Space Exploration Applications for Development of High Capacity Cryocoolers

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Introduction

- Long term storage of cryogens is necessary to enable NASA's crewed missions to both the lunar and Martian surfaces.
- NASA is currently investing in passive and active thermal control technologies that will enable long term in-space storage of cryogenic propellants at zero boil-off.
- This is in line with NASA's goal of increasing payload mass beyond low Earth orbit by improving the mass efficiency of high-performing cryogenic propellants in upper stages and depots.
- This presentation will discuss:
  - Current state of the art (SOA)
  - Provide a survey of missions for which long duration storage of cryogens is critical
  - Current developments underway at NASA
  - Remaining gaps to a long duration flight unit

Current State of the Art (SOA)

- Current cryocooler technologies with flight operating experience include:
  - Pulse Tube Coolers, Single Stage or Two-Stage
  - Stirling Coolers, Single Stage or Multi-Stage
  - Turbo Brayton
  - Sorption/JT Coolers
- While flight cryocoolers at 20K and 90K exist, none exceed 1 W or 20 W of lift, respectively.
- Even at higher temperatures, no lift capacities for flight units have exceeded 100 W.

Long-Life Space Cryocooler Flight Operating Experience as of April 2020

Cooler / Mission	Hours/Unit	Comments
AIM Infrarot-Modul Pulse Tube Cooler		
KompSAT 3A (85K, SF400 Mini PT)	43,800	Turn-on 4/15, Ongoing, No degradation
Air Liquide Turbo Brayton		
(ISS MELFI 190K Turbo Brayton, FU1)	120,300	Turn-on 7/06, Ongoing, No degradation
(ISS MELFI 190K Turbo Brayton, FU2)	92,000	Turn-on 10/09, Ongoing, No degradation
(ISS MELFI 190K Turbo Brayton, FU3)	82,000	Turn-on 12/10, Ongoing, No degradation
Ball Aerospace Stirling		
HIRDLS (60K 1-stage Stirling)	83,800	8/04 thru 3/14, Instr. failed 2008; Turned off 3/14
TIRS/Landsat-8 (35K two-stage Stirling)	62,400	Turn-on 3/13, Ongoing, No degradation
Creare Turbo Brayton (77K NICMOS)	57,000	3/02 thru 10/09, Off, Coupling to Load failed
Fujitsu Stirling (ASTER 80K TIR system)	176,000	Turn-on 3/00, Ongoing, No degradation
JPL Sorption (PLANCK 18K JT (Prime & Bkup))	27,500	FM1 (8/10-10/13 EOM); FM2 failed at 10,500 h
Mitsubishi Stirling (ASTER 77K SWIR system)	171,800	Turn-on 3/00, Ongoing, Load off at 71,000 h
NGAS (TRW) Stirling & Pulse Tube Coolers		
CX (150K Mini PT (2 units))	195,900	Turn-on 2/98, Ongoing, No degradation
HTSSE-2 (80K mini Stirling)	24,000	3/99 thru 3/02, Mission End, No degrad.
MTI HXRS (60K 6020 10cc PT)	175,900	Turn-on 3/00, Ongoing, No degradation
Hyperion (110K Mini PT)	140,900	12/00 to 3/17, Mission End, No degradation
SABER on TIMED (75K Mini PT)	163,900	Turn-on 1/02, Ongoing, No degradation
AIRS (55K 10cc PT (2 units))	155,900	Turn-on 6/02, Ongoing, No degradation
