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

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Introduction

- Capability to store large quantities of cryogens is critical to enabling manned missions to Lunar and Martian surfaces.
- NASA is currently developing a reverse turbo-Brayton (RTB) cycle cryocooler capable of removing 20W at 20K to help achieve this objective.
- Thermodynamic testing of this hardware occurred in May 2022
- This presentation will discuss:
  - Key performance parameters
  - An overview of the hardware
  - Acceptance testing setup and objectives
  - Testing results and analysis
  - Future Testing

Key Performance Parameters

- Primary objectives of the 20W at 20K cryocooler is to design, build, and operate a RTB cryocooler, while meeting mass and power efficiency requirements anticipated of a flight system.
- The table below highlights the goals of the project with respect to the previous state of the art (SOA), as well as what testing achieved.

Key Performance Parameters for the 20 W/20 K RTB Cryocooler Project

Parameter	State of the Art	Threshold Value	Project Goal	Tested Values[1]	Projected Values[2]
1) Lift Capacity (W)	1	17	20	19.2	20.4
2) Specific Mass (kg/W)[3]	18.7	5.5	4.4	5.5	5.2
3) Specific Power (W/W)	370	80	60	91.6	86.3

Notes:

KPPs assume a fully integrated cryocooler operating and are based on a 20K design point, and do not include the mass and inefficiency of the drive electronics.

1. **Tested values were only able to be achieved at a heat rejection temperature of 285K.**
2. **Projected values are based on data projections from a heat rejection temperature of 285K to 270K.**
3. **Specific mass values are based on flight-like projections.**

Hardware Overview

- Tested hardware consists of a single-stage turbo-Brayton cryocooler.
  - Three compression stages
  - Liquid-cooled heat rejection surface
  - Five-shell-recuperator
  - Broad area cooling (BAC) simulator
- Testing occurred inside a vacuum bell jar.
- BAC simulator mimics pressure loss, heat load, and volume of a BAC network via an orifice plate, interface heat exchanger with trim heaters, and an accumulator with variable volumes.
- Mass of ground system is 336.9 kg.
- Mass of flight like projection is 106.3 kg.

Acceptance Testing Setup and Objectives

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

- Test Point 1: Demonstrate 20W of heat input at 22.8K (corresponding to a temperature for ZBO of LH2 at 25 psia)
- Test Point 2: Maximize heat input at 22.8K
- Test Point 3: Minimize return temperature at a heat input of 20W and return temperature of 300K.
- Test Point 4: Maximize heat input at a return temperature of 20K (300K rejection)

Acceptance Testing Setup and Objectives

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

- Test Point 5-9: Hold 20K return temperature and gradually reduce lift to evaluate cryocooler performance.
- Test Point 10: Maximize heat input at a set return temperature of 20K and a heat rejection temperature of 270K.
- Test Point 11: Evaluate system performance at a minimal lift of 3W at a return temperature of 20K and heat rejection temperature of 270K.

Testing Results and Analysis

- Steady State Criteria:
  - Heat input changed by less than 1% over 1 hour
  - Load temperature changed by less than 1% over 1 hour
  - Compressor input power changed by less than 2% over 1 hour
  - Heat rejection temperature changed by less than 1% over 1 hour
  - Pressure at compressor inlet changed by less than 1% over 1 hour

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.

*Test Point 5 was eliminated after test point 4 demonstrated the maximum lift at a 20K return temperature and 300K rejection temperature was already less than 17W.

Testing Results and Analysis

- Equations used in the analysis.
- Note that the input power does not correct for loss in the 40 ft of non-prototypical test harnesses, or for power recovery from the turboalternator.

