Characterization Testing of a 20 Kelvin Cryocooler for Space Applications

B.T. Nugent[1], W.L. Johnson[1], R.J. Grotenrath[1], J.R. Stephens[2], M.G. Perkins[3]

[1]NASA Glenn Research Center, Cleveland, OH 44135
[2]NASA Marshall Space Flight Center, Huntsville, AL 35808
[3]HX5, LLC, Brook Park, OH 44142

ABSTRACT

Future NASA space exploration missions will require long-duration storage and liquefaction of cryogenic liquids, enabled by active cooling provided by cryocoolers. Recent gap analyses of Lunar and Mars transportation systems have identified 20 K-class cryocoolers as a critical enabling technology for chemical and nuclear thermal propulsion architectures using liquid hydrogen propellant. To address this technology gap, NASA has undergone the development of a high-efficiency, high-capacity 20 K cryocooler via an SBIR partnership with Creare. While the January 2025 testing demonstrated functionality and compliance with contractual requirements, the objective of the NASA-led characterization effort was to generate a dataset for supporting future mission designs across a broader operating envelope, including off-nominal conditions. The cryocooler demonstrated strong performance, achieving a peak coefficient of performance of 17.68% relative to Carnot efficiency and a maximum lift capacity of 24.4 W at 21 K. Overall, the results confirm that the 20 W 20 K cryocooler provides a flexible range of capabilities to enable zero boil-off storage of liquid hydrogen for future Lunar and Mars missions. The data collected provides a strong foundation for model validation and future system design efforts.

INTRODUCTION

High-capacity 20 K-class cryocoolers have been identified by NASA's Space Technology Mission Directorate (STMD) as a critical enabling technology for future Lunar and Martian missions requiring liquid hydrogen propellant transfer, storage, and liquefaction [1][2]. While NASA has flown cryocoolers for more than 30 years on various missions, many of these systems were designed for cooling science instruments and optics at significantly lower capacities [3]. Reverse turbo-Brayton cryocoolers offer several advantages over the existing technology for higher capacity cryogenic fluid management applications. First, they can achieve higher efficiency at larger power scales than Stirling or pulse tube cryocoolers. Second, the directional flow of the working fluid allows the system to provide distributed cooling through concepts such as Broad Area Cooling (BAC), which are beneficial for integration with large cryogenic storage tanks.

To address this gap, NASA initiated the development of high-efficiency, high-capacity 20 K-class cryocoolers under a Phase I Small Business Innovative Research (SBIR) award in 2008 [4]. This effort advanced through Phase II and culminated in a recently completed Phase III contract. Through these contracts, Creare developed a Reverse Turbo-Brayton (RTB) cycle cryocooler capable of delivering approximately 20 W of cooling at 20 K [5].

Following initial acceptance testing in January 2025, extended cryocooler characterization testing (CCT) was conducted from March through July 2025. Testing focused on characterizing the impact of several key operating parameters to generate a broad envelope of operating conditions for future mission designs. This paper presents a summary of the characterization testing results and key system-level performance trends.

TEST OVERVIEW

Cryocooler characterization testing was conducted from March 3 to July 7, 2025. Testing operations consisted of establishing heater setpoints, commanding the return temperature in LabVIEW, adjusting the lab chiller to control the heat rejection temperature (HRT), and verifying system pressure in accordance with the Test Matrix. The cryocooler control system would adjust the cryocooler until it was stable at the desired point, and a test point would be recorded over the course of several hours. Typically, 2-3 test points were captured per day, depending on the test series. The cryocooler operated continuously over the weekends without changes to test conditions to demonstrate automated control and stability of the system.

TEST HARDWARE

CCT utilized a single-stage reverse turbo-Brayton cryocooler (RTB) consisting of three compression stages, a liquid-cooled heat rejection interface, a single-stage turboalternator (TA), and a five-stage recuperator coupled with a BAC simulator. Figure 1 provides a CAD model of the hardware. The flight-like mass of the system is estimated to be 106.3 kg. A detailed description of the hardware can be found in Creare's "Development and Testing of a High Capacity 20 K Cryocooler" [6].

