Characterization Testing of a 20 Kelvin Cryocooler for Space Applications

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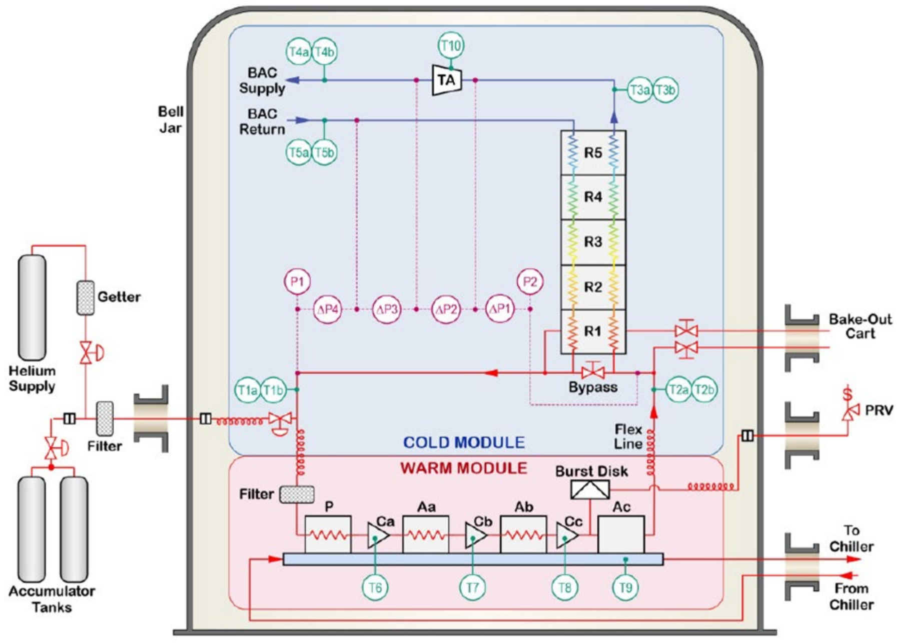
INTRODUCTION

- NASA has identified high-capacity 20 K-class cryocoolers as a critical technology to enable future Lunar and Martian missions that require liquid hydrogen propellant transfer, storage, and liquefaction operations.
- While NASA has a 30+ year history with flight cryocoolers, these systems were primarily designed to cool scientific instruments and optics at lower capacities.
- Reverse turbo-Brayton (RTB) cryocoolers have several advantages for high-capacity cryogenic fluid management applications.
  - Higher efficiency and power scales than Stirling or pulse tube cryocoolers
  - Circulating flow that can provide distributed cooling over a cryogenic tank through broad area cooling (BAC)
- NASA initiated the development of a high-efficiency, high-capacity 20 K-class cryocooler under a Phase 1 Small Business Innovative Research (SBIR) award in 2008 that has since advanced through a Phase II and Phase III SBIR.
- At the end of the Phase III SBIR, Creare, LLC delivered a RTB cycle cryocooler capable of providing approximately 20 W of cooling at 20 K.
- From March through July 2025, extended cryocooler characterization testing occurred to investigate the impact of adjusting several key operating parameters across a range of operational scenarios the system could encounter on future Lunar and Martian missions.

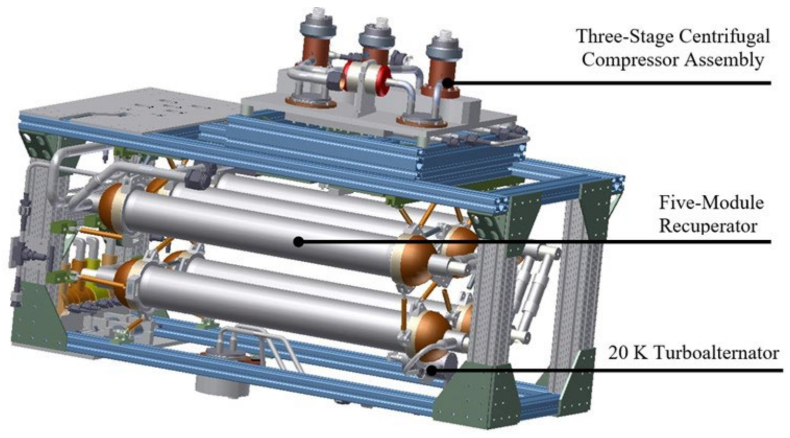
TEST OVERVIEW & HARDWARE

- Cryocooler characterization testing occurred from March 3rd – July 7th 2025.
- The cryocooler was ran continuously outside of any shutdowns.
- The following parameters were adjusted during testing:
  - BAC heater load (W)
  - Target BAC return temperature (K)
  - Heat rejection temperature (HRT) via adjusting facility chiller temperature (K)
  - System pressure (psia)
- The cryocooler controls set the cryocooler to the desired test point.
- Once steady-state criteria was achieved over a couple hour period for a test, the cryocooler was commanded to the next test point in the test matrix.

