Development and Testing of a High-Capacity 20 K Cryocooler

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ABSTRACT

Creare is developing a high-capacity 20 K cryocooler to support NASA's initiatives for zero-boil-off storage and liquefaction of hydrogen. The specific type of cryocooler is a single-stage turbo-Brayton cryocooler that is designed to produce up to 20 W of refrigeration at 20 K and rejects heat at 300 K. The turbomachines are derived from prior designs optimized for operation in helium and at high volumetric flow rates. The recuperator is new technology developed through a collaboration with Mezzo Technologies and Edare LLC, Creare's sister company, and optimized for high mass flow rates, low pressure drop and high thermal effectiveness. The high effectiveness recuperator enables the cryocooler to operate between 300 and 20 K in a single stage. Three centrifugal compressors plumbed in series provide the pressure ratio which is expanded through a single turbo-alternator. The cryocooler components were tested and then packaged and integrated in a flight-like configuration suitable for launch vibration testing. Thermodynamic characterization testing demonstrated up to 22.5 W of refrigeration at 22.7 K and up to 19.2 W of refrigeration at 20 K. Maximum cryocooler COP was 15.9% of the Carnot cycle and the minimum specific power was 80 W/W. The cooling capacity and performance of this cryocooler are new benchmarks for 20 K cryocoolers for space. This paper reviews the component testing, integration, and initial testing of the cryocooler.

INTRODUCTION

NASA is supporting the development of technologies to support future long-term human exploration missions beyond low-Earth orbit. A critical aspect of these missions is the long-term storage and transfer of the cryogenic propellant to support the chemical propulsion needs of future missions. Liquid hydrogen and liquid oxygen provide the highest specific impulse of any practical chemical propellant, permitting longer range and higher payload mass. For long-duration missions, the cryogen storage tanks must be cooled to reduce or eliminate boil-off. For some architectures, the net heat load to store 38-metric tons of liquid hydrogen is estimated to be 20 W at 20 K, including design margin. [1] To enable long-duration zero boil-off storage, this heat load must be lifted using an active refrigerator. However, this heat load exceeds the capacity for any space cryocooler demonstrated to date by a significant margin.

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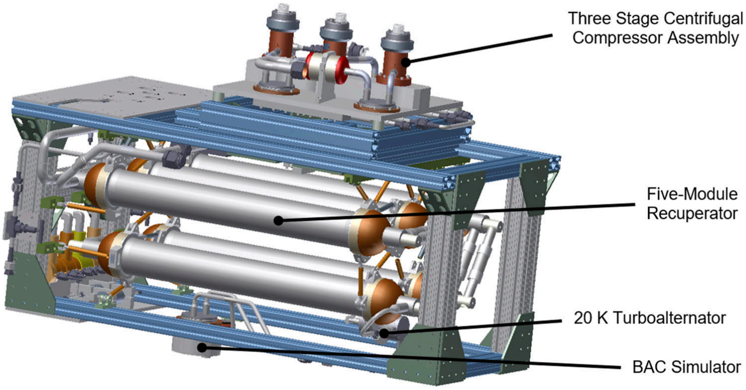

Figure 1. Creare's 20 K, 20 W cryocooler for zero-boil-off cryogen storage.

Creare is addressing this shortcoming by developing for NASA a turbo-Brayton cryocooler that provides 20 W of refrigeration at 20 K. [2] Turbo-Brayton cryocoolers are ideal for long-term liquid hydrogen storage in space because of favorable mass and performance scaling to high capacities and low temperatures relative to other refrigeration cycles. In addition, the continuous-flow nature of the Brayton cycle is ideal for cryogen storage missions because the cycle gas can be directly interfaced with a broad area cooling (BAC) system attached to the storage tank without the mass and performance penalties associated with cryogenic heat pipes or circulation loops. The cryocooler developed for this application is shown in Figure 1. It delivers nominally 20 W of cooling at 20 K with an input power around 1.8 kW, corresponding to a specific power below 100 W/W. The coefficient of performance of the cryocooler is 15% of the Carnot cycle, an extremely high value for a 20 K cryocooler.

