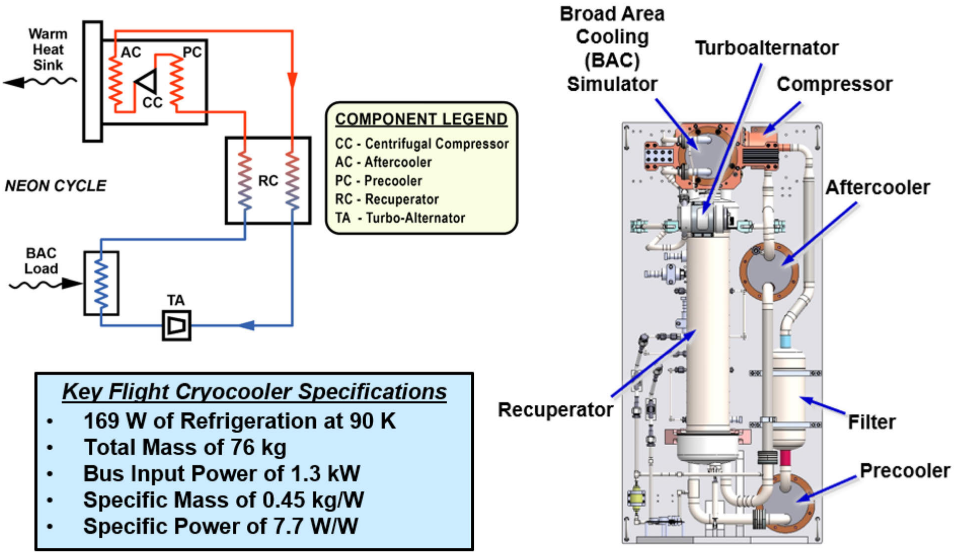
ABSTRACT

Creare is developing for NASA a high-capacity turbo-Brayton cryocooler to support their initiatives for space-borne zero-boil-off storage and liquefaction of oxygen and methane. The cooler is optimized to provide more than 150 W of refrigeration at temperatures from 90 to 120 K for compatibility with a broad range of storage pressures for both cryogens. The cryocooler is a scaled-up version of the 20 W at 90 K cryocooler that Creare delivered to NASA in 2012 and was used in NASA's seminal demonstrations of reduced boil-off hydrogen storage and zeroboiloff oxygen storage. The 150 W cryocooler includes (1) a new 2 kW-class permanent magnet compressor that incorporates efficiency improvements demonstrated in other Creare turbomachines over the last 10 years, (2) a micro-tube recuperator that is a larger version of the unit developed for our highcapacity 20 K cryocooler, and (3) a high-capacity turboalternator that was based on our prior 500 W class compressor with materials updated for operation at cryogenic temperatures and optimized aerodynamics. The cryocooler will utilize these components in two development and test cycles. In the first cycle, we will integrate the components in a brassboard configuration to obtain initial performance data before committing to a flight-like configuration. In the second cycle, we will configure the cryocooler to an engineering model (EM) in a flight-like configuration and complete thermodynamic performance testing, which will advance the Technology Readiness Level (TRL) from 4 to 5, and launch vibration testing followed by verification testing, which will raise the TRL to 6. This paper reviews the component testing.

INTRODUCTION

Future space missions will require long-term storage of cryogen in large tanks to provide a source of chemical propellants. Liquid hydrogen and liquid oxygen are the typical cryogens of consideration, as they provide the highest specific impulse of practical propellants. Maintaining this cryogen in a zero-boil-off configuration is critical to conserving the cryogen and extending mission duration and capability, and studies have suggested that reduced or zero boil-off cryogen technology could provide a 40% mass savings for a Mars mission relative to a reference mission [1,2]. Due to the large size of the tanks, refrigeration loads to maintain zero-boil-off are high. To optimize the thermal management of the cryogen, researchers at NASA have investigated a costorage concept for cryogenic propellants [3]. Based on this assessment, the required cooling loads for some configurations are nominally 20 W at 20 K and 150 W at 90 K.

Cryocoolers 22, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller



Key Flight Cryocooler Specifications

- **169 W of Refrigeration at 90 K**
- **Total Mass of 76 kg**
- **Bus Input Power of 1.3 kW**
- **Specific Mass of 0.45 kg/W**
- **Specific Power of 7.7 W/W**

Figure 1. Cycle Schematic, EM Layout, and performance specifications of 90K cryocooler.