- Creare's high-efficiency, high-capacity 20 K-class cryocooler consists of:
  - Three compressor stages with aftercoolers
  - A liquid-cooled heat rejection interface
  - A five-stage recuperator module
  - A single stage turboalternator
  - A BAC simulator (orifice)



Cryocooler Characterization Testing P&ID



CAD Representation of the Creare 20-K Class RTB Cryocooler

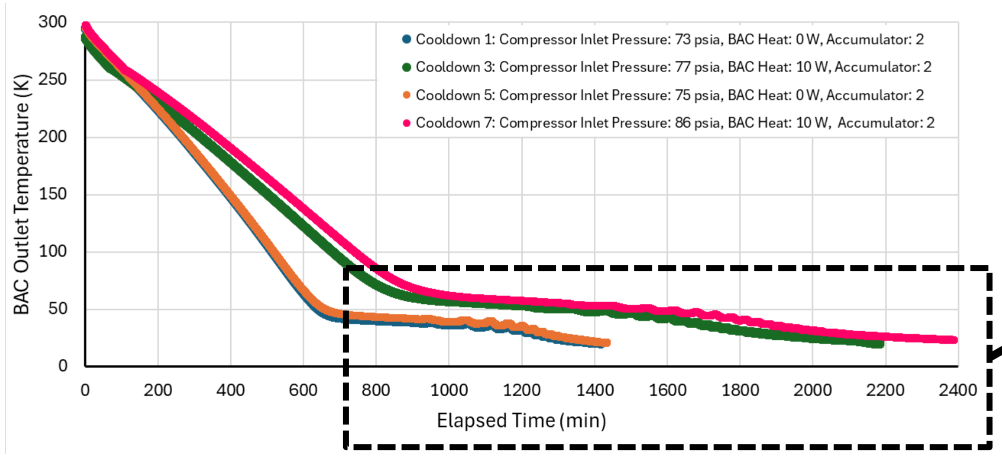
TEST MATRIX

Test Series	Accumulator Volume	Compressor Inlet Pressure (psia)	Rejection Temperature (K)	Return Temperature (K)	Duration (days)	Lift* (W)
0	Cooldown Baseline				2-5	5/10
1	Baseline	Nominal (75-80 psia)	300	19 (min), 20, 21 (Max)	TBD (~10)	3 (min), 5, 10, 15, 18, 20, max
2	Baseline	Nominal (75-80 psia)	285	19 (min), 20, 21 (Max)	6	3 (min), 5, 10, 15, 20, max
3	Baseline	Nominal (75-80 psia)	270	19 (min), 20, 21 (Max)	6	3 (min), 5, 10, 15, 20, max
4	Baseline	High (85 psia)	285	19 (min), 20, 21 (Max)	6	3 (min), 5, 10, 15, 20, max
5	Baseline	85, 82, 79, 76, 73, 70, 67, 64, 61	285	20	4	10
6	Baseline	Low (65 psia)	285	19 (min), 20, 21 (Max)	6	3 (min), 5, 10, 15, 20, max
7	Warmup/Cooldown/Baseline	Low (65 psia)			3	0
8	Baseline x 2	Nominal (75-85 psia)	300	19 (min), 20, 21 (Max)	6	3 (min), 5, 10, 15, 20, max
12	Baseline	Nominal (75-85 psia)	276	19 (min), 20, 21 (Max)	6	3 (min), 5, 10, 15, 18, 20, max
13	Baseline	Nominal (75-85 psia)	273, 279, 282, 288, 291, 294, 297	20	4	10
14	Warmup/Cooldown/Baseline (0.5, 1)	Nominal/High			5	0, 10
15	Baseline	Nominal (75-85 psia)	300	20	Min – 10 (Max remaining)	(min), 3, 5, 10, 15, 18, 20
				Total:	120	

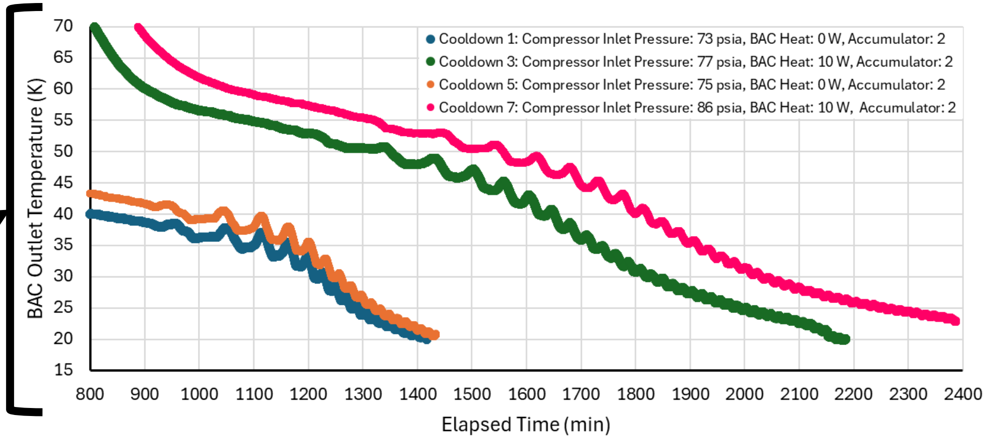
*Not all lifts will be achievable at all temperature combinations (Rejection temperature and Return temperature).

COOLDOWNS

- The cryocooler's components start at a relatively warm ambient temperature (273–293 K).
- Data from six cooldowns were captured during characterization testing.
- Variables adjusted to assess impact of system performance:
  - System Pressure
  - BAC heater power
  - Accumulator volume
- For all cooldowns, temperature oscillations were seen starting around 40-50K.



