20 Watt 20 Kelvin Reverse Turbo-Brayton Cycle Cryocooler Testing and Applications

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ABSTRACT

Long-term storage of cryogens is an essential capability required to enable NASA's anticipated missions to both the Lunar and Martian surfaces. A key component to furthering these capabilities is the development of a high capacity, low temperature cryocooler to allow for zero-boil-off storage of liquid hydrogen propellant. The technology being developed by NASA to meet this objective is a reverse turbo-Brayton cycle cryocooler capable of removing 20 Watts (W) of heat at 20 Kelvin (K). This hardware was recently tested at Creare LLC in a vacuum chamber to simulate a relevant mission environment. This testing demonstrated the hardware's functionality and established a baseline for the cryocooler's capabilities. Additional NASA led characterization testing is underway and will provide a broader picture of the operational capability of the cryocooler. This paper discusses the results of this recent testing, along with highlighting the applications for high capacity cryocoolers on future NASA missions, such as Nuclear Thermal Propulsion (NTP) and a sustainable lunar architecture.

INTRODUCTION

To enable future manned missions to both the Lunar and Martian surfaces, NASA must develop the capability to store large quantities of cryogens (LH2, LCH4 (or LNG) and LOx) in orbiting depots, on landers and transit in-space vehicles, and on Lunar or Martian surfaces. A critical component to furthering this capability is a high capacity, low temperature cryocooler capable of maintaining hydrogen in its liquid state and minimizing losses due to boil-off. The technology being developed by NASA to meet this objective is a reverse turbo-Brayton (RTB) cycle cryocooler capable of removing 20 watts (W) of heat at 20 Kelvin.

The primary goal of the 20 W/20 K project is to design, build, and operate a cryocooler employing a Reverse Turbo-Brayton (RTB) thermodynamic cycle capable of providing cooling to maintain temperatures of 20 K with 20 watts of lift while meeting the mass and power efficiency requirements anticipated by a flight worthy cryocooler. Prior to testing of this hardware, the previous state-of-the-art (SOA) for this level of technology was 1 W of heat removal at 20 K, with a specific power of 370 $W_{electrical}/W_{thermal}$ a specific mass of 18.7 kg/$W_{thermal}$.[1] Table 1 shows the project goals and measured values in comparison to the previous SOA.

HARDWARE OVERVIEW:

The tested hardware nominally consists of a single-stage turbo-Brayton cryocooler, composed of three compression stages, a liquid-cooled heat rejection interface, single-stage turboalternator (TA), and five-shell-recuperator with a broad area cooling (BAC) simulator, and tested inside a vacuum bell jar. The BAC simulator mimics pressure loss, heat load, and volume of a BAC network via an orifice plate, an

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Table 1. Key Performance Parameters for the 20W 20K RTB Cryocooler Project [2]

Data Point	1	2	3	4	5	6	7	8	9	10	11
BAC Heat Input (W)	20.0	23.3	20.0	19.1	17.0	14.0	11.0	7.0	3.0	20.0	3.0
BAC Return Temp. (K)	22.8	22.8	20.4	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Heat Rejection Temp. (K)	300	300	300	300	300	300	300	300	300	270	270

Table 2. Simplified Acceptance Test Matrix

Data Point	1	2	3	4	5	6	7	8	9	10	11
BAC Heat Input (W)	20.0	23.3	20.0	19.1	17.0	14.0	11.0	7.0	3.0	20.0	3.0
BAC Return Temp. (K)	22.8	22.8	20.4	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Heat Rejection Temp. (K)	300	300	300	300	300	300	300	300	300	270	270

interface heat exchanger with trim heaters, and a changeable accumulator. The mass of the system is 336.9 kg, with a flight-like projection of 106.3 kg.

ACCEPTANCE TESTING SETUP AND OBJECTIVES:

Table 2 shows a simplified version of the test matrix for cryocooler testing, covering a range of objectives. Data point 1 was to demonstrate 20 W of heat removal at a temperature (22.8 K) corresponding to a temperature low enough for zero boil-off of liquid hydrogen at 25 psia. Data point 2 was to maximize the lift at this 22.8 K temperature. The objective of data point 3 was to minimize the return temperature at a set heat input of 20 W and heat rejection temperature of 300 K. Data point 4 was to maximize the lift at a temperature of 20 K and return temperature of 300 K. Data points 5-9 were to hold the 20 K return temperature, and gradually reduce lift to evaluate cryocooler performance. The objective of data point 10 was to maximize the lift at a set return temperature of 20 K and heat rejection temperature of 270 K. The objective of data point 11 was to evaluate the system performance at a minimal lift of 3W at a return temperature of 20 K and heat rejection temperature of 270 K.