TEST MATRIX

Cryocooler characterization testing was divided into 15 test series. During testing, the matrix was modified to prioritize critical data points and account for deviations during testing. Because of this, the test series numbers skip to align with the original test matrix. For these test series, pressure is defined as low, nominal, and high. During testing pressures were measured at the compressor inlet. These pressures correspond to stagnant system pressures of 139 psia, 154 psia, and 160 psia at room temperature.

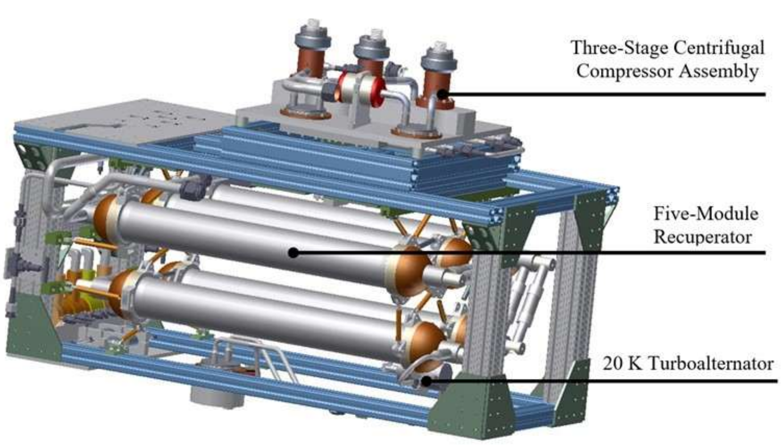

Figure 1. 3D CAD Representation of the 20 W 20 K Cryocooler.

Test Series 0 provides the initial cooldown of the system. This was the first cooldown to be completed with a heat load applied to the system, and thus the performance during cooldown was unknown. Once it was determined the 5 W heat load did not prohibitively slow cooldown, the heat load was increased to test capability.

Test Series 1 established performance of the cryocooler at the maximum heat rejection temperature (HRT) (300 K) at three return temperatures and a sweep of heat lifts at nominal pressure.

Test Series 2 is a repeat of Test Series 1 at a different heat rejection temperature (285 K). This allows the impact of the heat rejection temperature at varying heat loads to be isolated.

Test Series 3 is a repeat of Test Series 1 at the minimum heat rejection temperature (270 K). This allows the impact of the heat rejection temperature at varying heat loads to be isolated.

Test Series 4 is a repeat of Test Series 2 at a higher system pressure. This allows the impact of the system pressure at varying heat loads to be isolated. For this test, high pressure is defined as a system pressure of 160 psia at room temperature.

Test Series 5 characterizes the impact of system pressure at a constant heat rejection temperature, return temperature, and heat load.

Test Series 6 is a repeat of Test Series 4 at a low system pressure. This allows the impact of the system pressure at varying heat loads to be isolated.

Test Series 7 allowed for a cooldown at a lower system pressure than Test Series 0. Because Test Series 6 ended at the lowest allowable system pressure at cryogenic temperatures, this ensured the system would not fault during the low pressure cooldown.

Test Series 8 is a repeat of Test Series 1 with twice the accumulator volume. This allows the impact of BAC volume on the system to be isolated.

Test Series 12 is a sweep of heat loads at a return temperature of 20 K and heat rejection temperature of 276 K. This heat rejection temperature was selected as the lowest heat rejection temperature achievable due to laboratory chiller restrictions while still obtaining the maximum possible lift.

Test Series 13 characterizes the impact of the heat rejection temperature at a constant system pressure, return temperature, and heat load.

Test Series 14 is a series of cooldowns performed at different accumulator volumes and heat loads applied during the cooldown.

Test Series 15 is a repeat of Test Series 1, to demonstrate the repeatability of performance after a long period of operation. This test series also included a minimum possible heat load case and concluded with the final point being held for a minimum of 10 consecutive days.

CHARACTERIZATION RESULTS

Cooldowns

The cryocooler's components start at a relatively warm ambient temperature (273–293 K). The cryocooler goes through a transient process from ambient down to cryogenic temperatures referred to as cooldown when powered on for operation. The cooldown process involves the slow, incremental start-up of compressors to enable the circulation of helium to begin the removal of heat from the five recuperators, the TA, any heat load imposed by the BAC heater, line lengths, and the fittings connecting the system components.