SIGNIFICANCE OF DEVELOPMENT

The cryocooler being developed at Creare represents a considerable advance in the state of the art for space cryocoolers providing refrigeration around 20 K. The cooling capacity for this cryocooler at temperatures near 20 K is more than an order of magnitude greater than any currently available space cryocooler at these temperatures, as shown in Figure 2. Furthermore, the cryocooler efficiency is high, achieving 15% of the Carnot cycle. This results in a specific power less than 100 W/W, representing a

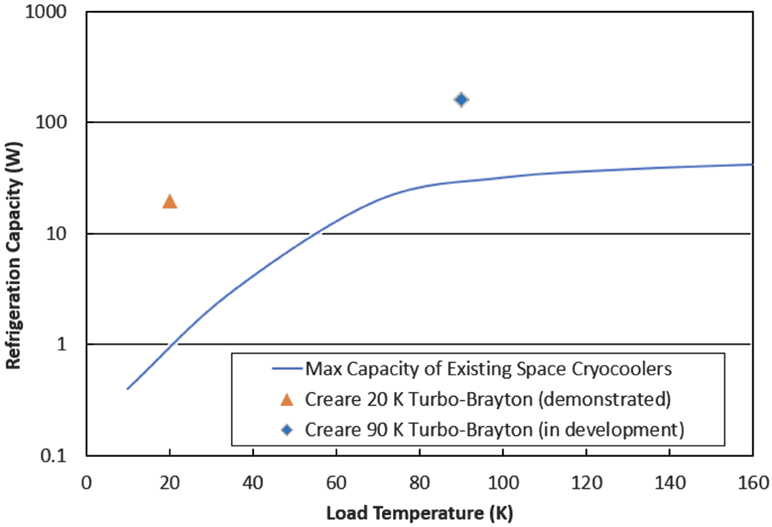

Figure 2. Creare's 20 K and 90 K cryocoolers compared with available space coolers.

considerable improvement over 20 K cryocoolers demonstrated to date and thus minimizing mass penalties associated with the spacecraft heat rejection and power generation systems. The cryocooler is also novel in that refrigeration at 20 K is produced from a single-stage cooler, which is not typical for a low-temperature (below 40 K) cooler where multiple stages are typically employed, and this is enabled by the high effectiveness recuperative heat exchanger. The large refrigeration capacity and high efficiency provided by this cryocooler represents a key enabling technology for zero boil-off cryogen storage on space-based platforms, allowing for increased mission duration and capability.

SYSTEM AND COMPONENT DEVELOPMENT

The cryocooler (Figure 1) is a single-stage turbo-Brayton cryocooler, composed of three compression stages with intercooling to meet pressure ratio requirements, a high-effectiveness 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 expand the gas and provide net refrigeration. The working fluid is gaseous helium. The recuperator is divided into five identical modules to simplify packaging. The compressors reject heat to a baseplate at 270–300 K, cooled by liquid-cooled cold plates. In a flight system, this heat of compression and dissipation losses would be removed by the spacecraft thermal management system. For characterization testing prior to delivery, the cryocooler was interfaced with broad area cooling (BAC) simulator, which replicates the volume, heat loads and pressure drop of the BAC tubing network surrounding the cryogen storage tank. Heat loads are applied using electric resistance heaters for characterization of the cryocooler lift and cycle efficiency at various operating points. An interface heat exchanger transfers the applied heater power into the cycle gas. The cryocooler is monitored and controlled by a set of rack-mounted electronics. The mass of the flight system is 106.3 kg.

Each of the main cryocooler components (compressors, turboalternator, and recuperator) was designed, fabricated, and tested at the component level before integration into the cryocooler assembly for thermodynamic performance testing. The cryocooler components were packaged and integrated in a flight-like configuration suitable for launch vibration testing. The sections below review the component testing, system integration, and initial test results for the cryocooler.