TES (60K 10cc PT (2 units))	117,200	8/04 to 1/18, Mission End, No degradation
Himawari-6/JAMI (65K HEC PT (2 units))	91,000	4/05 to 12/15, Mission End, No degrad.
GOSAT/IBUKI (60K HEC PT)	96,400	Turn-on 3/09, Ongoing, No degradation
STSS (Mini PT (4 units))	87,100	Turn-on 4/10, Ongoing, No degradation
OCO-2 (HEC PT)	49,200	Turn-on 8/14, Ongoing, No degradation
Himawari-8/AHI (55K HEC 2-Stg PT (2 units))	42,300	Turn-on 7/15, Ongoing, No degradation
Himawari-9/AHI (55K HEC 2-Stg PT (2 units))	~5000	Init-on 03/18, Off-standby, No degradation
GOES-R/16 ABI (55K HEC 2-Stg PT (2 units))	28,500	Turn-on 1/17, Ongoing, No degradation
GOES-S/17 ABI (55K HEC 2-Stg PT (2 units))	16,800	Turn-on 5/18, at low power due to LHP failure
GEO-KOMPSAT-2A/AMI (55K HEC 2-Stg PT (2 units))	6,600	Turn-on 7/19, Ongoing, No degradation
OCO-3 on ISS (HEC PT)	6,600	Turn-on 7/19, Ongoing, No degradation
Oxford/BAe/MMS/Astrium/Airbus Stirling		
ISAMS on UARS (80 K Oxford/RAL)	15,800	10/91 thru 7/92, Instrument failed
HTSSE-2 on Argos (80K BAe)	24,000	3/99 thru 3/02, Mission End, No degrad.
MOPITT on Terra (50-80K BAe (2 units))	172,900	Turn-on 3/00, Ongoing, lost 1 disp. at 10,300 h
Odin/SMR (50-80K MMS (1 unit))	166,900	Turn on 3/01, Ongoing, Degraded Perf.
AATSR on Envisat (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
MIPAS on Envisat (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
INTEGRAL (50-80K Astrium (4 units))	153,000	Turn on 10/02, Ongoing, No degradation
Helios 2A (50-80K Astrium (2 units))	130,900	Turn-on 4/05, Ongoing, No degradation
Planck (4K JT using 2 Astrium Comp.)	38,500	5/09 thru 10/13, Mission End, No Degrad.
Helios 2B (50-80K Astrium (2 units))	93,100	Turn-on 4/10, Ongoing, No degradation
Sentenel 3A/SLSTR (50-80K Airbus (2 units))	35,700	Turn-on 3/16, Ongoing, No degradation
Sentenel 3B/SLSTR (50-80K Airbus 2 units)	12,400	Turn on 11/18, Ongoing, No degradation
Raytheon ISSC Stirling (STSS (2 units))	87,100	Turn on 4/10, Ongoing, No degradation
Rutherford Appleton Lab (RAL) Stirling		
ATSR 1 on ERS-1 (80K Integral Stirling)	75,300	7/91 thru 3/00, Satellite failed
ATSR 2 on ERS-2 (80K Integral Stirling)	112,000	4/95 thru 2/08, Instrument failed
Sumitomo Stirling Coolers		
Suzaku (100K 1-stg)	59,300	7/05 thru 4/12, Mission End, No degradation
Akari (20K 2-stg (2 units))	39,000	2/06 to 11/11 EOM, 1 Degr., 2nd failed at 13 kh
Kaguya GRS (70K 1-stg)	14,600	10/07 thru 6/09, Mission End, No degradation
JEM/SMILES on ISS (4.5K JT)	4,500	Turn on 10/09, Could not restart at 4,500 h
Sunpower Stirling		
RHESSI (75K Cryotel)	145,800	Turn on 2/02, Mission End 10/18, Mod. degrad.
CHIRP (CryoTel CT-F)	19,700	9/11 to 12/13, Mission End, No degradation
Thales Cryogenics Pulse Tube Coolers		
ECOSTRESS (LPT9310-HP, 3 units)	14,000	Turn-on 7/18, Ongoing, No degradation