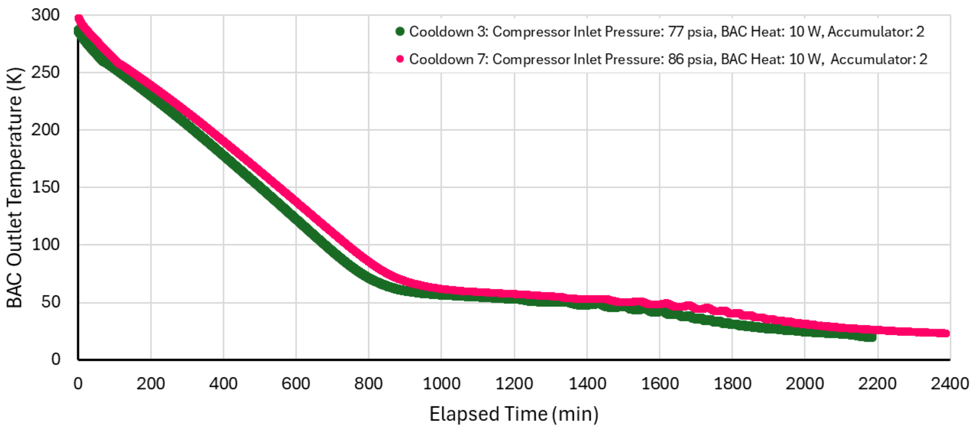
Greater heat loads and system pressures both increase cooldown duration



Oscillations were observed on all cooldowns when the BAC return temperature was between 53 K and 30K

COOLDOWNS

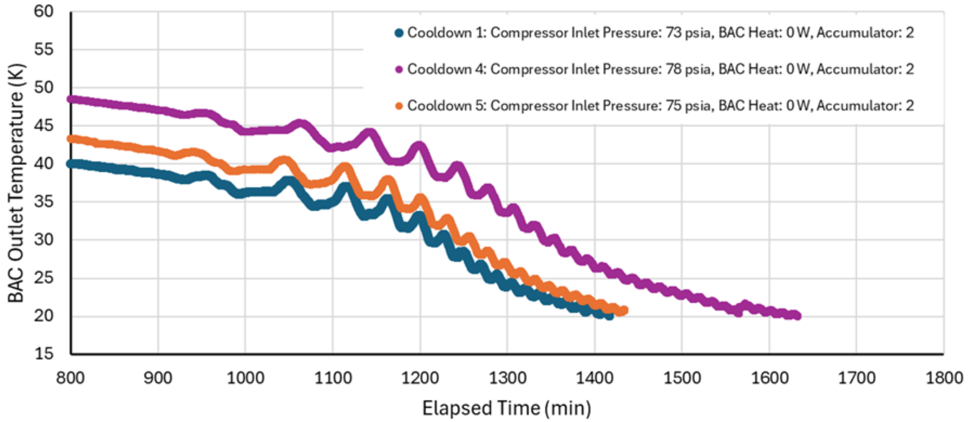
- For similar pressures, an increase in heat load from 0 W to 10 W extended the cooldown duration by 53%.
- For similar heat loads, an increase in final system pressure from 77 psia to 86 psia led to a 10% increase in cooldown duration.
- Doubling the accumulator volume led to a 30% increase in cooldown duration.
- These results demonstrate the sensitivity of startup timelines to system pressure and parasitic heat load conditions.



An increase in system pressure increases cooldown duration

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

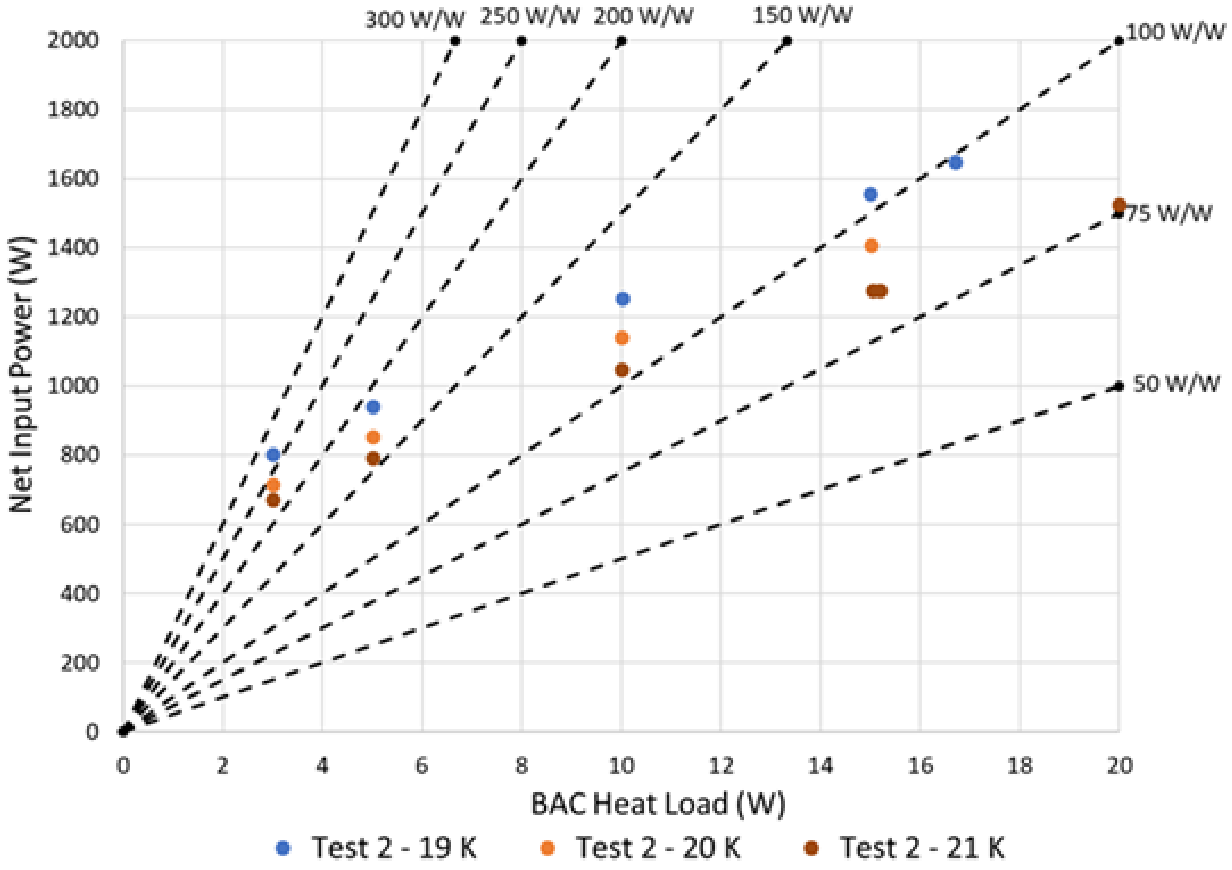
* *For Cooldown 2, accumulators were opened from 0 to 2 after the onset of oscillations*