Compressors

The cryocooler utilizes three compressors with intercooling to compress and circulate the helium cycle gas. The compressors operate on self-acting journal bearings, are driven by brushless permanent magnet motors at speeds exceeding 6,000 rev/s, and have a nominal input power capacity of 600 W. As a result of the high speed and flow rates, the efficiency is extremely high for all stages, resulting in net efficiencies of greater than 60% for the three compressor stages. This is significantly higher than prior permanent magnet motor compressors developed by Creare which have shown peak efficiency of around 50%. The compressors are identical except for the aerodynamic features in the impeller and diffuser blades, which were optimized for peak efficiency at the operating conditions for each stage. Figure 3 shows the rotor assemblies prior to assembly.

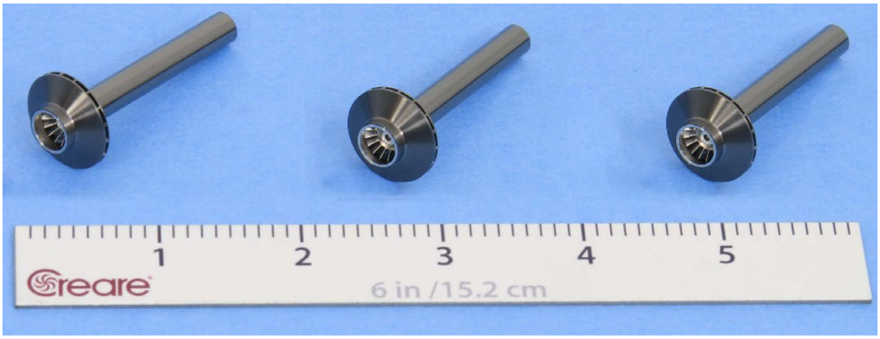

Figure 3. Compressor rotors.

All three compressors were operated to confirm satisfactory operation to the design speed and to measure thermodynamic performance in a closed-loop test facility. The testing confirmed stable operation at the design operating speed, measured the input power at the design point, and generated a head vs. flow performance curve, as well as a compressor efficiency curve over a range of operating conditions. Correlation between predictions and measured performance is very good. Additionally, the net efficiency for all three stages is greater than 60%, a considerable improvement on prior miniature turbo-compressors in this power class. The test results are reported in [3].

Turboalternator

The turboalternator, as shown in Figure 4, expands the cycle gas at the cold end to produce refrigeration. The turbine rotor has a permanent magnet bonded inside the rotor shaft. The spinning magnet couples with an integral alternator assembly to enable work to be extracted from the cycle gas electrically to produce net refrigeration. Operating speed is over 3,000 rev/s at 20 K. It is designed to produce nominally 40 W of alternator power at the design point, with a net efficiency around 75%. Nominally half of this refrigeration is used to accommodate losses in the recuperator, leaving nominally 20 W for net refrigeration to the load. The turboalternator is an isothermal design, with the rotor tip and the journal and thrust bearings all operating at the nominal 20 K refrigeration temperature. The design was based on prior isothermal turboalternator designs for space applications with aerodynamic optimization of the aerodynamic features for high performance at the 20 K design operating point.

Testing a high-capacity turboalternator at low temperatures is quite difficult as a stand-alone component. To cool 4 g/s of helium from 300 K to 20 K requires nearly 6 kW of refrigeration, which is significant. Alternatively, testing using vaporized liquid helium is possible but temperature and pressure control in this configuration is difficult. Creare upgraded an existing test facility routinely used for low-temperature, low-capacity turboalternator testing at flowrates up to 0.5 g/s at 20 K to allow testing at flow rates up to 4 g/s at 20 K. We obtained performance data at a turbine inlet temperature of 20 K and over a range of operating pressures and pressure ratios surrounding the design point. The rotational speed was varied from nominally 2750 rev/s up to 4000 rev/s to create a performance map. The measured net efficiency was 78%, an extremely high value, and the measured performance was in good agreement with predictions. The turboalternator test results are reported in [4].