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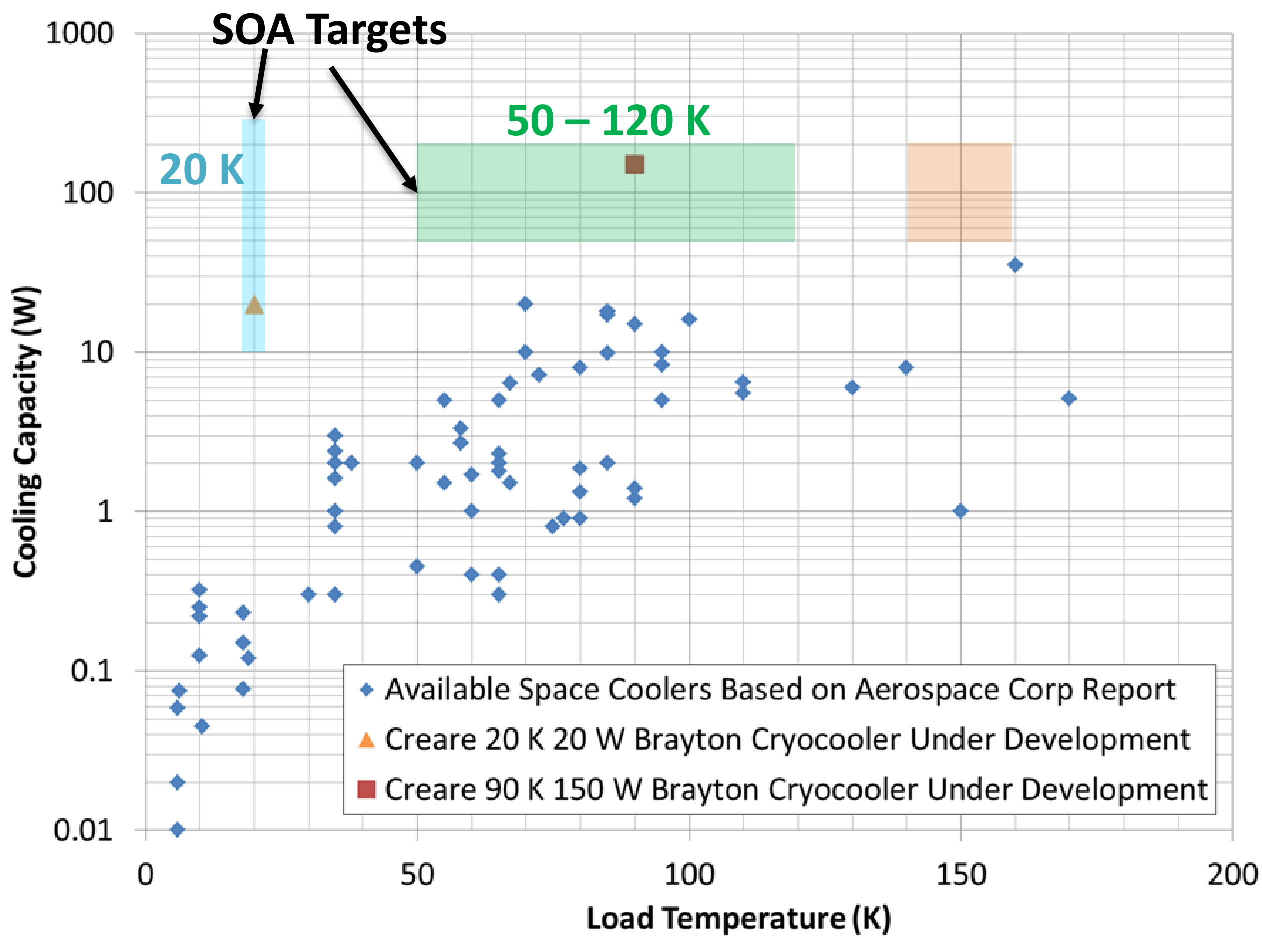
Current State of the Art (SOA)