$$P_{Input} = P_{Compressor\ 1} + P_{Compressor\ 2} + P_{Compressor\ 3} \quad (1)$$

$$\text{Specific Power} = \frac{P_{Input}}{P_{BAC\ Heater}} \quad (2)$$

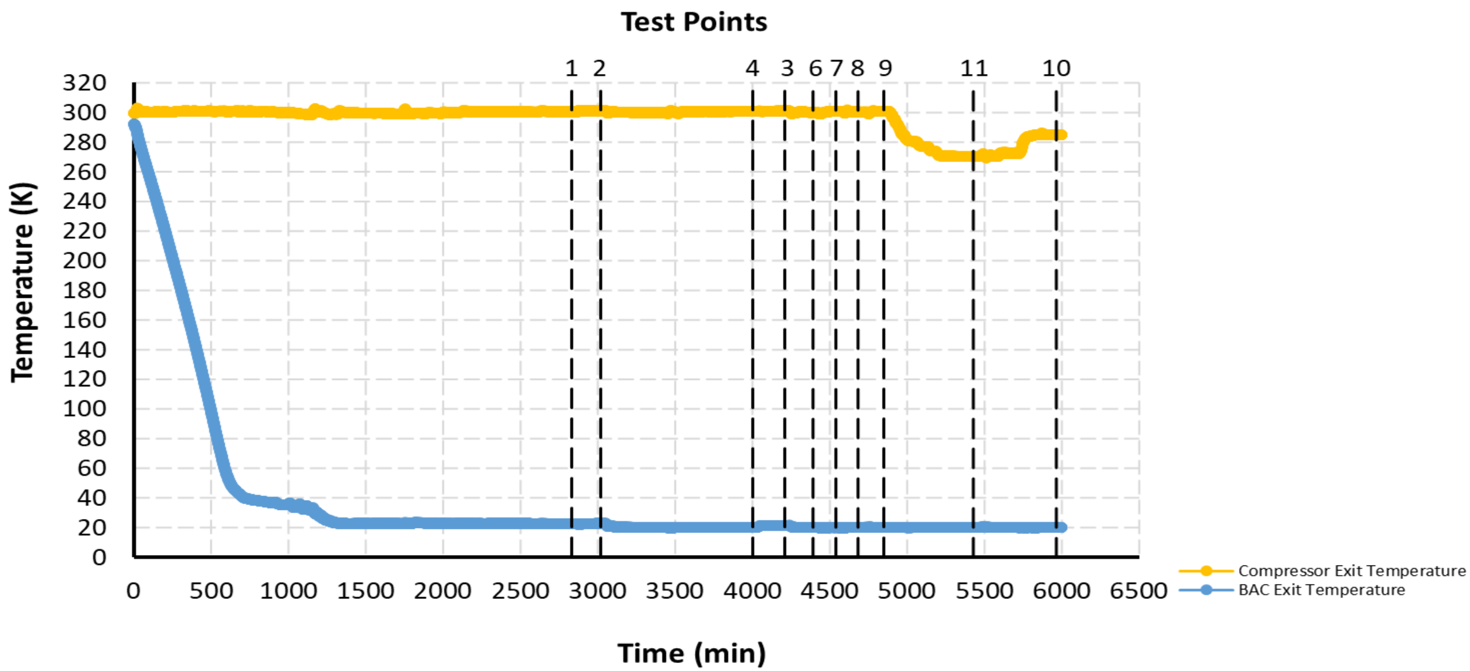
$$\text{Specific Mass} = \frac{m_{system}}{P_{BAC\ Heater}} \quad (3)$$

$$\varepsilon_{Carnot\ Refrigeration} = \frac{T_{BAC\ Exit}}{T_{Compressor\ Exit} - T_{BAC\ Exit}} \quad (4)$$

$$COP_{\ Carnot} = \frac{1}{\text{Specific Power} * \varepsilon_{Carnot\ Refrigeration}} \quad (5)$$