An increase in system volume increases cooldown duration

RETURN TEMPERATURE SENSITIVITY

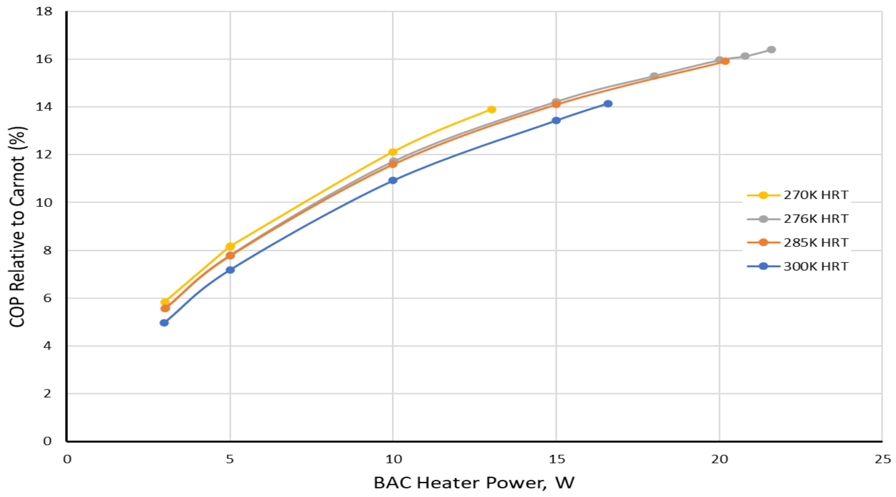
- BAC return temperatures of 19 K, 20K, and 21 K were swept to simulate performance across a range of potential liquid hydrogen storage pressures.
- Lower BAC return temperatures limited the maximum lift capacity while requiring greater input power.
- Higher specific powers were observed as the BAC heat load was lowered from the systems design point of 20 W.
- The maximum lift at a 19 K BAC return temperature was observed at 276 K heat rejection temperature.
  - Lift of 18.6 W
  - Specific Power of 95 W/W
- At 21 K the maximum lift was 24.4 W and a specific power of 72 W/W.
- This trade between lift capacity and return temperature is important for balancing propellant storage pressure requirements against spacecraft power consumption.

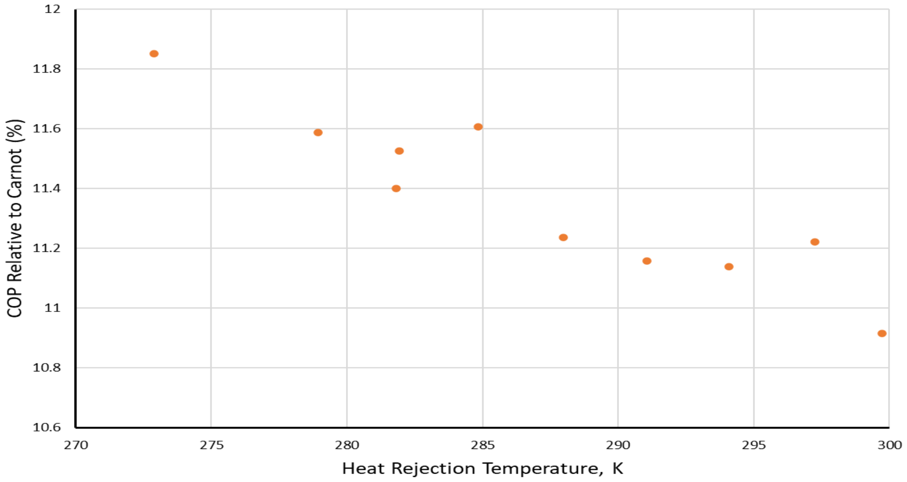


Ross plot for Test Series 2 at a 285 K heat rejection temperature and BAC return temperatures of 19 K, 20 K, and 21 K

HEAT REJECTION TEMPERATURE SENSITIVITY

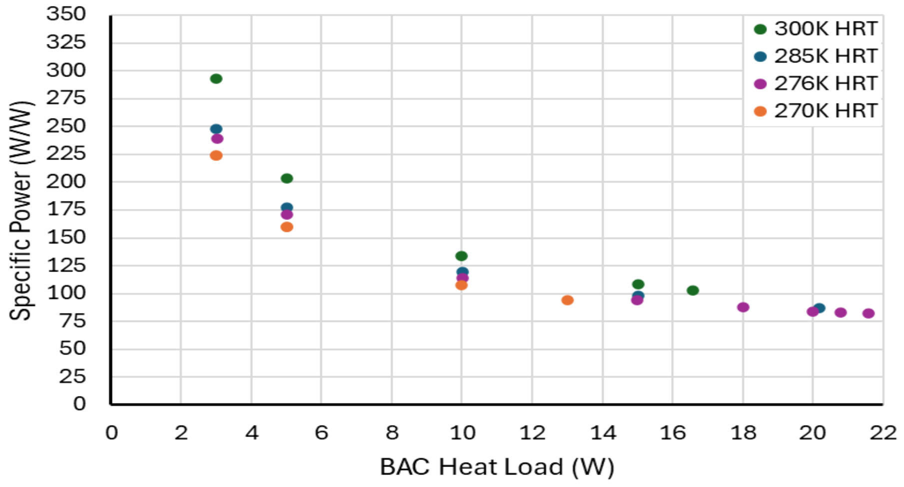
- Heat Rejection Temperature (HRT) represents the temperature the outlet gas leaving the last compressor was cooled to prior to entering the recuperator.
- HRTs of 270 K, 276 K, 285 K, and 300 K were tested across a wide range of inputs, as well as one test holding a constant 10 W lift and reducing HRT in steps of 3 K.
- COP relative to Carnot increases with lower HRTs at a constant heat load.