- In order to achieve the goals of projects such as Nuclear Thermal Propulsion and Lunar/Martian surface ISRU, a substantial jump in SOA capacity is required.

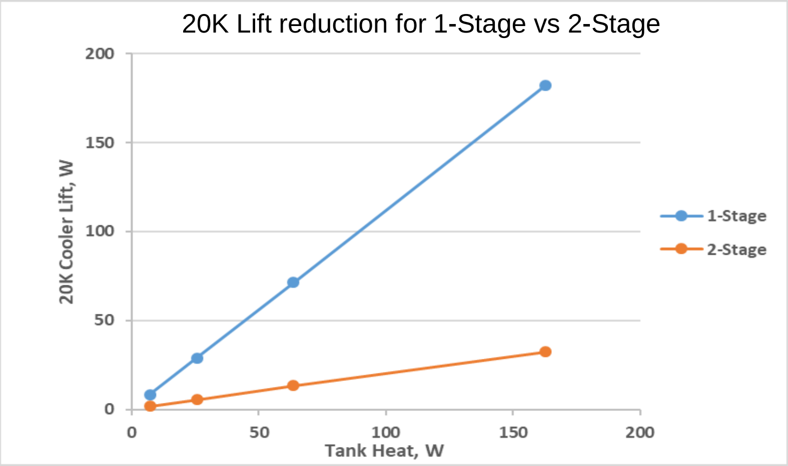


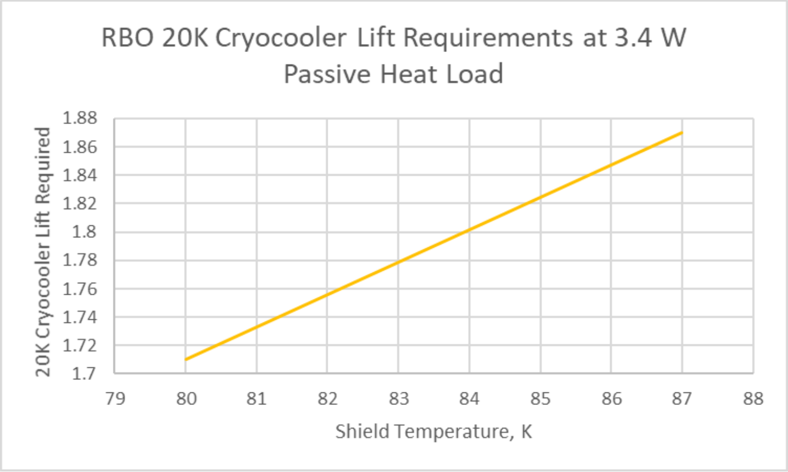
Survey of Missions

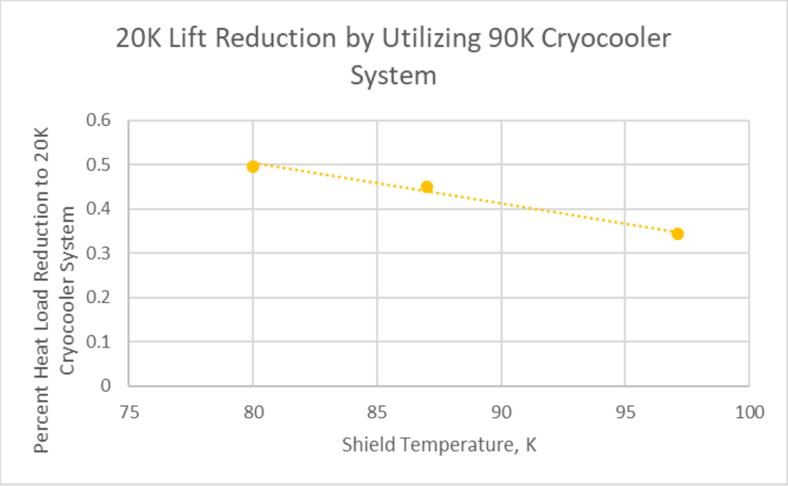
- Nuclear Thermal Propulsion
- Ascent/Descent - Suitable Lunar Architecture
- In-Situ Resource Utilization - Liquefaction on Lunar/Martian Surfaces
- Regenerative Fuel Cells

Nuclear Thermal Propulsion

- NTP is one of the leading propulsion options for human Mars missions
- Requires liquid hydrogen to be stored on-orbit for over four years
- 1-Stage vs 2-Stage Cryocooler Systems
  - 1-Stage requires 20K class cryocooler to provide 114W of lift.
  - 2-Stage requires 20K class cryocooler to provide 16.5W of lift.
  - Reduce Boil-Off testing provided relevant data demonstrating 20K lift requirement reductions by modifying shield temperatures.







Ascent/Descent - Suitable Lunar Architecture

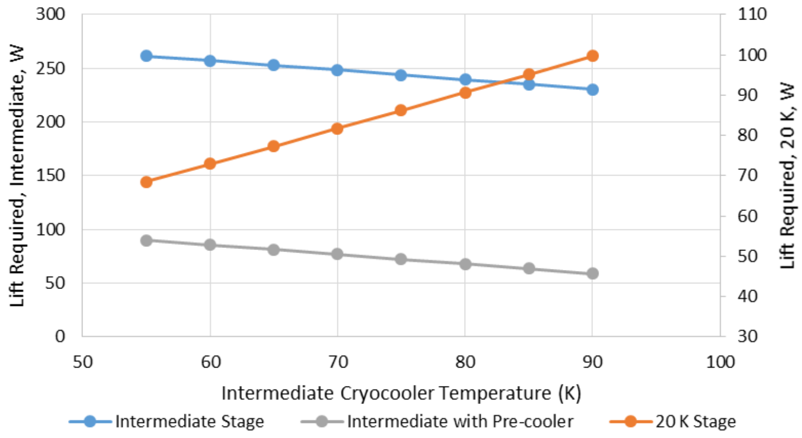
- In March 2019, NASA was tasked to have “boots on the moon” by 2024 followed by a sustained presence later in the decade.
- Under the Artemis program, NASA is engaging with industry partners to achieve these goals.
- In 2024, Orion will deliver crew to Near Rectilinear Halo Orbit (NRHO) where it will dock to a commercially developed lander and descend crew to the lunar surface for a six day stay
- On subsequent missions, Orion will transport the crew to Gateway for extended durations to conduct research and while making occasional descents to the lunar surface.