Recuperator

The recuperator is an all-welded stainless steel shell-and-microtube counterflow heat exchanger. The design and fabrication processes are new technology developed for high-capacity turbo-Brayton cryocoolers. The recuperator was a joint development effort between Creare, Mezzo Technologies, and Edare LLC, Creare's sister company.

Figure 4. Turboalternator for 20 W at 20K cryocooler.

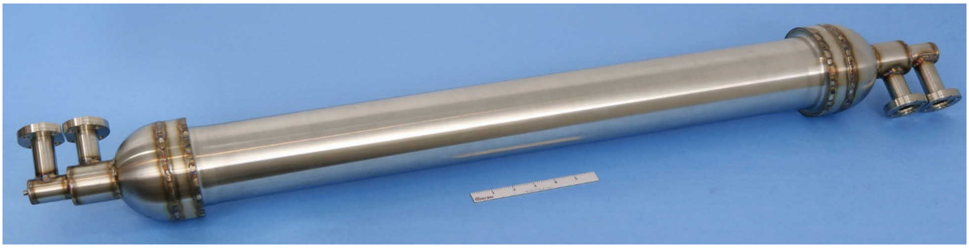

Figure 5. Completed recuperator module for the 20K cryocooler.

The performance requirements of the cryocooler resulted in the need for a recuperator over 150 inches long. Due to the excessive length, the recuperator was divided into five serial modules for ease of fabrication and packaging. Each module is nominally 40 inches long arranged in an annular layout within the core. The annular layout was chosen to increase flow uniformity in the shell-side flow thus increasing thermal effectiveness. The core is contained within a hermetic outer shell 10 cm (4 in.) in diameter.

The recuperator was designed by Creare to achieve the high effectiveness target (exceeding 0.995) required for the cryocooler. [2] The high thermal effectiveness allows the cryocooler to operate between 300 and 20 K in a single stage. Key challenges were addressed through fabrication trials and testing of preliminary units. Figure 5 shows a photograph of one of the completed recuperator modules. Following this successful demonstration, four additional recuperator modules were fabricated incorporating the newly developed fabrication and assembly techniques. The developing and testing of these recuperators is described in [5].

CRYOCOOLER ASSEMBLY AND TESTING

The cryocooler components were assembled in a flight-like configuration suitable for thermal and launch vibration testing. To accommodate differing test chamber dimensions and provide some flexibility in the system configuration, the cryocooler is integrated into separate warm and cold modules connected by flexible tubing. The warm module comprises the three-stage compressor assembly, intercoolers/aftercoolers, and the warm heat rejection interface. The cold module comprises the five recuperator assemblies, the turboalternator, and the BAC simulator used to provide heat loads at the cold end during characterization testing. The cryocooler is configured within an aluminum frame for lifting and rigging purposes and for ease of reconfiguration of the warm and cold modules. Flight versions of the cooler would be integrated directly with the spacecraft payload. Figure 6 shows the completed cryocooler assembly ready for installation into the thermal vacuum chamber for characterization testing. A warm accumulator volume is located outside the test chamber for space considerations and connected to the cryocooler warm end via a vacuum feedthrough. The control and monitoring electronics (not shown in Figure 6) have flight-like functionality but utilize mostly rack-mounted, commercial components and are also located outside of the test chamber.

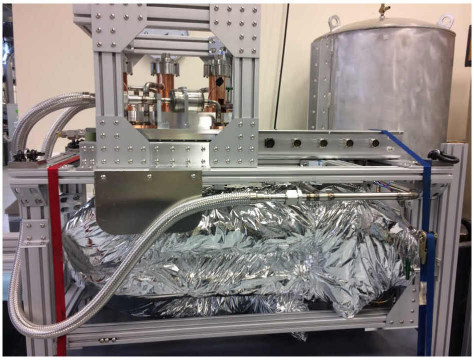

Figure 6. 20K Cryocooler assembly ready for installation in thermal vacuum chamber.