At present, space cryocoolers have been typically utilized for cooling space sensors that have modest cooling loads but are not suitable for the planned missions requiring higher capacity. The turbo-Brayton cryocooler, however, is ideally suited for this purpose: it scales favorably relative to other cryocooler technologies on a specific power basis [4]; further, it has low vibration, high reliability, and enables a versatile direct gas cooling to the cryogenic heat loads. The continuous flow nature of the cycle gas within a turbo-Brayton system provides a direct interface with a Broad Area Cooling (BAC) system attached to the cryogen tank. The direct gas cooling eliminates the performance and mass penalties associated with heat pipes or with indirect circulation loops utilizing an interface heat exchanger.

On a separate program for NASA, Creare has developed and recently tested a cryocooler that provides approximately 20W of cooling at 20K [5; 6]. On this program, we are developing a high capacity, single-stage turbo-Brayton cryocooler that is predicted to provide more than 150 W of refrigeration at 90 K, with a specific power of lower than 8 Watt input power per Watt of cooling. Efficiency relative to the Carnot cycle is predicted to be 29% at the 90 K design point. The cycle diagram and cryocooler solid model assembly for the engineering model (EM) in a flight-like configuration is shown in Figure 1, along with key performance parameters. It includes a single-stage permanent magnet compressor to pressurize the neon cycle gas, an aftercooler to remove the heat of compression, a higheffectiveness micro-tube recuperative heat exchanger that utilizes the return gas flow to cool the high-pressure gas stream to cryogenic temperatures, and a single-stage permanent magnet turboalternator to provide the expansion for cooling. After expanding through the turboalternator, the gas picks up the 90 K heat load of the Broad Area Cooling (BAC) network. For initial cryocooler characterization testing at Creare, heat will be transferred to the gas using electric heaters and a heat exchanger to simulate the BAC heat load.

SIGNIFICANCE OF DEVELOPMENT

Successful development of a cryocooler of this capacity advances the state-of-the-art of available space cryocoolers. The cooling capacity at temperatures of 90 to 120 K is 5–10 times the capacity of currently available space cryocoolers at these temperatures, as shown in Figure 2. The higher cooling capacity enables zero boil-off of larger cryogen tanks with associated higher parasitic heat loads, allowing for increased mission duration and capability.

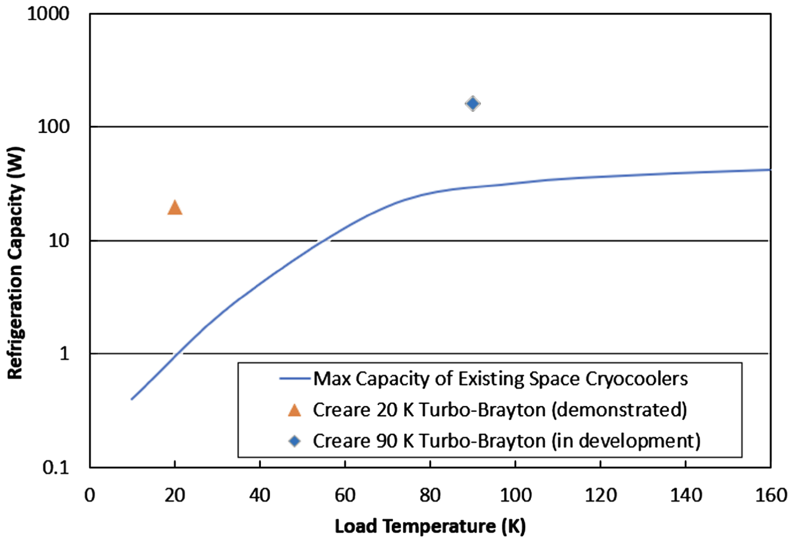


Figure 2. Creare's 20 K and 90 K cryocoolers compared to existing space cryocooler capacity

SYSTEM AND COMPONENT DEVELOPMENT

Key milestones in the cryocooler development completed to date include design, fabrication and performance testing of the compressor; design, fabrication, and testing of the recuperator; and finalized design, fabrication, and initial testing of a permanent magnet turboalternator (final preintegration testing is on-going at present). A CAD solid model design and layout of the brassboard and EM configurations have been completed, as well as a launch vibration stress analysis of the EM assembly in ANSYS Mechanical. Following final component verification testing, Creare will assemble and perform tests of the cryocooler in both brassboard and EM configurations to demonstrate performance of the integrated system.