Data from six cooldowns were captured during characterization testing. Cooldown data were also recorded during the 20 W 20 K cryocooler's acceptance test performed prior to the start of characterization testing (January 2025). The operational variables of system pressure, BAC heater power, and the number of accumulators were changed between cooldowns to characterize impact on system performance. Cooldown duration is the total elapsed time for the BAC exit temperature to cool from ambient to a given test series starting return temperature (20 K – 21 K). A summary of each cooldown can be found in Table 1.

Figure 2 illustrates the impact of system pressure and heat load on total cooldown duration. For similar pressures, an increase in heat load from 0 W to 10 W extended the cooldown duration by 53%. For similar heat loads, an increase in final system pressure from 77 psia to 86 psia led to a 10% increase in cooldown duration. These results demonstrate the sensitivity of startup timelines to system pressure and parasitic heat load conditions.

Table 1. Summary of Cooldown Data

Cooldown Number	Duration (mins)	BAC Heat Input (W)	Starting Compressor Inlet Pressure (psia, P1)	Ending Compressor Inlet Pressure (psia, P1)	Accumulator Number
1	1417	0	128	73	2
2	1928	Variable (0, 5, 10, 3.5)	154	80	0/2*
3	2167	10	153	77	2
4	1632	0	153	78	2
5	1413	0	139	75	2
6	1254	0	153	74	1
7	2388	10	160	86	2

* *For Cooldown 2, accumulators were opened from 0 to 2 after the onset of oscillations*

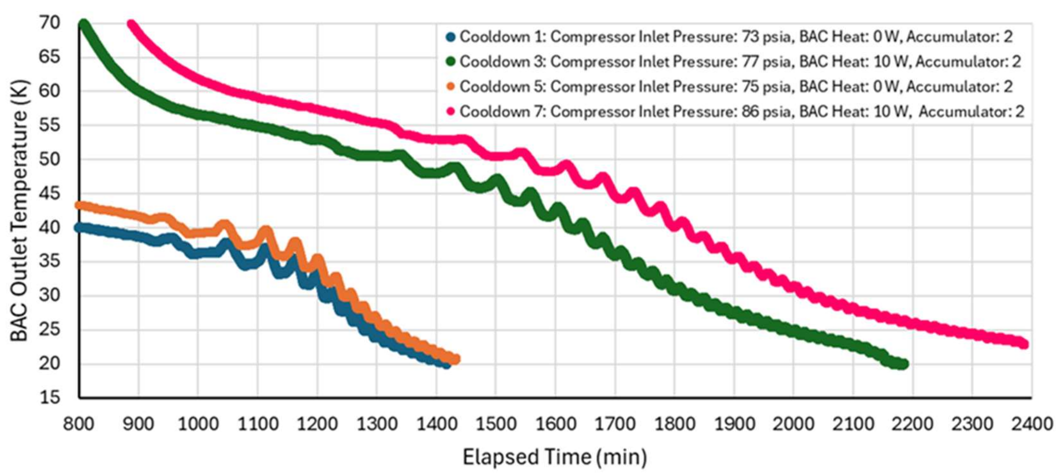

Figure 2. Cooldowns 1, 3, 5, and 7 with varying pressure levels, BAC heat loads, and 2 accumulators.

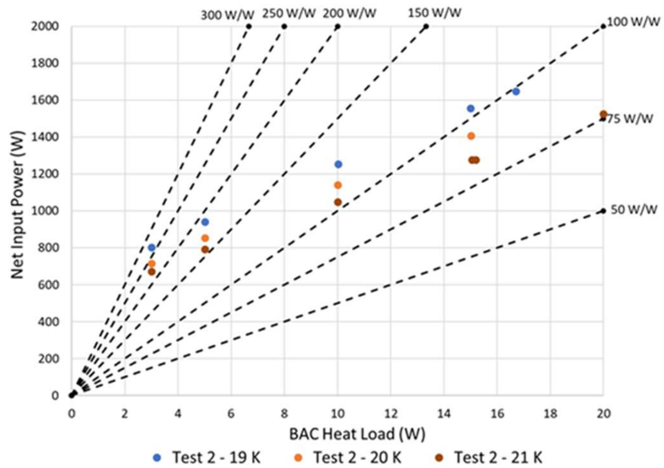

Figure 3. Ross plot for Test Series 2 at a 285 K heat rejection temperature, where the Input Power is plotted against the BAC Heat Load for load temperatures of 19 K, 20 K, and 21 K.