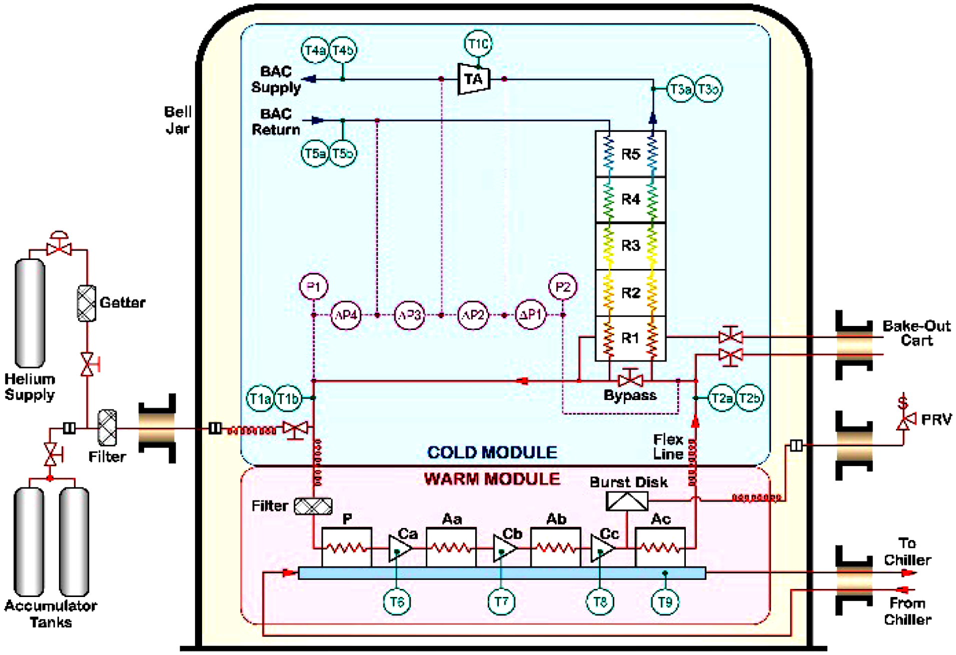

Figure 7. Cycle Schematic and instrumentation locations.

The thermodynamic performance of the cryocooler was measured at Creare in May 2022. The system was cooled to operating temperature and the performance was characterized for a range of cooling loads and heat rejection temperatures. Figure 7 shows a cycle schematic with pressure and temperature measurement locations. The objectives of the test were to characterize the thermodynamic performance of the cryocooler, assess the accuracy of predictive models and verify functionality of the controls, telemetry, instrumentation, and mechanical hardware. Key performance measurements resulting from the testing include the cooling capacity at 22.8 and 20.0 K (as measured by the BAC return temperature), the specific power (input power / refrigeration power), the specific mass (flight cryocooler mass / refrigeration power), and the Carnot efficiency.

The figure of merit η_{Carnot} for a cryocooler 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. That is:

$$\eta_{Carnot} = \frac{\dot{Q}_{net}}{\dot{P}_{AC,comp} - \dot{P}_{AC,TA}} \left(\frac{T_{rej}}{T_{load}} - 1 \right) \qquad (1)$$

where $\dot{Q}_{net}$ is the net cooling load, $\dot{P}_{AC,comp}$ is the total AC input power to the compressors, $\dot{P}_{AC,TA}$ is the AC output power from to the turboalternator that is recovered, T_{rej} is the heat rejection temperature, and T_{load} is the load temperature. Because the nominal 40 W of turboalternator output power is small in comparison to the total input power, and to simplify the control electronics, recovery of the TA power was not pursued for the demonstration cryocooler and the recovery benefit is not included in the Carnot efficiency calculations presented below.