Compressor

The compressor (Figure 3) is a 2-kW class machine that utilizes a permanent magnet motor, and self-acting tilt-pad journal bearings. The design was based on a scale-up of a previous 500 W machine and was optimized for this cryocooler by performing CFD optimization of the aerodynamic features, in conjunction with advanced rotor fabrication techniques. Relative to its scaled initial design from the helium-based 500-W machine, this compressor's rotor was revised to utilize a smaller

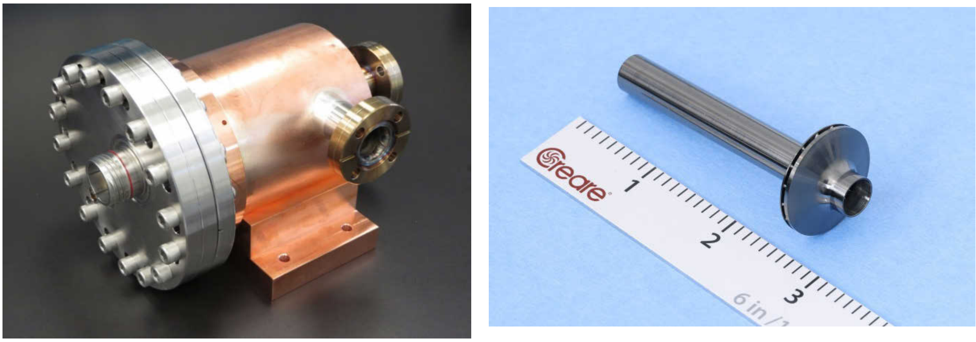


Figure 3. 1500 W-class compressor (left) and its rotor (right).

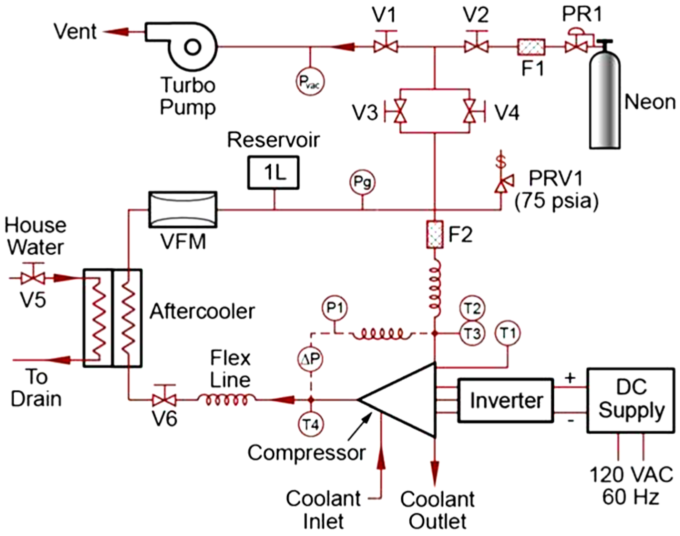


Figure 4. Schematic of compressor test loop.

compressor eye diameter and seal diameter to reduce bypass leakage. Internal drag and stator losses are removed via a conductively cooled interface in contact with the heat rejection system.

This compressor was successfully built and tested. During testing, the compressor was operated to confirm satisfactory operation to the design speed and to measure its thermodynamic performance, as well as mechanical verification of the thrust bearing and journal bearings. To test the compressor, we designed and assembled a closed-loop test facility (Figure 4) to enable operation in clean neon gas at prototypical operating conditions and with the required instrumentation to accurately characterize the thermodynamic performance of the compressor.

Thrust bearing and journal bearing verification tests were first performed to verify operational stability. With stable operation verified, we then operated the compressor to characterize its performance. The goals of the testing were to measure the input power at the design point, and generate a head vs. flow performance curve, as well as a compressor efficiency curve over a range of operating conditions.