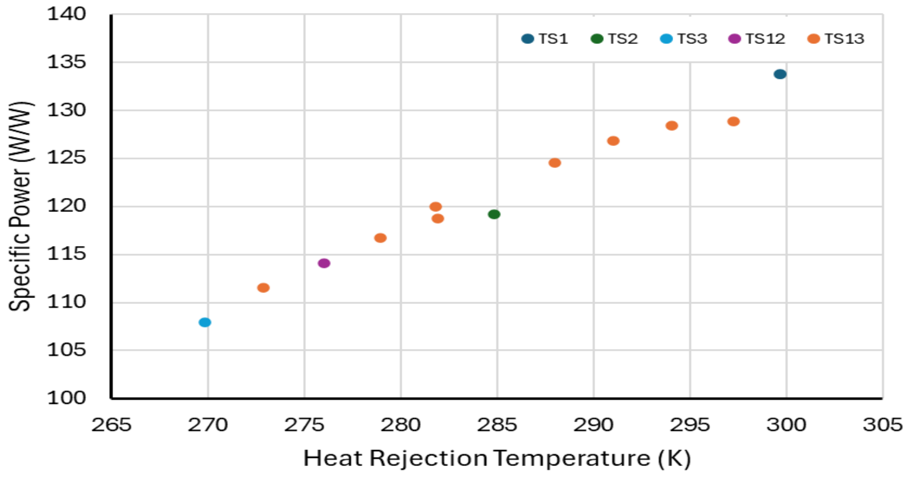




HEAT REJECTION TEMPERATURE SENSITIVITY

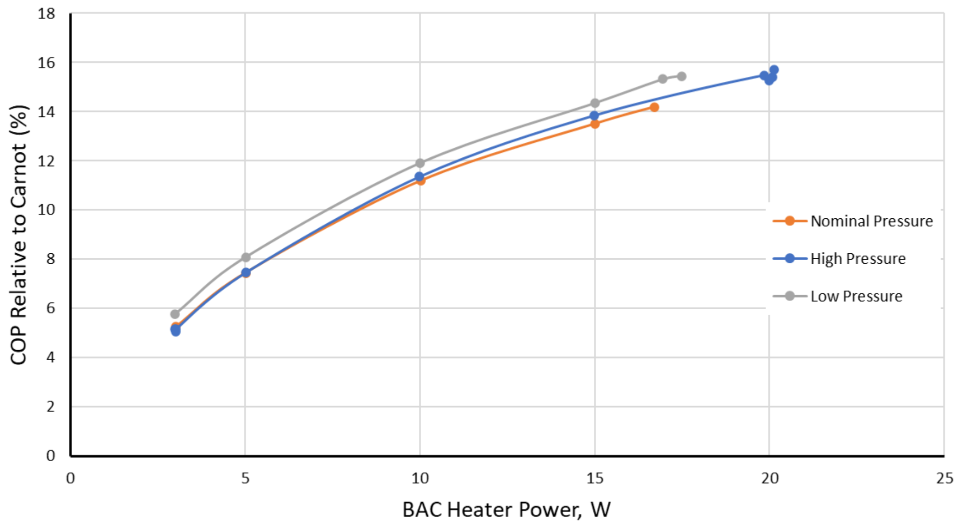
- Higher heat rejection temperatures produce higher specific powers.
- Lower heat rejection temperatures allow for higher maximum lift capacity.
- These results indicate that modest reductions in HRT can substantially improve cryocooler efficiency, reducing spacecraft power demand for long-duration LH2 storage systems.

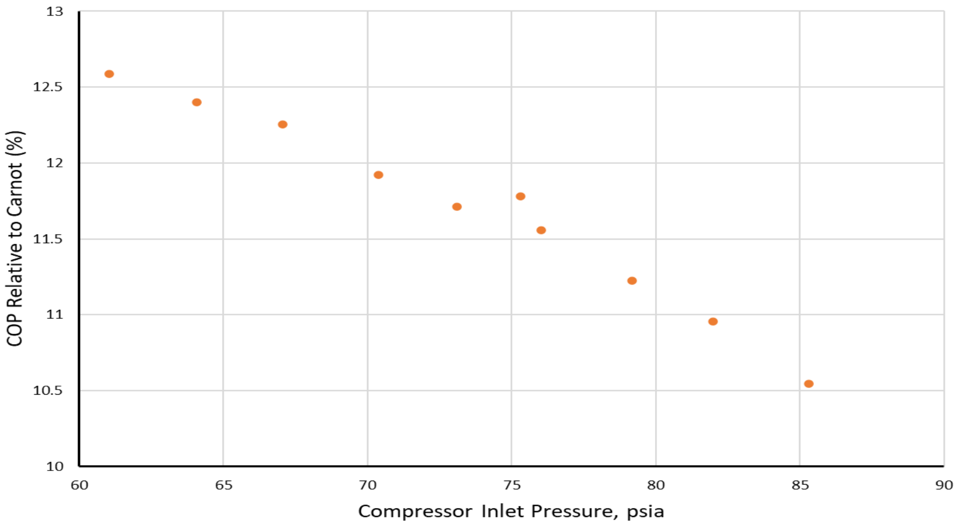




SYSTEM PRESSURE SENSITIVITY

- Three system pressures (low, nominal, high) were tested across a wide range of inputs, as well as one test holding a constant 10 W lift and reducing pressure in steps.
- COP relative to Carnot is higher at lower pressures for a constant heat load.
- COP relative to Carnot is higher at lower pressures at varying heat loads, but at the nominal and high pressures was approximately the same.
  - At high heat load test points, both the low- and high-pressure cases produced better COP relative to Carnot results.