The temperature history over the duration of performance testing is shown in Figure 8. A summary of the test points achieved, the heat lift at each point, and the system efficiency are shown in Table 1. The AC input power in Table 1 is corrected to remove resistive losses in the non-prototypical 40 ft. harnesses external to the test chamber. Testing was performed at nominally 22.8 and 20.0 K, to cover the expected BAC return temperature for different

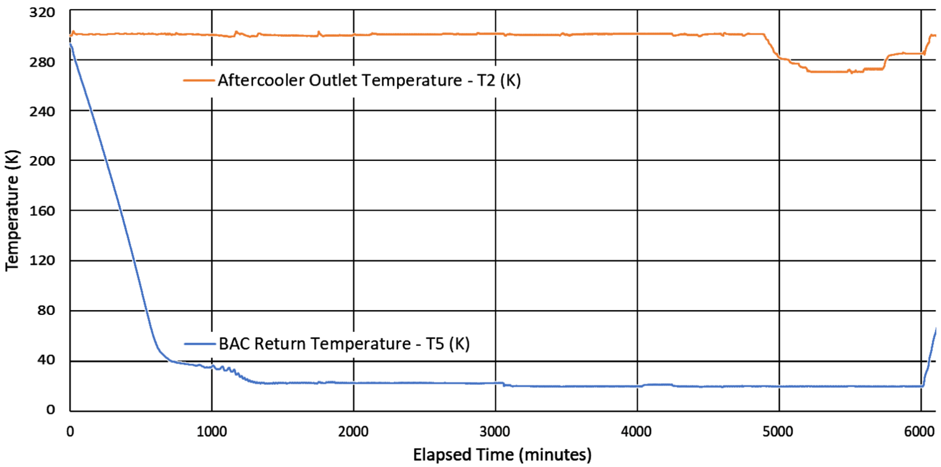

Figure 8. Temperature history over test campaign.

Table 1. Primary cryocooler performance data.

Test Point	1	2	3	4/5	6	7	8	9	10	11
BAC Return Temp. (K)	22.5	22.7	21.4	20.1	19.9	19.9	20.1	20.1	20.0	20.0
BAC Heat Input (W)	19.6	22.5	20.0	16.7	14.0	11.0	7.0	3.0	19.2	3.0
AC Input Power (W)[1]	1642.3	1728.7	1721.4	1711.9	1587.2	1390.5	1080.5	828.7	1722.7	727.5
Recup HP In Temp. (K)	300.5	301.0	301.1	300.8	300.0	300.7	300.4	300.6	285.0	270.4
Actual/Carnot COP (%)[2]	14.7	15.9	15.2	13.6	12.4	11.2	9.0	5.1	14.8	5.2
Specific Power (W/W)[3]	87	80	90	107	119	133	162	291	94	255
Specific Mass (Kg/W)[4]	5.4	4.7	5.3	6.4	7.6	9.7	15.2	35.4	5.5	35.4

[1] Measured AC input power corrected for resistive losses in non-prototypical 40-ft. external harness length
[2] As demonstrated, without TA power recovery
[3] Calculated from expected DC bus input power with TA power recovery
[4] Based on flight cryocooler mass of 106.3 Kg

cryogen storage pressures. In addition, data were obtained for various values of lift at 20 K to characterize the cryocooler performance. Test points 4 and 5 were intended for heat loads of 20 and 17 W respectively, but the maximum cooling load at a 300 K heat rejection temperature was determined to be 16.7 W. The key measurements are presented graphically in Figure 9.

Figure 10 shows the measured cryocooler efficiency over the range of operating points during performance testing. The measured Carnot efficiency is just below 15% at 20 K and decreases as the heat load is reduced. The peak Carnot efficiency is 15.9%. Figure 11 compares performance predictions with the measured performance. The measured performance is in good agreement with the model.

CONCLUSION

Creare recently demonstrated a turbo-Brayton cryocooler that represents a considerable advance in the state of the art for space cryocoolers providing refrigeration around 20 K. The cooling capacity for this cryocooler at temperatures near 20 K is more than an order of magnitude greater than previously demonstrated space cryocooler at these temperatures. Furthermore, the cryocooler efficiency is high, achieving 15% of the Carnot cycle at 20 K. The cryocooler specific power is less than 100 W/W. The cryocooler provides a key enabling