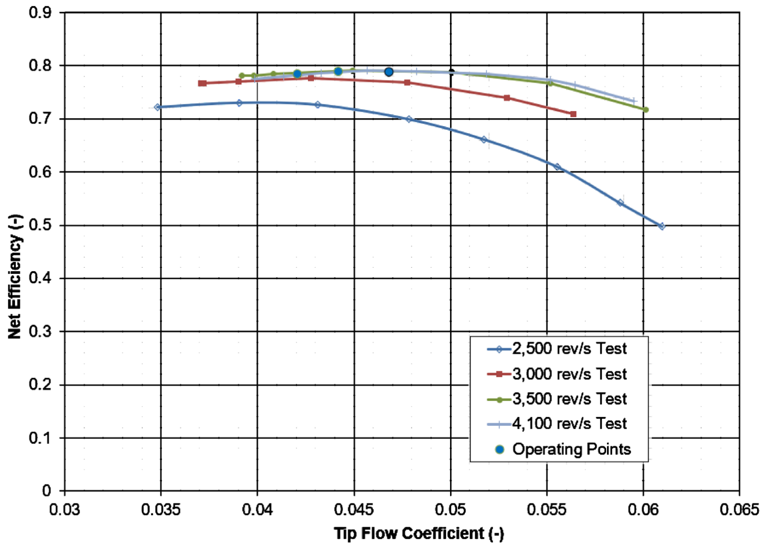


Figure 5. Compressor efficiency vs. flow coefficient.

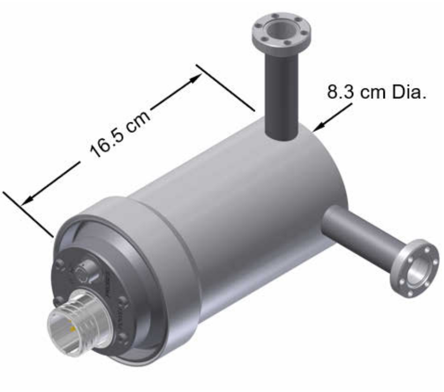


Figure 6. Turboalternator for 150 W at 90 K cryocooler.

The measured compressor net efficiency vs. flow coefficient is shown in Figure 5 [7]. We measured compressor performance at four different speeds and over a range of flow rates. The measured peak compressor efficiency is 79% at a power level of 1600 W. This represents the highest efficiency compressor built by Creare to date. Overall, the compressor demonstration was extremely successful and greatly reduces the performance risk for the cryocooler demonstration. The design, fabrication and testing increased the compressor TRL from 3 to 5.

Recuperator

The recuperator for the 90 K cryocooler is an all-welded stainless steel shell-and-microtube counterflow heat exchanger. The design and fabrication processes for this technology were developed for the 20 W, 20 K cryocooler, and the technology has since been utilized on other turbo-Brayton cryocooler and turbo-Brayton power system programs. The recuperator design consists of over 17,500 stainless steel microtubes arranged in an annular layout within the core. The annular layout accommodates a shell-side flow arrangement with both radial inflow and radial outflow, to promote uniform flow distribution. The tube bundle is contained within a welded hermetic shell of outer diameter 15.4 cm and core length of 74 cm. The tubes transport the lowpressure flow from the coldend header to the warm-end header. At each end of the tube bundle, the tubes are laser-welded to a tubesheet to separate the two flow streams. The shell-side interstitial space is used to transfer the high-pressure flow in the counter-flow direction to the tube flow. The reinforced torispherical header assemblies on each end of the core contain and distribute the incoming and outgoing flow. The headers add additional length to the recuperator body, bringing the total body length to 94 cm (not including flow tube ports). The total mass of the recuperator module is approximately 24.6 kg. Table 1 summarizes the recuperator design and operating parameters.

The recuperator was designed by Creare using analytical models that have been validated on previous Brayton cryocooler and power cycle programs. ANSYS structural and Fluent fluid dynamic

Table 1. Recuperator Design and Performance Predictions

Outer Diameter	15.4 cm
Core Length	74.0 cm
Number of Microtubes	17,550
Mass	24.6 kg
Effectiveness	0.990
Total Pressure Loss (dP/P)	2.80%
Recuperator Loss, including Parasitics	48 W

Figure 7. Completed recuperator for the 90K cryocooler.

models were used to analyze the static stress, vibration stress, and mass flow distribution performance. The recuperator was fabricated in partnership with Mezzo Technologies. Mezzo completed the core assembly and laser welding of the microtubes to the tubesheets. The shell and inner tube assembly were fabricated in a collaboration of Creare and Edare, LLC. Header fabrication and final closeout welding were performed at Creare. Figure 7 shows a photograph of the completed recuperator.

Once assembled, workmanship tests were completed on the recuperator to verify the performance fundamentals. The recuperator was leak tested with a helium mass spectrometer. External leak rate is hermetic, measuring less than 7E-10 atm-cc/s of helium. Cross-stream leak rate is small enough to be negligible for system performance, measuring 3.2E-4 atm-cc/s of helium.