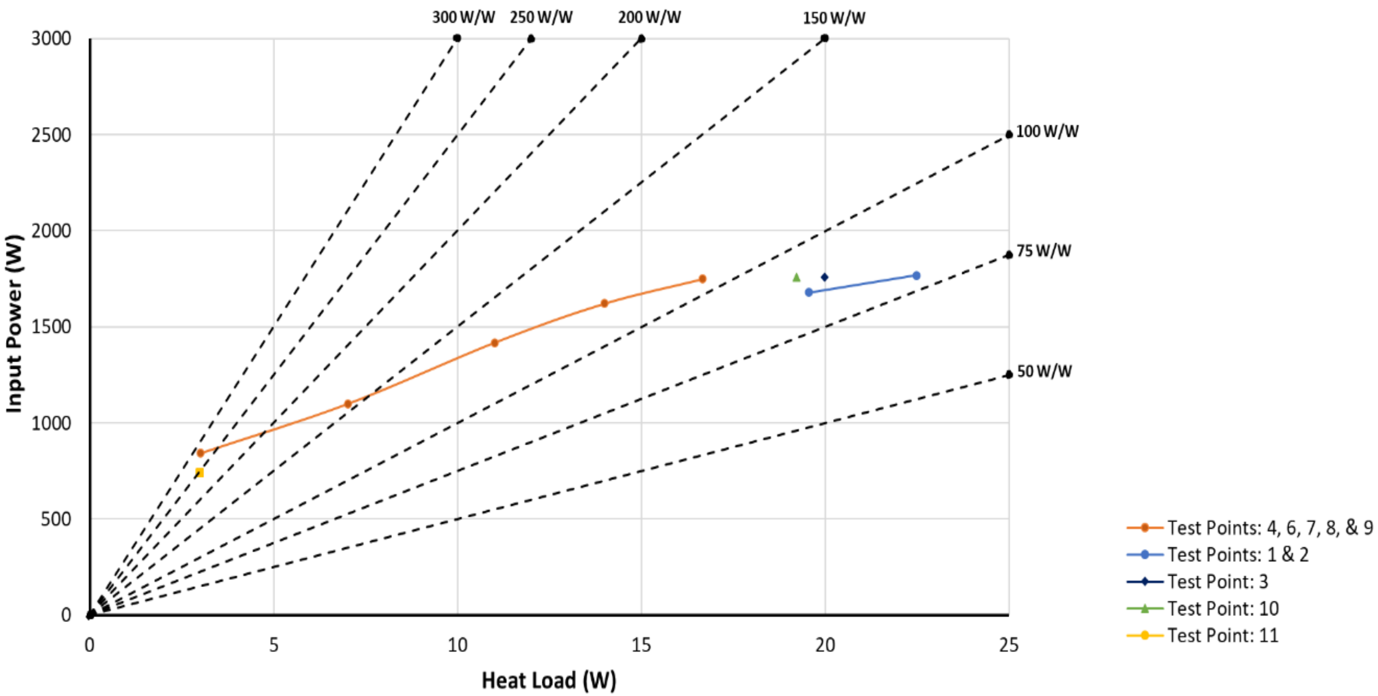
Testing Results and Analysis

- Compressor and BAC exit temperatures plotted over time.
- The system cooldown progressed linearly until approximately 40K, after which cooldown slowed drastically.
- Helium in the system required venting to allow for higher compressor speeds while adhering to other turbomachinery limitations and to reach the final desired operating (BAC exit) temperature.