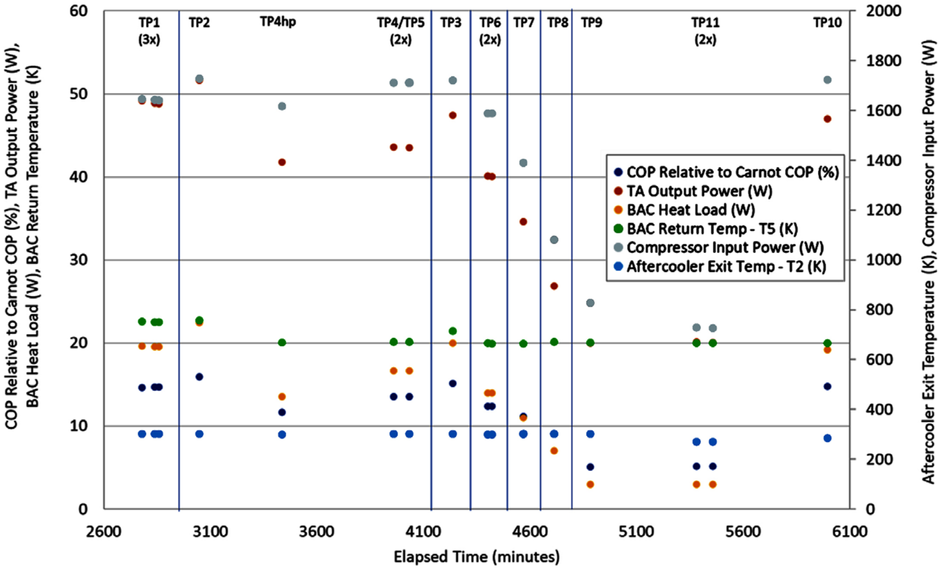

Figure 9. Key steady-state performance data.

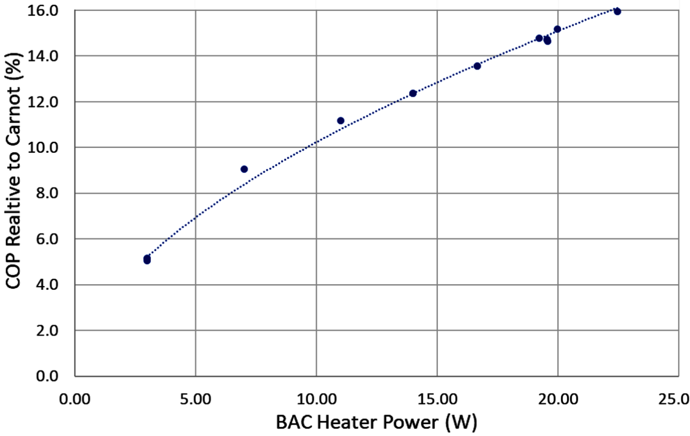

Figure 10. Cryocooler Carnot efficiency over a range of cold end heat loads at 20–23 K.

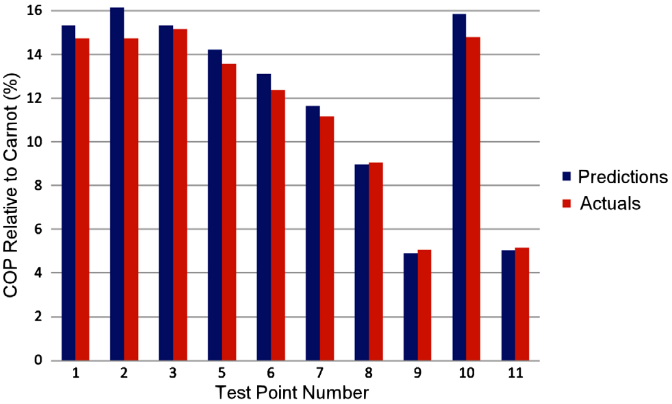

Figure 11. Comparison between performance predictions and test results over the testing campaign. Measured performance is nominally 1% below predictions at the high load points.

technology for zero boil-off cryogen storage on space-based platforms, allowing for increased mission duration and capability. In addition, the performance data provide critical information for optimization of future high-capacity cryocoolers for space.

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