A pressure-flow test was performed on the recuperator to assess pressure loss performance and verify conformance to design intent. This was done using filtered air at various flow rates, a mass flow controller and a pressure transducer. The flow rates were scaled from the design conditions to achieve dynamic similarity (Reynolds Number matching). Shell-side and tube-side flows were assessed separately, and a range of flow rates were collected to generate pressure-drop versus flow curves. The data points collected were compared to the system models and showed excellent agreement, as shown in Figure 8. These test results demonstrate that the recuperator flow characteristics match the design intent very closely and provide a strong initial indication that it should meet thermal performance predictions when tested as part of a cryocooler later this year.

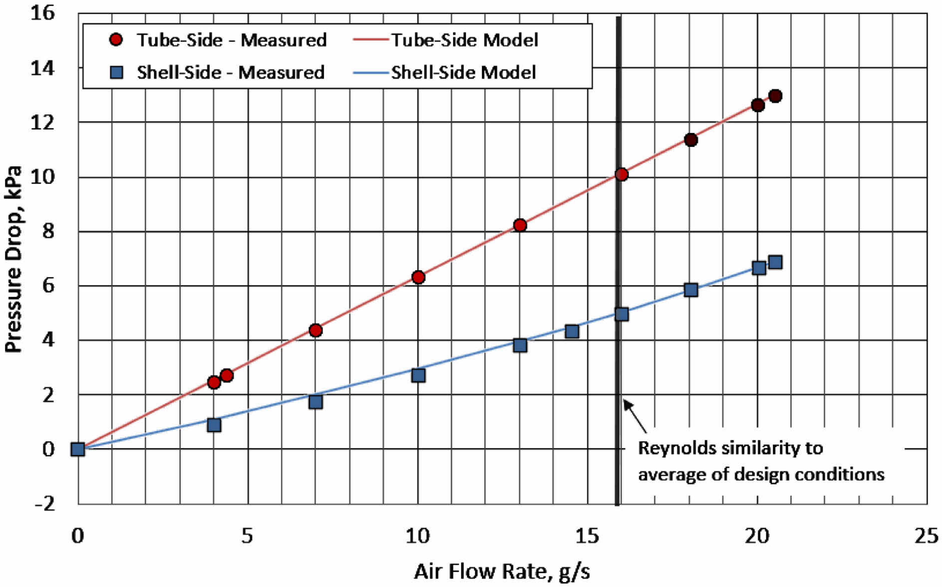


Figure 8. Recuperator pressure loss performance using pressurized air. Shell-side and tubeside pressure loss matches up well with model predictions.

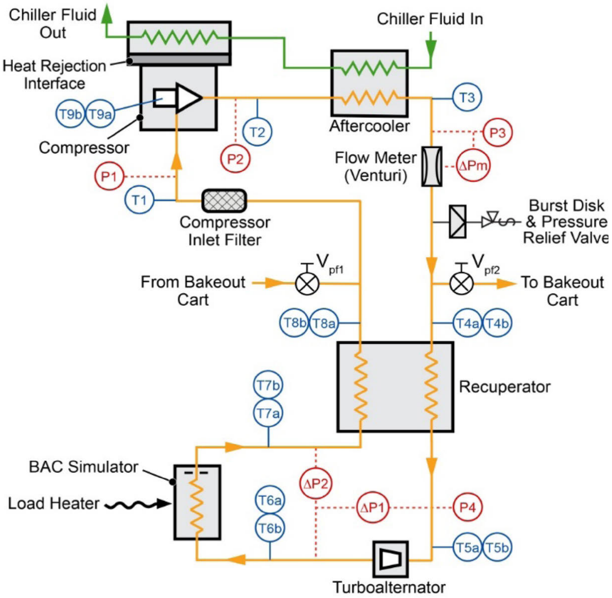


Figure 9. Cryocooler test loop schematic.

SYSTEM ASSEMBLY AND TESTING

The cryocooler components will be assembled into a brassboard system configuration and tested in a vacuum bell jar. The brassboard test configuration will be used to characterize the performance of the recuperator and turboalternator in prototypical operating conditions but without the prototypical mounting configuration. Following the brassboard testing, the system will be reconfigured into an EM configuration with automatic system controls and flight-like component mounting. The system will undergo cryogenic thermal performance testing in the EM configuration to raise the system Technology Readiness Level (TRL) from 4 to 5, as well as NASA GEVS [8] launch vibration testing and follow-on verification testing, which will further advance the TRL to 6.