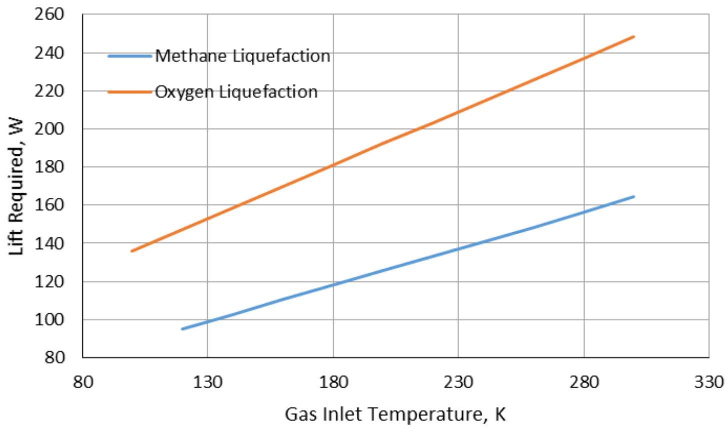
Concept image of an Artemis Human Landing System approaching the lunar surface

- The 2024 Artemis mission will require cryogens to be available for durations <u>greater than 100 days</u>, while subsequent missions will likely require replenishing propellant tanks on-orbit and eventually making use of in-situ produced propellant on the lunar surface.
- All decent/ascent vehicles will need to determine how to mitigate propellant loss whether it be a combination of passive storage and/or propellant replenishment, and with or without the implementation of Active Cooling (Cryocoolers)
- Cryocoolers can be enabling to achieve Zero Boil-Off (ZBO) or Reduced Boil-Off (RBO) conditions to extend propellant life, and will be needed for the liquefaction of ISRU propellants on the lunar surface.

In-Situ Resource Utilization

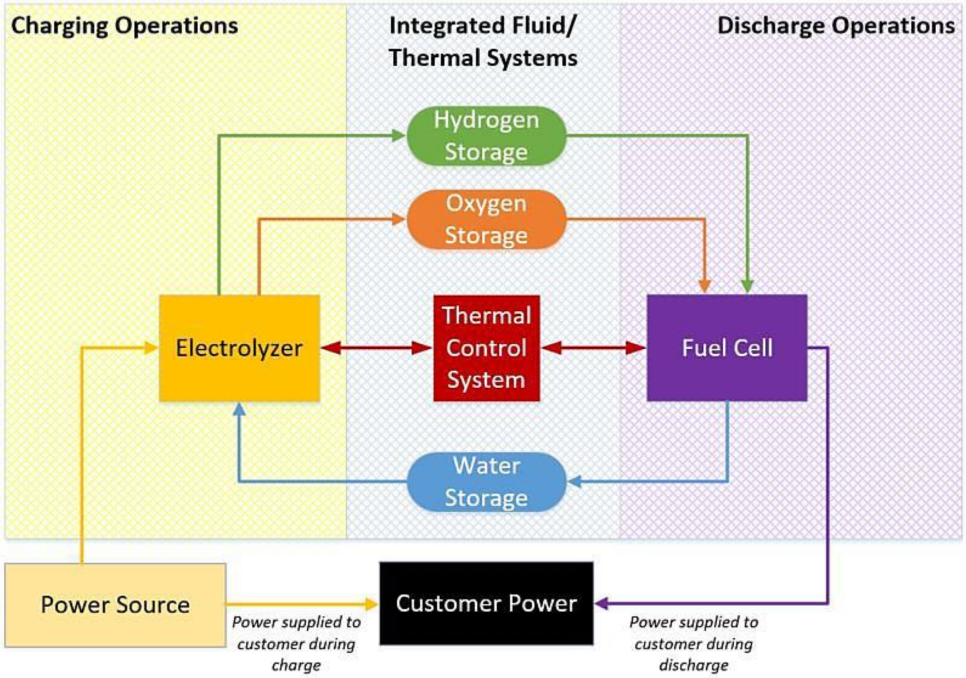
- Current NASA focus in the ISRU community targets hydrogen liquefaction rates of approximately 10,000 kg/yr
  - NASA's ISRU community typically includes some level of contingency for various issues that might pop up.
  - Flow rates of interest have been identified as: 0.3 kg/hr hydrogen, 0.65 kg/hr methane, 2.2 kg/hr oxygen.
- Trades between multiple different concepts were explored in Cold Facts Vol. 36, Issue 2.
  - Use of an intermediate temperature cryocooler for hydrogen liquefaction (between 50 K and 90 K).
  - Use of a radiator pre-cooler for hydrogen liquefaction (target temperature approximately 150 K).