TESTING RESULTS AND ANALYSIS

Following the system cooldown, a total of 10 data points were collected during acceptance testing. They were collected under the steady state criteria below and can be found in Table 3.

A test data point was assumed to achieved steady state when the following four criteria were met: (1) the load heat input changed by less than 1% over 1 hour and was not adjusted during the time period, (2) the load temperature changed by less than 1% over 1 hour, (3) the compressor input power changed by less than 2% over 1 hour, and (4) the heat rejection temperature changed by less than 1% over 1 hour. During testing, it was determined these criteria alone were not stringent enough to confidently assess steady state. A fifth criteria of pressure stabilization at the compressor inlet (less than 1% change over 1 hour) was added to the procedure.

Table 3. Acceptance Test Matrix Performance Results

Data Point	1	2	3	4	6	7	8	9	10	11
BAC Heat Input (W)	19.56	22.46	19.98	16.67	13.99	11.00	7.02	3.00	19.21	2.99
BAC Return Temp. (K)	22.48	22.70	21.42	20.14	19.94	19.88	20.13	20.09	19.99	19.99
Heat Rejection Temp. (K)	300.5	301.0	301.0	300.8	300.0	300.7	300.4	300.6	285.0	270.4
Input Power (kW)	1.68	1.77	1.76	1.75	1.62	1.42	1.10	0.84	1.76	0.74
TA Output Power (W)	36.59	39.05	34.67	32.61	29.85	26.14	20.80	15.70	34.61	15.77
Specific Power (W/W)	85.9	78.7	88.0	122.2	115.8	128.9	156.9	281.2	91.6	247.2
Specific Mass (kg/W)	5.4	4.7	6.4	5.3	7.6	9.7	15.2	35.5	5.5	35.5
Carnot Efficiency (%)	8.1	8.2	7.7	7.2	7.1	7.1	7.2	7.2	7.5	8.0
Carnot COP (%)	14.4	15.6	14.8	13.3	12.1	11.0	8.9	5.0	14.5	5.1

Notes:

1. Tabled data is averaged over a 30-minute period from the 1-hour steady state collection requirement.

Two of the data points in the test matrix were collected out of numerical order but was planned ahead of time to accommodate the flow of testing. Data point 5 was eliminated from the test matrix after data point 4 demonstrated the maximum lift at a 20 K return temperature and 300 K heat rejection temperature was already less than 17W. Due to facility chiller limitations, data point 10 could not reach a heat rejection temperature of 270 K at the higher compressor input powers required for the increased lift. For this point, the lowest achievable heat rejection temperature was reached (285 K) at maximum compressor inlet power, and the maximum achievable lift was determined.

The post acceptance test analysis completed in Table 3 includes specific power, specific mass, Carnot efficiency, and Carnot coefficient of performance (COP). The equations used in the analysis are included below. Note that the input power includes loss in the 40 ft of non-prototypical test harnesses.

$$P_{\text{Input}} = P_{\text{Compressor 1}} + P_{\text{Compressor 2}} + P_{\text{Compressor 3}} \tag{1}$$

$$\text{Specific Power} = \frac{P_{\text{Input}}}{P_{\text{BAC Heater}}} \tag{2}$$

$$\text{Specific Mass} = \frac{m_{\text{system}}}{P_{\text{BAC Heater}}} \tag{3}$$

$$\varepsilon_{\text{Carnot Refrigeration}} = \frac{T_{\text{BAC Exit}}}{T_{\text{Compressor Exit}} - T_{\text{BAC Exit}}} \tag{4}$$

$$\text{COP}_{\text{Carnot}} = \frac{1}{\text{Specific Power} * \varepsilon_{\text{Carnot Refrigeration}}} \tag{5}$$

The temperatures exiting the BAC simulator and exiting the compressors are plotted over time for each data point in Figure 1. The system cooldown progressed linearly until approximately 40K, after which cooldown slowed drastically. At this point helium in the system required venting to allow higher compressors speeds while adhering to other turbomachine limitations and to reach the final desired temperature.