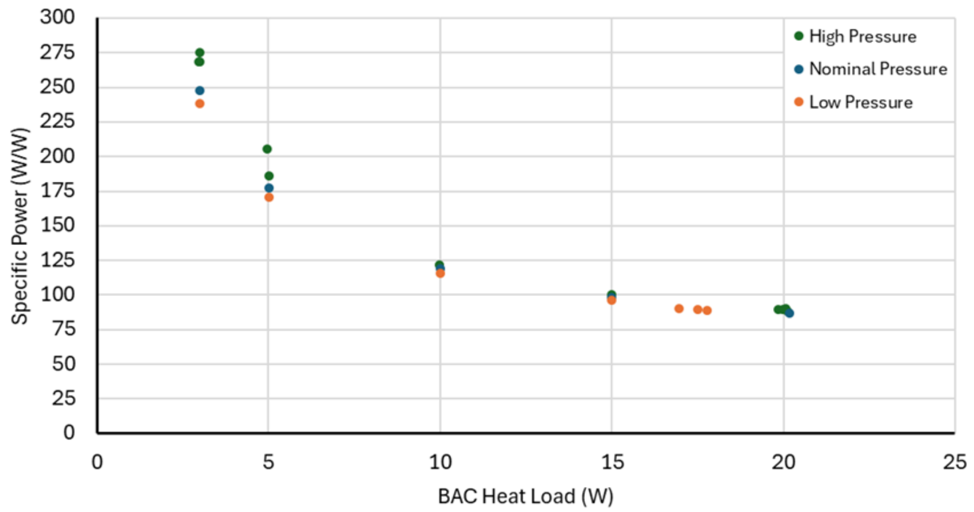


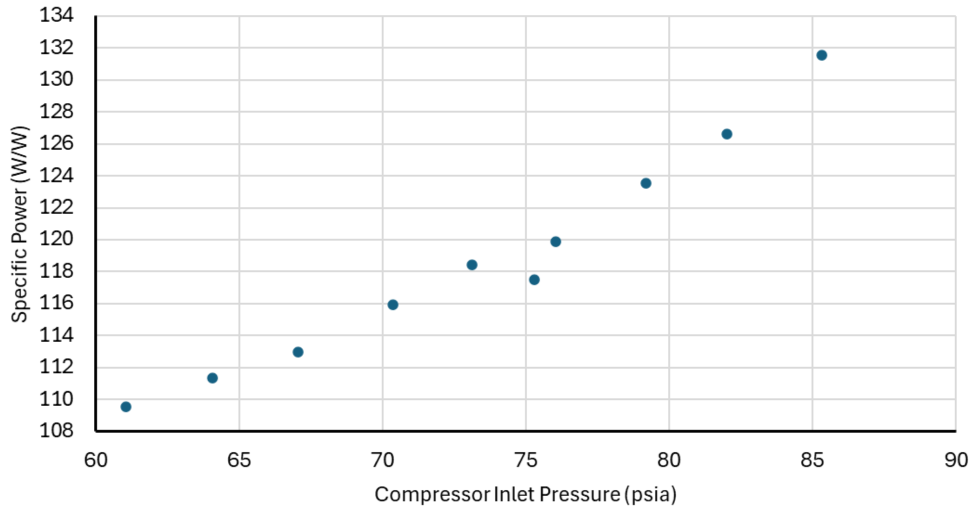


SYSTEM PRESSURE SENSITIVITY

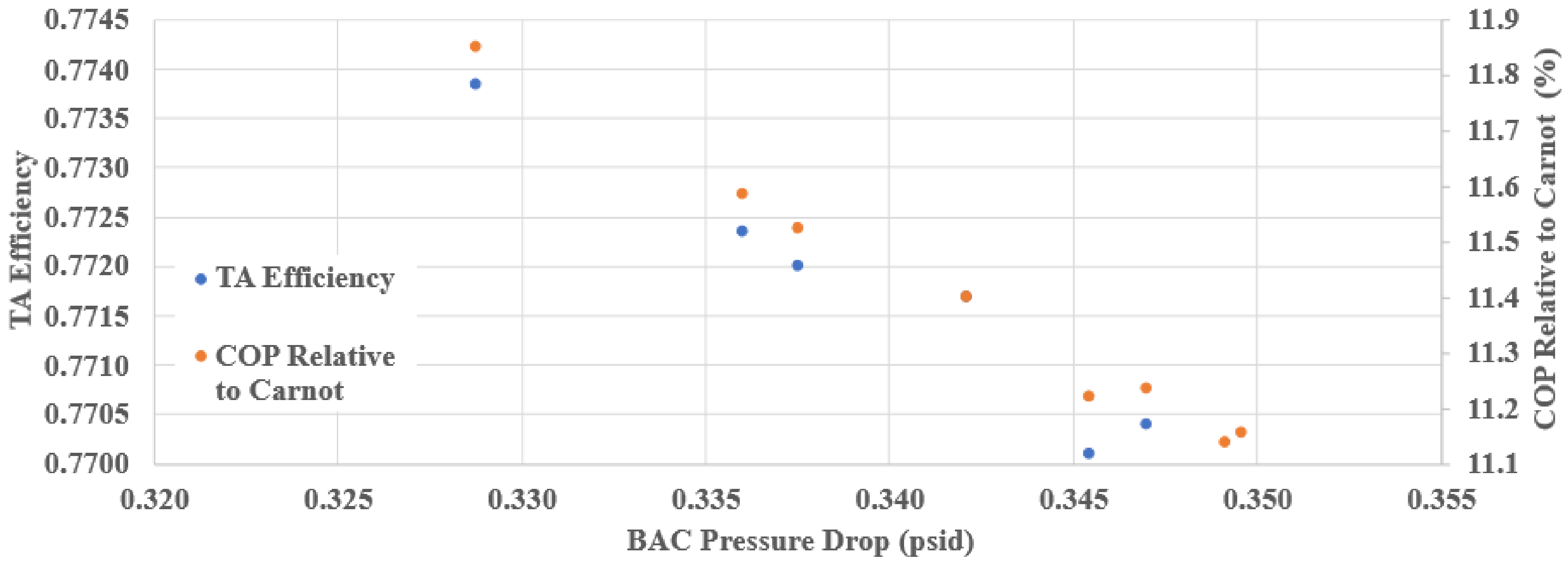
- Specific Power is lower at lower systems pressures, which can be seen for both the varying heat load and constant heat load cases.