Return Temperature

Cryocooler performance at BAC return temperatures of 19 K, 20 K, and 21 K was evaluated to simulate performance at different potential hydrogen storage pressures or subcooled storage. Lower return temperatures limit the maximum possible lift capacity and result in a higher specific power. The maximum lift at 19 K return was 18.6 W at a 276 K heat rejection temperature, resulting in a specific power of 95 W/W. Comparatively, the maximum lift at 21 K return was 24.4 W at a heat rejection temperature of 276 K, resulting in a specific power of 72 W/W.

Figure 3 depicts a Ross plot for the three different return temperatures at a heat rejection temperature of 285 K. This trade between lift capacity and return temperature is important for balancing propellant storage pressure requirements against spacecraft power consumption.

Heat Rejection Temperature

The heat rejection temperature (HRT) represents the temperature the outlet gas leaving the last compressor was cooled to prior to entering the recuperator. Test Series 1, 2, 3, and 12 focused on varying the HRT to evaluate the overall system impact. As expected, lowering the HRT increased the overall system efficiency, as measured by coefficient of performance (COP) relative

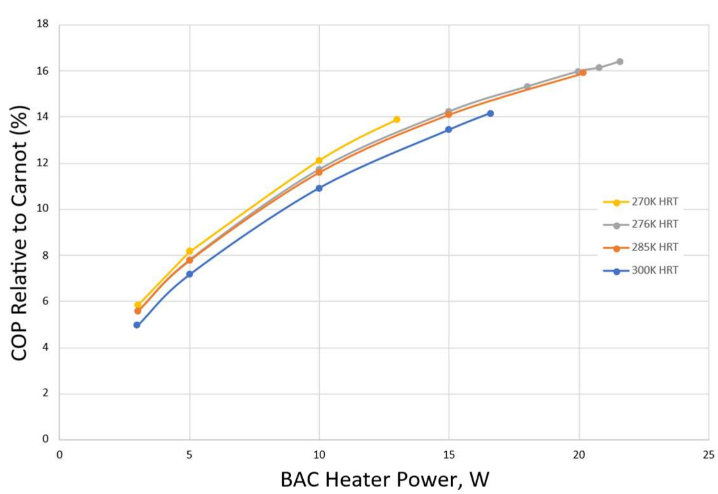

Figure 4. COP relative to Carnot as a function of BAC Heater Power for 20 K return at a range of HRTs (TS 1, 2, 3, and 12).

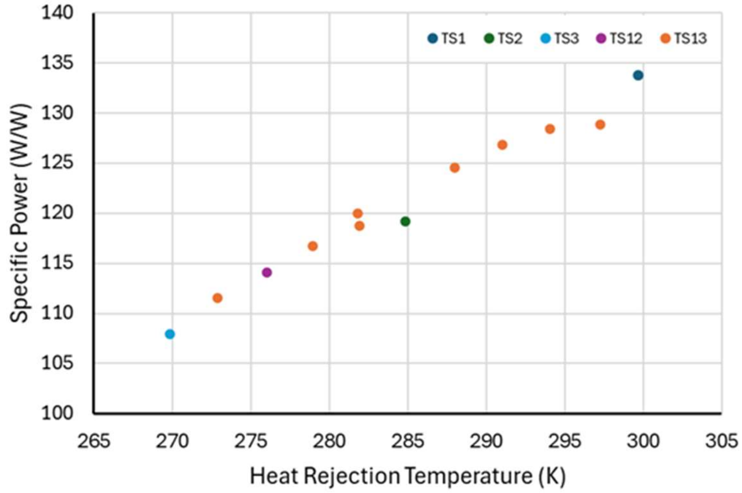

Figure 5. Specific Power as a function of HRT with Nominal Compressor Inlet Pressure, 2 accumulators, 10 W on the BAC simulator, and a 20 K return (TS 1, 2, 3, 12, and 13).

to Carnot and specific power. Figure 4 provides a curve for the COP relative to Carnot as a function of lift capacity for a 20 K return temperature at different HRTs. The HRT was further characterized as part of Test Series 13, where a constant 10W heat load was held and the heat rejection temperature was varied. Figure 5 shows the specific power trends nearly linearly with HRT at a constant heat load.