Knowing that data points 4, 6, 7, 8, & 9 have similar heat rejection (300 K) and BAC return (20 K) temperatures, those data points can be plotted across the various heat loads they removed against the input power required to remove those heat loads. The plotted line then represents the cryocooler's specific

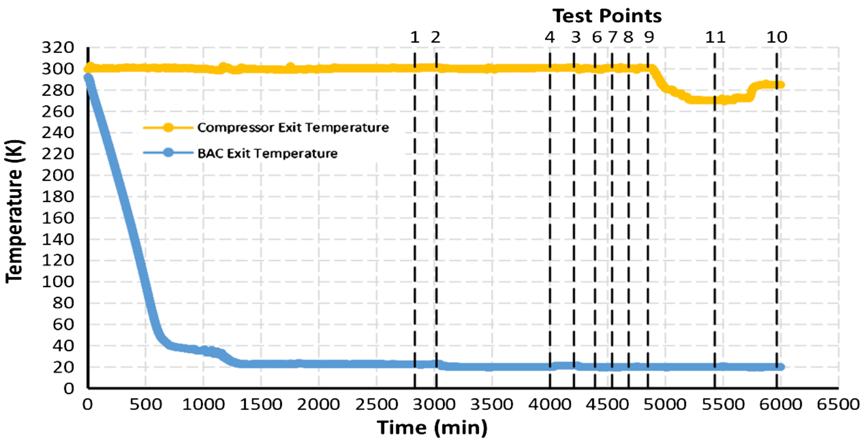

Figure 1. Compressors and BAC exit temperatures with data collection points.

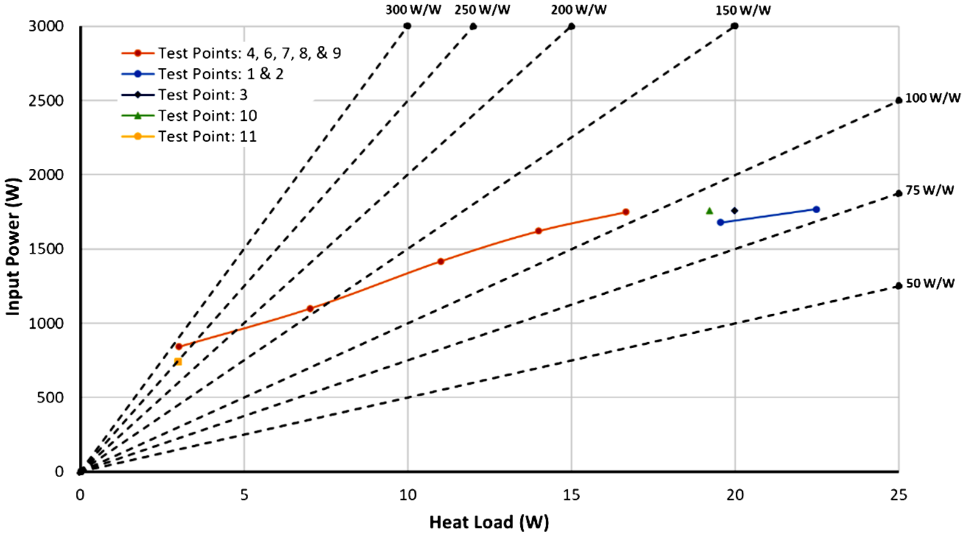

Figure 2. Ross plot of test point results

power at the stated conditions and can be compared to known specific powers of other cryocoolers at the same heat rejection and return temperatures. A Ross plot is located in Figure 2. Additional data points are shown for reference on the plot.

Figure 3 shows the cryocooler performance as a function of lift. A maximum COP Efficiency of 15.6% was achieved at Test Point 2, with a lift of 22.46 W. Figure 4 shows the change in specific power at different lift capacities.

FUTURE TESTING

Characterization Test

Cryocooler characterization testing (CCT) is anticipated to start in July 2022. The primary focus of this testing will be to characterize the performance of the cryocooler across an expanded envelope of operating parameters to better quantify capabilities for future operations A basic understanding of the capabilities of the cryocooler system outside of a single test point is required for future testing and mission designs. The key parameters being varied are lift, rejection temperature, return temperature, accumulator