- These trends indicate that minimizing system pressure can improve cycle efficiency, though operational constraints of the turbomachinery must also be considered.





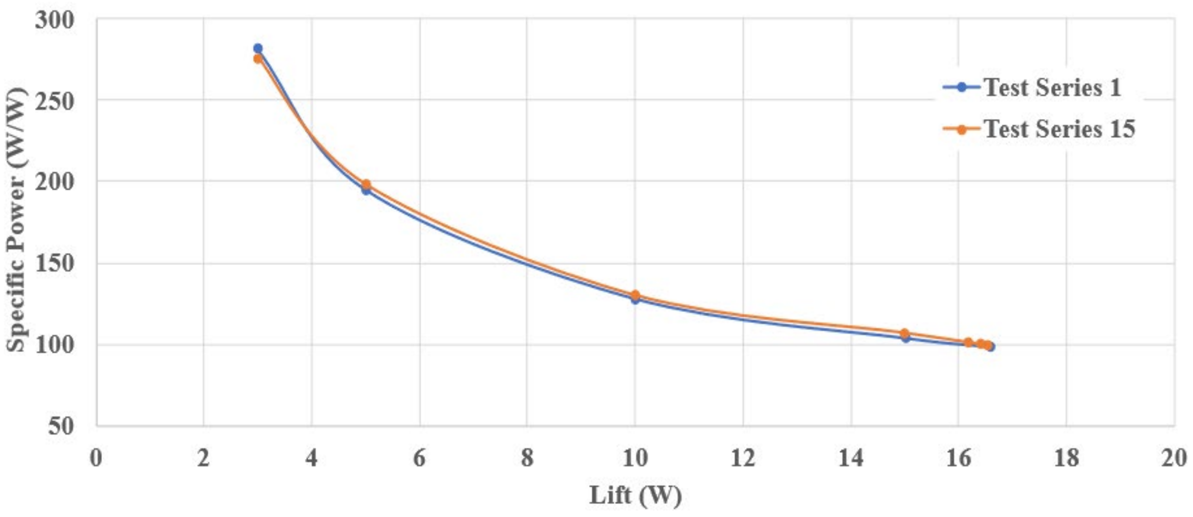
EFFECT OF BAC PRESSURE DROP



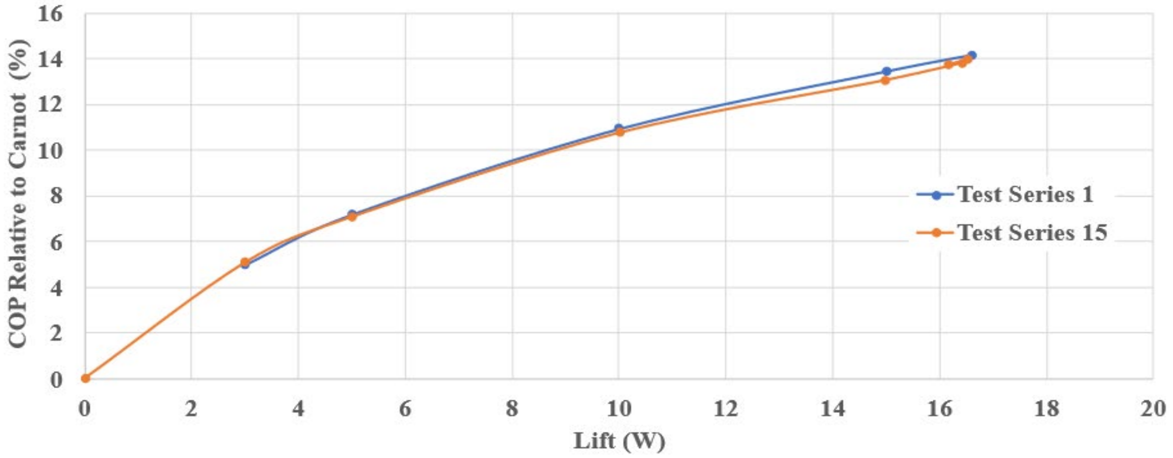
- The RTB cryocooler’s performance and maximum lift capacity is sensitive to pressure drop in the refrigeration loop.
- Any additional flow resistance is an irreversibility that the turboalternator can’t use for cooling.
- A fixed diameter orifice was used to simulate the pressure drop across a BAC tubing network.
- Test data with variations in mass flow rate, pressure, and temperature show that as little a 0.09 psid can decrease TA efficiency and COP relative to Carnot by 2%.
- This sensitivity highlights the importance of minimizing BAC hydraulic losses during cryocooler integration with hardware.