These results indicate that modest reductions in HRT can substantially improve cryocooler efficiency, reducing spacecraft power demand for long-duration LH2 storage systems.

System Pressure

To characterize the impact of pressure on the system performance, Test Series 2, 4, and 6 repeated the same heat load tests at three different pressures, while Test Series 5 held a constant heat load and heat rejection temperature and systematically stepped down the system pressure. Figures 6 and 7 show that an increase in system pressure results in a lower COP relative to Carnot

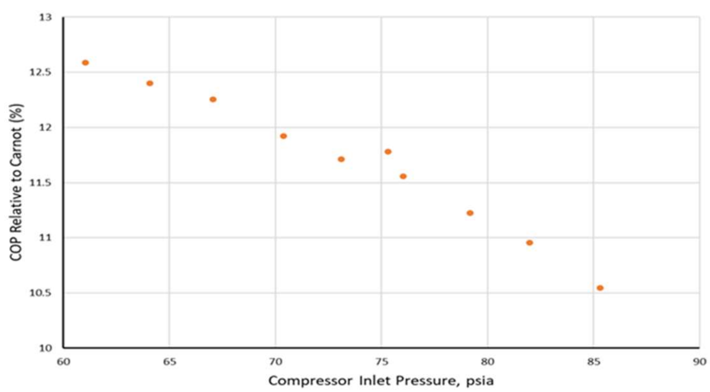

Figure 6. – COP Relative to Carnot as a function of system pressure at 285 K HRT, 20 K Return, and 10 W Lift (TS 5).

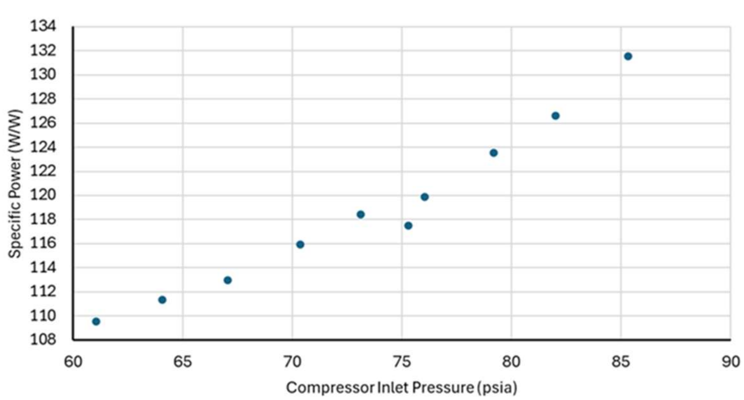

Figure 7. – Specific Power as a function of system pressure at 285 K HRT, 20 K Return, and 10 W Lift (TS 5).

and a higher specific power. These trends indicate that minimizing system pressure can improve cycle efficiency, though operational constraints of the turbomachinery must also be considered.

Repeatability

To demonstrate the performance repeatability of the cryocooler, Test Series 15 repeated the 20 K return temperature points from Test Series 1. Test Series 15 started approximately 107 days after the first data point in Test Series 1. The system pressure in Test Series 15 was adjusted to match the test point pressures in Test Series 1 within 0.6%. Figure 8 and Figure 9 show the comparison of the specific powers and Carnot relative to COP, respectively. The values demonstrate a high level of repeatability, with a maximum specific power difference of 3.2% and maximum Carnot relative to COP difference of 3.0%. This level of repeatability over extended durations supports confidence in performance predictability for long-duration missions.