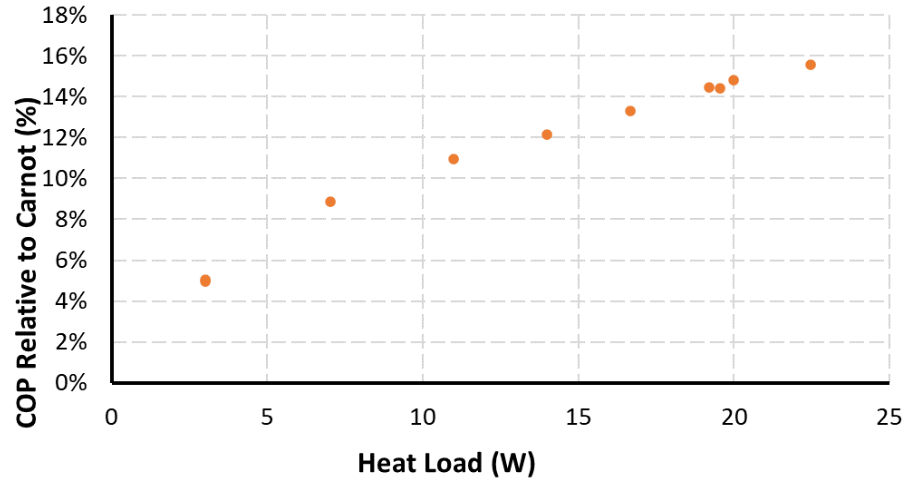
Testing Results and Analysis

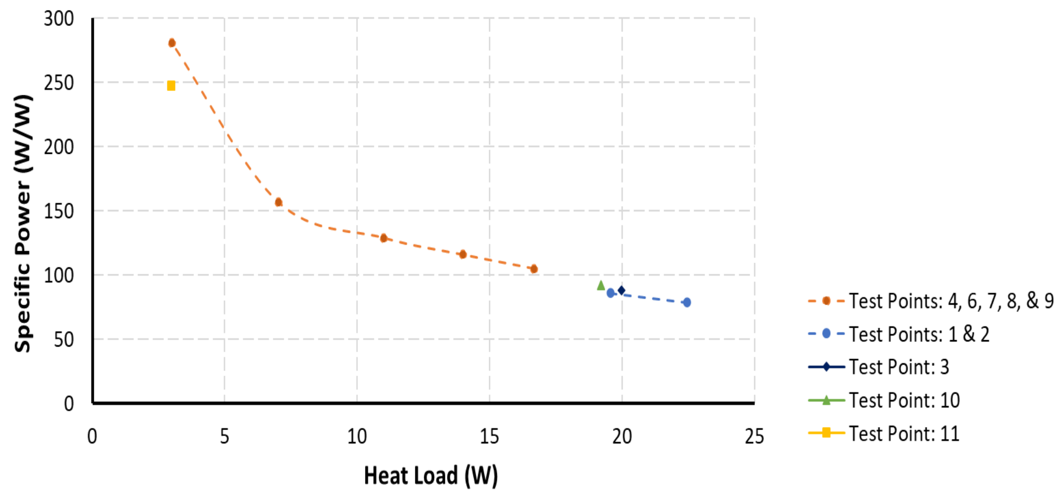
- Since test points 4, 6, 7, 8, and 9 have similar heat rejection (300K) and BAC return temperatures (20K), the heat loads they removed can be plotted against the required input power.
- The plotted orange line represents the cryocooler's specific power at the stated conditions.
- Additional data points are shown for reference.



Testing Results and Analysis

- The top figure shows the cryocooler performance as a function of lift.
- Max COP Efficiency of 15.6% was achieved at Test Point 2 (22.46W @ 22.7K)
- The bottom figure shows the change in specific power at different lift capacities.





Future Testing

- Characterization Testing
- Vibration Testing
- Zero Boil-Off Using Intermediate Temperature Cooling

Future Testing – Characterization Testing

- Cryocooler characterization testing (CCT) is anticipated to start in July 2022.
- 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.
- Key parameters being varied:
  - Lift
  - Rejection temperature
  - Return temperature
  - Accumulator volume
  - System Pressure
- Secondary objective of this testing will be to provide data to validate analytical cryocooler models in development.

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).

Future Testing – Vibe/ZBO Intermediate

Vibe Testing:

- Following CCT, vibration testing will be conducted at Glenn Research Center.
- Will bring thermo mechanical unit system components to a TRL-6.
- Following vibration testing there will be six months of follow-on performance testing.

Zero Boil-Off Intermediate Temperature Cooling:

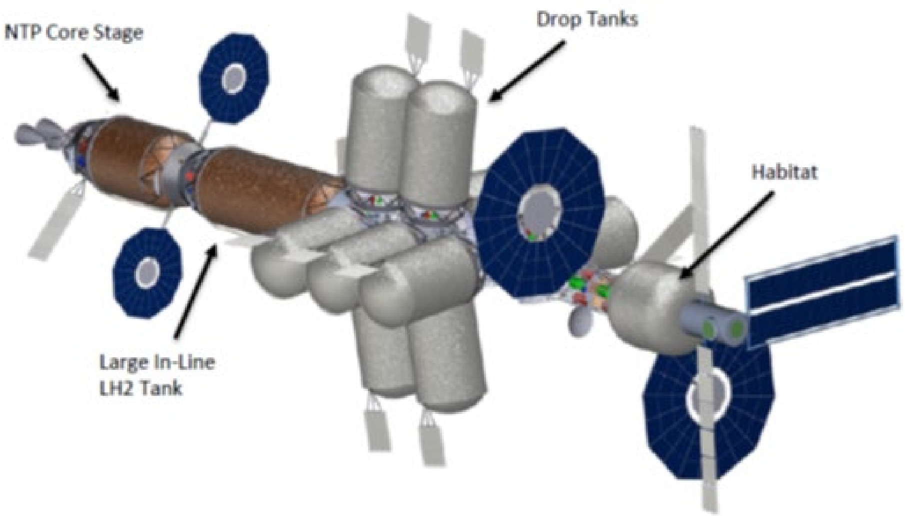
- An internal NASA project is currently planning to demonstrate active LH2 cooling via a tube-on-shield heat exchanger in parallel with a tube-on-tank heat exchanger.
- Has the potential to reduce the power and mass required to maintain cryogens in a liquid state compared to cooling only at the storage temperature.
- The 20W at 20K RYB cryocooler would provide cooling via tube-on-tank heat exchanger, while a 90K RTB cryocooler would provide cooling through tube-on-shield heat exchanger.

NASA Applications

- NASA has determined long duration hydrogen storage is required for future exploration systems.
- Near term applications start with the initial flight demonstration of net zero heat load (ZBO) systems for hydrogen.

Future applications:

- Nuclear thermal propulsion (NTP) Mars transportation systems
  - Require several more cryocoolers (10s of individual systems)
  - Mission life could exceed 5 years.
- Liquefaction on surface of Moon or Mars
  - Estimated at approximately 0.3 kg/hr of hydrogen.
  - Requires 150-300W of refrigeration at 20K
  - Initial proof of concept demonstrations may be as low as 1/10th of the anticipated flow rates.



References

1. Cha, J.S., and Yuan, S.W, Space Cryocooler Vendor Survey update: 2013, Aerospace Report number TOR-2013(3905)-4, 2013.
2. Nugent, B.N, Johnson, W.L., Guzik, M.G., Stephens, J. "Space Exploration Applications for Development of High Capacity Cryocoolers", *International Cryocooler Conference 21 (2020).*
3. T Plachta, D.W., Feller, J.R., and Guzik, M.C. "In-Space Cryogenic Propellant Storage Applications for a 20 W at 20 K Cryocooler, Cryocoolers 19, ed. Miller, S.D. and Ross Jr, R.G., Boulder, CO, 2016.
4. U Plachta, D.W., Feller, J., Johnson, W.L., and Robinson, C., *Liquid Nitrogen Zero Boiloff Testing*, NASA TP-2017-219389, 2017.
5. V Plachta, D.W., Christie, R.J., et.al. "**Cryogenic Boil-off Reduction System Testing**", presented at the 2014 AIAA Propulsion and Energy Forum, Cleveland, OH, AIAA paper 2014-3579, 2014.
6. X Johnson, W.L. and Stephens, J.R., **NASA's Cryogenic Fluid Management Technology Development Roadmaps**, presented at the JANNAF In-Space Chemical Propulsion Technical Interchange Meeting, Huntsville, AL, August 2018.
7. Y Meyer, M.L., Hartwig, J.W., Sutherlin, S.G., and Colozza, A.J., Recent Concept Study for Cryogenic Fluid Management to Support Opposition Class Crewed Missions to Mars. Presented at 2021 Space Cryogenic Workshop
8. Z Dankovich, J. , "GO: Cryogenic Fluid Management, NASA Space Technology Mission Directorate", published on NSPIRES, March 2022.
9. ZA Sanders, G. "In Situ Resource Utilization (ISRU) – Surface Excavation and Construction", Presented to the NASA Advisory Council Technology, Innovation, and Engineering Committee, Jan 21, 2021. https://www.nasa.gov/sites/default/files/atoms/files/jsanders_lunar_isru_tagged_0.pdf
10. Plachta DW, Johnson WL, Feller JR. Zero boil-off system testing, Cryogenics 2016;74:88–94.
11. Plachta DW, Johnson WL, Feller JR. Cryogenic boil-off reduction system testing, AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2014