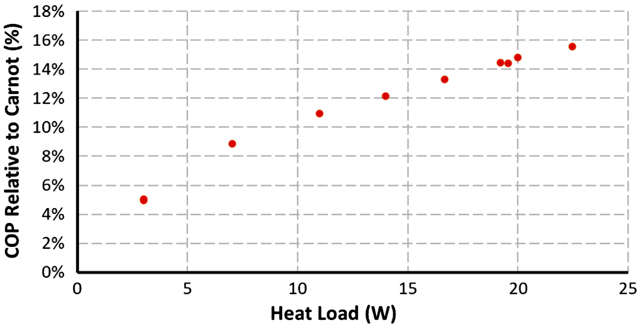

Figure 3. Cryocooler Carnot efficiency as a function of heat removal power

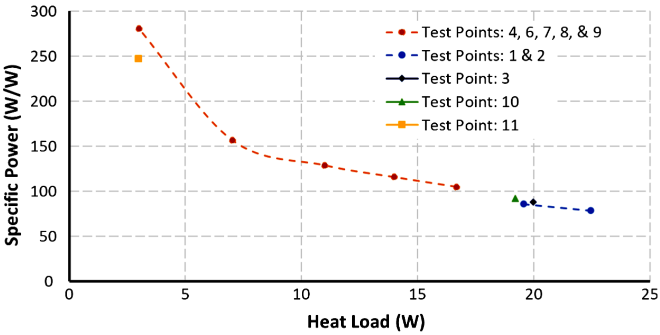

Figure 4. Specific power as a function of cryocooler lift

volume, and system pressure. A secondary objective of this testing will be to provide data to validate analytical cryocooler models in development. Table 4 shows a preliminary test matrix for CCT.

Table 4. Preliminary Test Matrix for CCT

Test Series	Accumulator Volume	Compressor Inlet Pressure	Rejection Temp, K	Return Temp, K	Duration, days	Lift*, W
0	Cooldown				2	
1	Nominal	Nominal (75-85 psia)	300	18 (min), 20, 22.5 (Max)	TBD (~15)	3 (min), 5, 10, 15, 18, 20, max
2	Nominal	Nominal (75-85 psia)	270	18 (min), 20, 22.5 (Max)	10	3 (min), 10, 15, 20, max
3	Nominal	Nominal (75-85 psia)	285	18 (min), 20, 22.5 (Max)	10	3 (min), 10, 15, max
4	Low	Nominal (75-85 psia)	300	18 (min), 20, 22.5 (Max)	12	3 (min), 10, 15, 20, max
5	High	Nominal (75-85 psia)	300	18 (min), 20, 22.5 (Max)	12	3 (min), 10, 15, 20, max
6	High	Nominal (75-85 psia)	270	18 (min), 20, 22.5 (Max)	10	3 (min), 10, 15, ma
7	High	Nominal (75-85 psia)	285	18 (min), 20, 22.5 (Max)	6	3 (min), 10, 15, max
8	Low	Nominal (75-85 psia)	285	18 (min), 20, 22.5 (Max)	6	3 (min), 10, 15, max
9	Low	Nominal (75-85 psia)	270	18 (min), 20, 22.5 (Max)	7	3 (min), 10, 15, max
10	Nominal	Low (10% less than nominal)	270	18 (min), 20, 22.5 (Max)	10	3 (min), 10, 15, 20, max
11	Nominal	High (10% above nominal)	270	18 (min), 20, 22.5 (Max)	10	3 (min), 10, 15, 20, max
12	Nominal	Nominal	300	20	10	3 (min), 5, 10, 15, 18, 20

*Not all lifts will be achievable at all temperature combinations (Rejection temperature and Return temperature).

Vibration Test

Testing of the 20W 20K cryocooler in a relevant environment is required to bring the cryocooler thermo mechanical unit (TMU) system components to a TRL-6 in anticipation of development of a flight unit. Vibration testing of the flight-like components using a generalized launch vibration spectrum will complete the demonstration of the 20W 20K cryocooler in a relevant environment.

Following completion of CCT, vibration testing will be conducted at Glenn Research Center (GRC). Six months of follow-on performance testing in a thermal vacuum environment will then be conducted to ensure hardware is continuing to operate as anticipated.

Zero Boil-off Using Intermediate Temperature Cooling

NASA has recently emphasized the use of cryogenic systems to enable sustainable, long duration space missions to further explore both Lunar and Martian surfaces. Long duration, exploratory missions require the advancement of passive and active cooling techniques to prevent the boil-off of liquid cryogens. While variations of active cooling have been demonstrated with the zero boil-off (ZBO) [3] and reduced boil-off (RBO) [4] experiments, an optimized case consisting of both ZBO and RBO active heat removal techniques can provide two loops of active cooling. The use of a tube-on-shield heat exchanger in parallel with a tube-on-tank heat exchanger with appropriate insulation has the potential to reduce the power and mass required to maintain cryogens in a liquid state compared to cooling only at the storage temperature. This approach to active cooling using both RBO and ZBO concurrently has been studied for several mission profiles [5] but has not been demonstrated. An internal NASA project is currently planning to initially demonstrate this cooling approach for LH2 using a two-stage industrial cryocooler. After the first demonstration, a follow-on demonstration using a combination of flight-like RTB cryocoolers to provide active cooling to LH2 has been proposed. The 20W / 20K RTB cryocooler would provide cooling via a tube-on-tank heat exchanger, while a 90K RTB cryocooler would provide cooling through a tube-on-shield heat exchanger. This demonstration would directly feed into several of the applications mentioned below, including a flight demonstration. The maturation of these technologies is essential in enabling sustainable, long-duration space missions for humans.