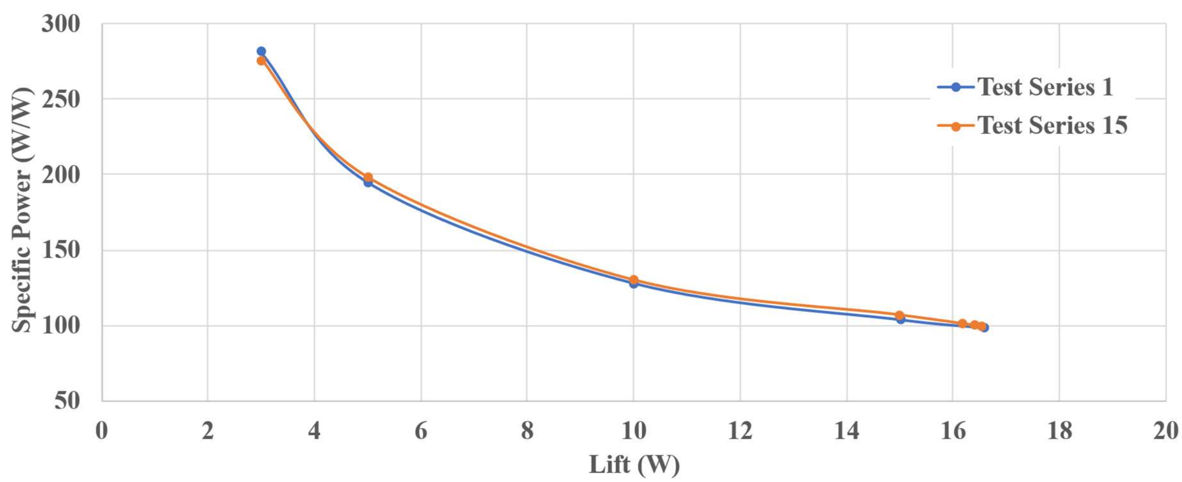

Figure 8. System Repeatability of Specific Power at 300 K HRT, Nominal Pressure, and 20 K Return Temperature (TS 1 and 15).

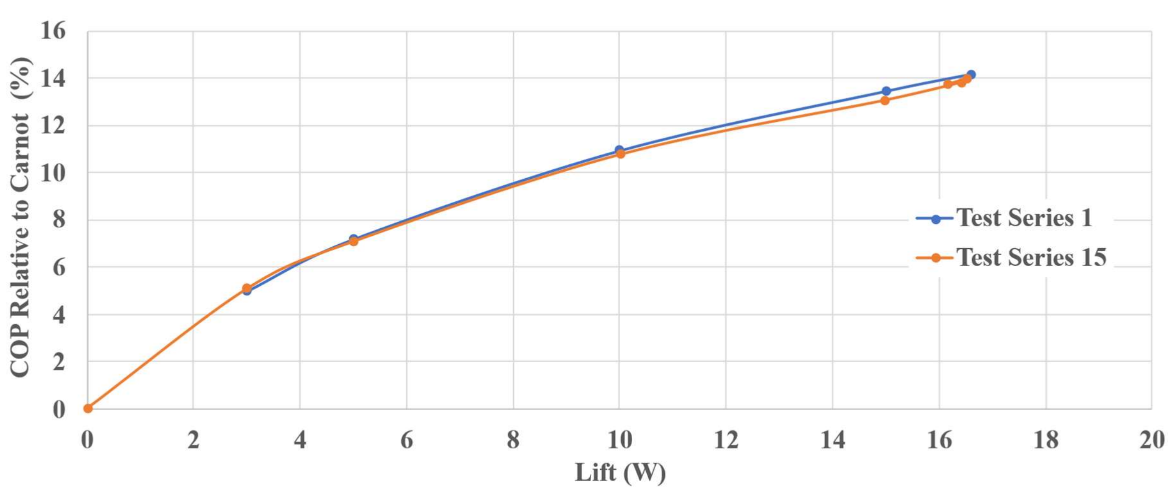

Figure 9. System Repeatability of COP Relative to Carnot at 300 K HRT, Nominal Pressure, and 20 K Return Temperature (TS 1 and 15).

BAC Pressure Drop

The pressure drop through the BAC simulator has a critical impact on the overall system performance and maximum lift capacity. Any pressure drop that occurs in the BAC simulator is pressure drop unavailable for turbine cooling. For this cryocooler, the pressure drop is established by a fixed-diameter orifice, making it a constant parameter that could not be adjusted during testing. The pressure drop across the BAC simulator did change with system temperature, pressure, and mass flow rate. Figure 10 shows that as little as 0.09 psid can result in a decrease in TA efficiency and COP relative to Carnot by 2% each. This sensitivity highlights the importance of minimizing BAC hydraulic losses during cryocooler integration with hardware.