A schematic of the brassboard configuration is shown in Figure 9 and physical hardware assembly in Figure 10. Neon will be the circulating gas. Instrumentation includes pressure transducers

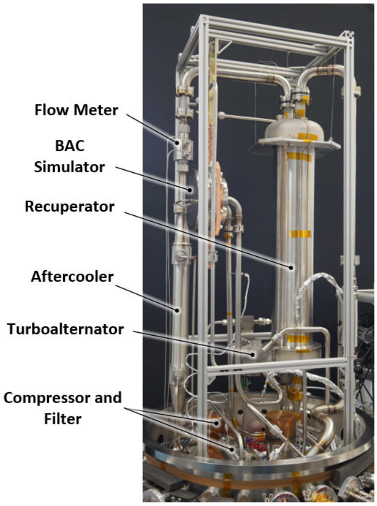


Figure 10. Brassboard cryocooler physical hardware assembly.

and redundant temperature sensors at the inlet and outlet of the key system components, to measure the thermodynamic state; a venturi flow meter to measure flow rate; power meters to measure compressor input and turboalternator output power, voltage, current, and frequency; and power supply voltage and current measurements of the BAC cooling load power to measure system refrigeration capacity. Ancillary hardware will include a compressor inlet filter to capture system contaminants and protect the turbomachines, a chiller loop to remove heat from the aftercooler and compressor body, a bakeout cart to perform a heated bakeout of the system, a pressure relief valve and burst disc for overpressure safety, a data acquisition system to provide manual system control inputs and measure data, and transducer and power supply hardware to interface with instrumentation. Cryocooler control electronics will be used to control the inverter drive for the compressors as well as a programmable load to dissipate turboalternator power.

Key performance measurements resulting from the testing will be the cooling capacity at 90 to 120 K (as measured by the BAC load heaters), the specific power (input power / refrigeration power), the specific mass (total cryocooler mass / refrigeration power), and the fraction of Carnot efficiency. Performance predictions for these key performance metrics are given in Figure 1.

CONCLUSION

Creare is developing for NASA a turbo-Brayton cryocooler that can provide more than 150 W of cooling at 90 K. This cryocooler will greatly advance the state of the art in cooling capacity at this temperature and will enable zero-boil-off of larger propellant tanks for future space missions. Fabrication and testing of key components for this cryocooler is almost complete. Final fabrication, system assembly, and brassboard cryogenic testing of the cryocooler is planned for the near future. EM cryogenic performance testing is to follow and will raise the system TRL from 4 to 5; subsequent vibration and verification testing will further advance the TRL to 6.

ACKNOWLEDGMENT

The authors would like to thank NASA for their support of the work presented in this paper.

REFERENCES

1. Christie, R.J., Tomsik, T.M., Elchert, J.P., Guzik, M.C., “Broad Area Cooler Concepts for Cryogenic Propellant Tanks,” *Thermal and Fluid Analysis Workshop (TFAWS)*, (2011).

2. Braun, R.D., *Investment in the Future: Overview of NASA’s Space Technology*, http://images.spaceref.com/news/2010/Braun.5may2010.pdf (2010).

3. Mustafi, S., Canavan, E.R., Boyle, R., “Co-Storage of Cryogenic Propellants for Lunar Exploration,” *AIAA SPACE 2008 Conference & Exposition*, (2008).

4. Zagarola, M.V., McCormick, J.A., “High-Capacity Turbo-Brayton Cryocoolers for Space Applications,” *Cryogenics*, Vol. 46 (2006), pp. 169–175.

5. Cragin, K.J, Zagarola, M.V., “Development and Testing of a High-Capacity 20 K Cryocooler,” *Cryocoolers 22*, ICC Press, Boulder, CO (2022), (this proceedings).

6. Deserranno, D., Zagarola, M.V., Li, X., Mustafi, S., “Optimization of a Brayton Cryocooler for ZBO Liquid Hydrogen Storage in Space,” *Cryogenics*, Vol. 64 (2014), pp. 172–181.

7. Zagarola, M.V., Cragin, K.J., Hill, R.W., McCormick, J.A, “Efficiency Improvements for TurboBrayton Cryocoolers for Space,” *Cryocoolers 21,* ICC Press, Boulder, CO (2021), pp. 397–404.

8. NASA Goddard Space Flight Center, “General Environmental Verification Specification for STS & ELV Payloads, Subsystems, and Components,” *GEVS-SE*, Rev A (1996).