REPEATABILITY

- Repeatability of system performance was demonstrated through Test Series 15 which repeated the 20 K BAC return temperature points from Test Series 1.
- There was ~107 days between TS 1 & TS 15 data points.
- System pressures were within 0.6%.
- Max specific power difference of 3.2%.
- Max Carnot relative to COP difference of 3.0%.
- TS 1 & 15 Test Conditions
  - Nominal Pressure: 73 psia
  - BAC Return Temperature: 20 K
  - Heat Rejection Temperature: 300 K
- This level of repeatability over extended durations supports confidence in performance predictability for long-duration missions.



Specific Power as a function of Lift for TS 1 & 15



COP Relative to Carnot as a function of Lift for TS 1 & 15

TURNDOWN RATIO

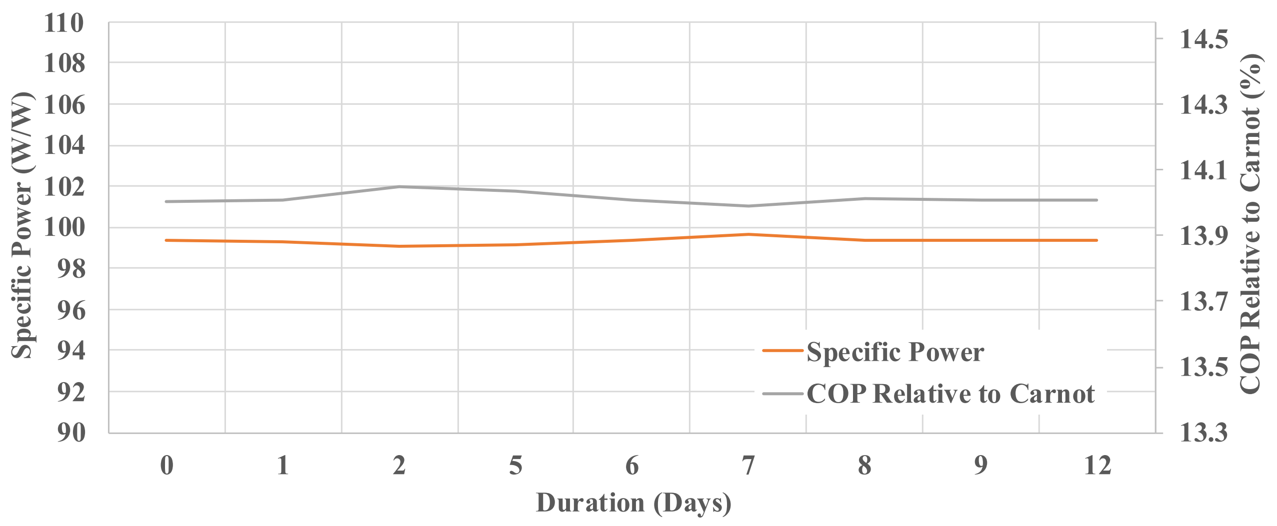
Lift Turndown Performance

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

- 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.
- This turndown capability provides operational flexibility for transient storage demand and supports use of the hardware for multiple mission applications.

LONG DURATION PERFORMANCE

- To demonstrate the cryocooler's ability to sustain steady performance over a longer period.
  - Nominal Pressure: 73 psia
  - BAC Return Temperature: 20 K
  - Heat Rejection Temperature: 300 K
  - BAC Lift: 16.5 W
  - Duration: 12 Days
- The maximum fluctuation in Specific Power was 0.6%.
- The maximum fluctuation in Carnot relative to COP was 0.4%.
- The limited drift in performance over the test duration supports the feasibility for use in long-duration cryogenic storage operations.



LESSONS LEARNED

- Redundant sensors on critical instrumentation are essential to maintain testing continuity and avoid hardware disassembly.
- Fault logic should require multiple consecutive deviations before triggering shutdowns to reduce unnecessary system interruptions.
- Non-critical support system errors (e.g., backup UPS issues) should generate warnings instead of automatic shutdown faults.
- Thorough operator understanding of cryocooler control algorithms and operational modes is critical to prevent faults and potential hardware damage.
- Facility cooling infrastructure may require additional optimization and benchtop validation to support maximum cryocooler heat rejection loads.
- Recuperator thermal mass causes much longer stabilization times than anticipated, even after steady-state criteria are met.
  - Small, long-term variances in recuperator effectiveness had minimal impact on overall key performance parameters.
- Extensive turbomachinery limit mapping and robust fault protections enabled reliable long-duration operation, including at extreme boundary conditions.
  - None of the system shutdowns during testing were caused by inadequately defined control parameter limits, demonstrating effective fault management design.

CONCLUSIONS

- Characterization testing of the 20 W 20 K cryocooler demonstrated performance meeting and exceeding future NASA mission requirements.
  - Achieved a peak coefficient of performance (COP) of 17.68% relative to Carnot efficiency
  - Demonstrated a maximum lift capacity of 24.4 W at 21 K
- Successfully validated cryocooler operation across a wide range of performance parameters.
- Developed a comprehensive database of operating points to support future mission design efforts.
- Results confirm that high-capacity reverse turbo-Brayton cryocoolers are a viable solution for future long-duration cryogenic fluid management architectures.
- The cryocooler utilizes a closed gaseous helium cycle, making its expected performance gravity independent.
- NASA plans to publish a comprehensive report with full data, component performance analysis, and conclusions in late 2026.

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