Turndown Ratio

One of the objectives of Test Series 15 was to determine the lowest simulated BAC lift at which the cryocooler could still operate without the system faulting. The cryocooler was designed for a minimum lift of 3 W, however during testing it was demonstrated that the system could successfully operate with 0 W of additional heat added. Table 2 shows the performance at this point. Additional points from the same test conditions (return temperature, pressure, HRT) with different heat loads were included for direct comparison as the system turns down from the design point. This turndown capability provides operational flexibility for transient storage demand and supports use of the hardware for multiple mission applications.

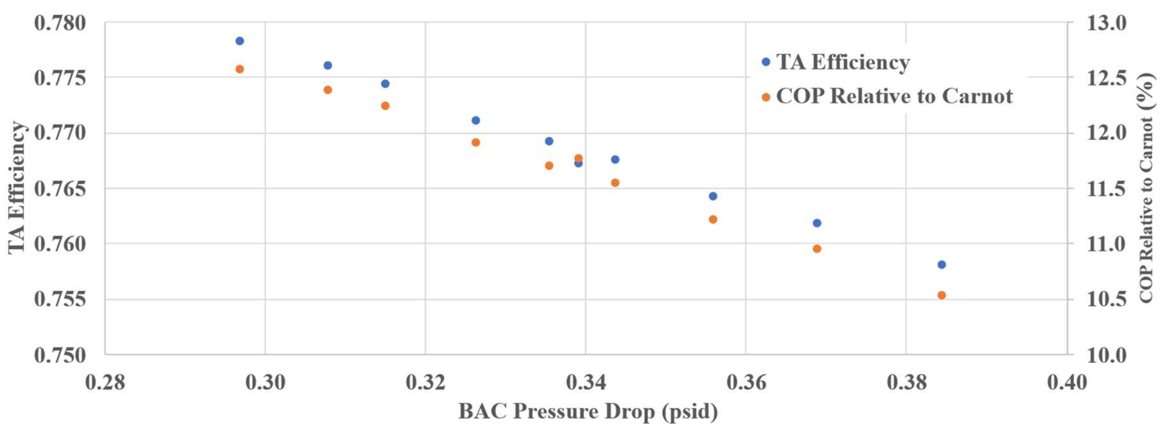

Figure 10. TA Efficiency and COP Relative to Carnot compared to BAC Pressure Drop at 285 K HRT, 10 W Lift, 20 K Return Temperature, Varying Pressures (TS 5).

Table 2. Lift Turndown Performance

BAC Heat Input (W)	BAC Return Temp. (K)	Heat Rejection Temp. (K)	Compressor Inlet Pressure (psia)	TA Output Power (W)	Corrected Power (W)	Corrected Specific Power (W/W)	Corrected Carnot COP (%)
0	20	300	76	14	631	N/A	N/A
3	20	300	75	20	830	276	5.07
5	20	300	75	24	992	198	7.07
10	20	300	74	32	1304	130	10.74
15	20	300	73	40	1607	107	13.04
16.5	20	300	73	41	1642	99	13.95

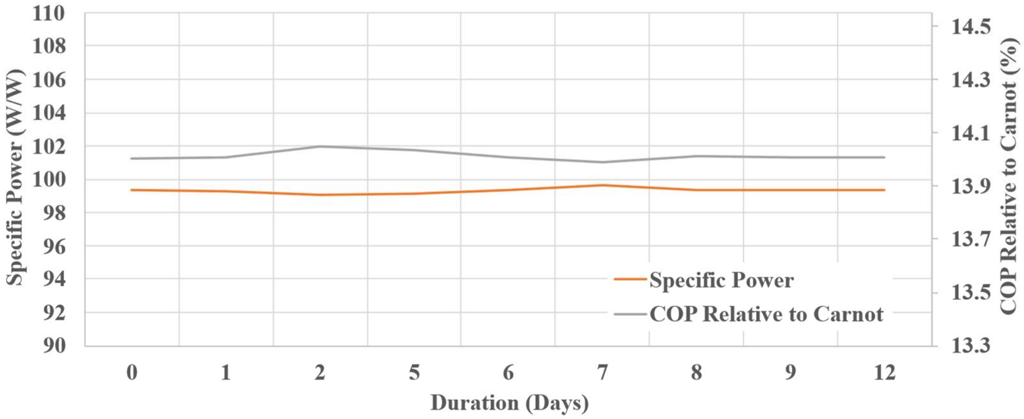

Figure 11. System Long-Duration Performance of Specific Power and COP Relative to Carnot at 300 K HRT, Nominal Pressure, 16.5 W Lift, and 20 K Return Temperature (TS 15)