NASA APPLICATIONS

In the development of future exploration systems, especially for Mars transport, NASA has repeatedly determined that long duration hydrogen storage is probably needed [6][7]. Whether for chemical or nuclear engine technology, the benefit of hydrogen to the specific impulse of the propulsion system outweighs its low density. However, in preparation for the development of these vehicles, a series of demonstrations are required [8]. Additionally, for both Lunar and Martian based production of propellants, hydrogen liquefaction is a strong driver for large, lightweight 20 K class refrigeration systems. Figure 5 provides a notional development schedule recently put out by NASA for industry input [8].

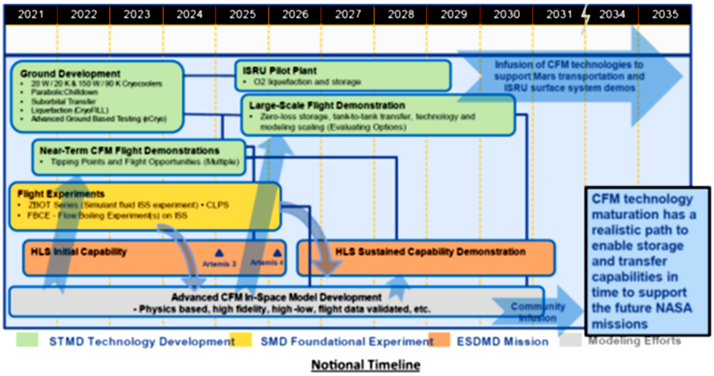

Figure 5. Notional Path to CFM Technology Maturity [8]

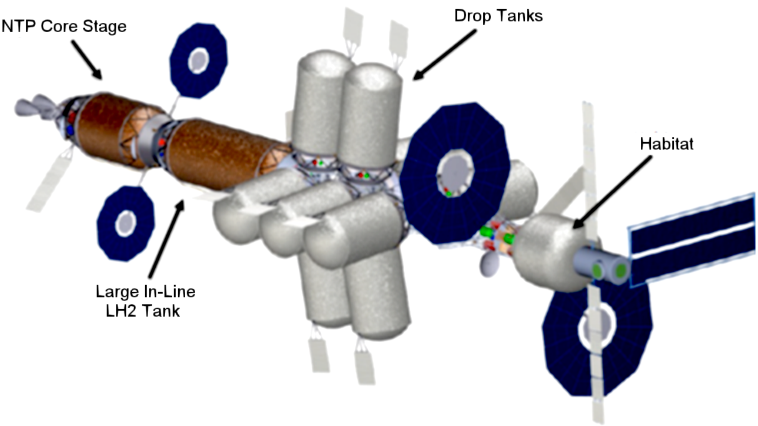

Figure 6. Conceptual NTP Mars Transportation System [7]

The near-term applications start with the initial flight demonstration of the net zero heat load (also known as ZBO) systems for hydrogen. One of the key technologies is the 20 W at 20 K cryocooler along with how it is integrated into the storage tank. Current studies are underway within NASA to determine the cost and configuration of possible flight demonstrations of a 20 W 20 K cryocooler integrated to a hydrogen storage tank. As these concepts are evaluated, the required refrigeration power and input power will be closely tracked based on the above test results to improve system level concepts.

Future applications such as the nuclear thermal propulsion (NTP) Mars transportation systems (Fig. 6) require several more cryocoolers (10s of individual systems), both due to the number of tanks as well as to meet redundancy requirements within the system design required for human transportation systems. The current mission life on some of the stages exceeds 5 years (including aggregation in Earth orbit and transportation to and from Mars).

For efforts related to liquefaction, application rates for NASA missions are often estimated to start at approximately 0.3 kg/hr of hydrogen. [9] This requires 150 – 300 W of refrigeration at 20 K depending on the stages of pre-cooling used. [2] Initial proof of concept demonstrations (Pilot Plant) may be as low as 1/10th of the initial flow rates of the initial applications, allowing for use of one to two 20 W cryocoolers. The integration of the cryocoolers into the liquefaction systems is still under development.

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