Long-Duration Performance

To demonstrate the cryocooler's ability to sustain steady performance over a longer period, Test Series 15 held a single data point of 16.5 W of lift, 20 K return temperature, 300 K HRT, and nominal pressure for approximately 12 days. Over this duration, the maximum fluctuation in specific power and Carnot relative to COP was 0.6% and 0.4% respectively. Results from this test can be seen in Figure 11. The limited drift in performance over the test duration supports the feasibility for use in long-duration cryogenic storage operations.

LESSONS LEARNED

Throughout the Cryocooler Characterization Testing, multiple lessons were learned, both in the operation of the cryocooler and through examining the test data.

The importance of having redundant sensors on critical instrumentation was realized when the sensors for the BAC return temperature and turboalternator inlet temperature experienced issues. After analysis of the data from these sensors, testing was able to continue using the backup sensors at both locations without needing to stop testing and disassemble the hardware to replace them. This issue resulted in multiple shutdowns, and it is recommended that future fault logic require multiple consecutive instances of instrumentation deviation prior to resulting in a system shutdown.

Understanding the programming logic behind warm-up commands is critical for reliable operation. For this cryocooler, a bypass valve is used during cooldown and warmup to prevent the compressors from surging - the valve position is based on a lookup table of BAC return temperatures. During steady-state operation the bypass valve is fully closed. Nominally during the warmup procedures, the bypass valve is opened as the compressors spin at a lower speed. For cooldown operations, the compressors are typically at max speed to accelerate the process. During the first cooldown for Test Series 14, a warmup command was issued after the cooldown progressed through oscillations and reached a 25 K return temperature. This immediately caused the system to fault, as the lookup table opened the bypass valve rapidly, resulting in the compressors (already spinning at maximum speed) exceeding power limitations. Having a thorough understanding of the control algorithms for each mode of operation is critical to prevent potential hardware damage during operation.

During testing, the facility chiller system, which was purchased for this test and sized to have excess cooling capacity, had difficulty removing the required heat load from the compressors to maintain the minimum heat rejection temperature at maximum heat load cases. This indicates modifications to the compressor heat rejection system may be required, along with benchtop testing, to optimize the cryocooler's potential performance.

During analysis, it was noted that while steady-state conditions were met, there was still a trend in recuperator effectiveness changing even 24 hours after the conditions were met. This change in effectiveness indicates the system needs much longer to reach a true steady state than anticipated due to the recuperator mass. These small changes in effectiveness do not appear to have a significant impact on key performance parameters.

The cryocooler system did shut down five times over the course of testing due to faults, however none of the faults were due to the system control parameters. Benchtop and acceptance testing put a strong focus on mapping the limits of the turbomachinery, such as the acceptable compressor head coefficients and TA voltage over frequency ratios. The development of well-tested fault limitations allowed for successful long-duration operation of the cryocooler, even when operating at extreme boundary cases, such as zero heat input to the BAC.

CONCLUSIONS

The characterization testing of the 20 W 20 K cryocooler successfully demonstrated the capability to meet and exceed the key performance parameters required for future NASA missions. The cryocooler achieved a peak coefficient of performance of 17.68% relative to Carnot efficiency and a maximum lift capacity of 24.4 W at 21 K with a heat rejection temperature of 276 K. The test campaign met the primary objective of demonstrating cryocooler capabilities across a wide range of parameters and developed a database of operating points to support future mission design efforts.

This paper presents a small snapshot of the characterization testing results. A comprehensive paper detailing all the data, component performance, and conclusions from testing will be published by NASA in late 2026. The results demonstrate that high-capacity reverse turbo-Brayton cryocoolers are a viable approach for future long-duration cryogenic fluid management architectures. Because the cryocooler utilizes a closed gaseous helium cycle, its performance is expected to be gravity independent.

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