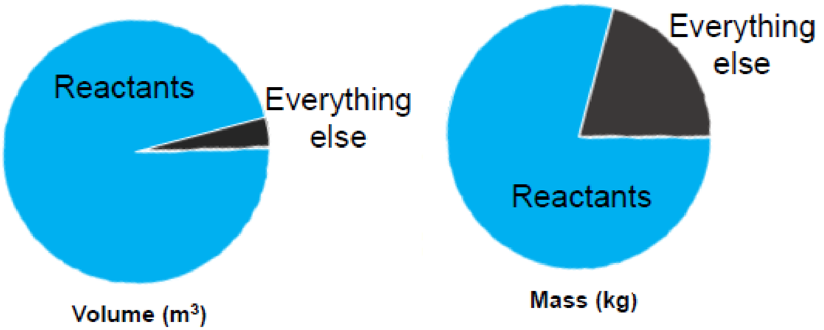




Regenerative Fuel Cells

- Regenerative fuel cells (RFCs) provide a mass-optimized energy source for lunar surface missions in locations with extended eclipse durations
- The gas storage system tends to dominate in calculating total RFC mass and volume, providing the limiting factor in most missions
- In some applications, liquefaction and cryogenic storage of the hydrogen and oxygen may provide a solution for reduction in overall system mass and volume, provided additional power is available to support liquefaction
  - Applications such as lunar landers or robotic vehicles may apply
- Primary fuel cells may also benefit from cryogenic propellants by scavenging already available propellant on a spacecraft



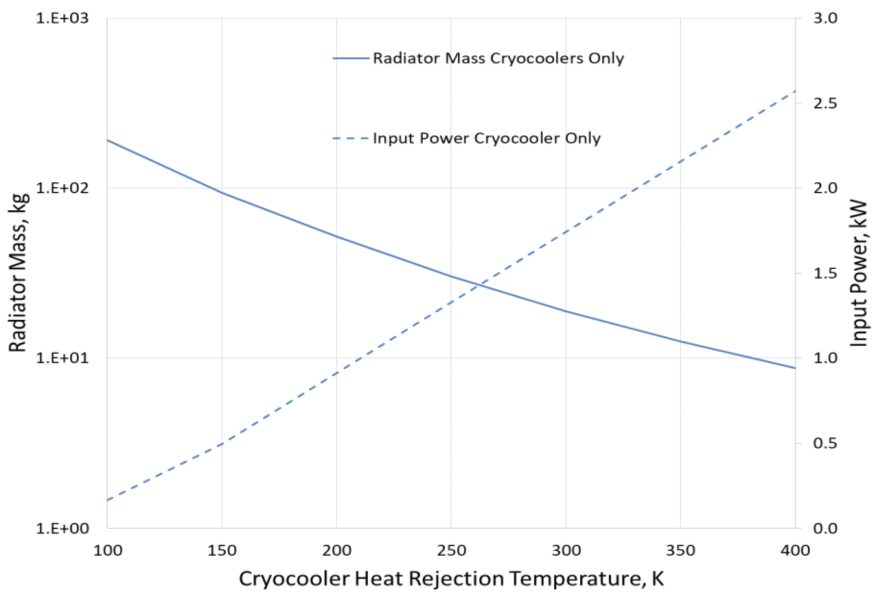


Typical RFC System Mass Breakdown

Other Operations

Cryocoolers in the right locations can make several other orbital applications either much simpler or more complicated:

- Fluid Transfer Systems: Removing energy from the system prior to initiating a transfer would come closer to making “cryogens flow like water” and greatly simplify operations associated with chilldown.
- Trade between input power mass and radiator (heat rejection) temperature (size/mass)
  - A simplified trade at 112 W @ 90 K system shown
  - As radiator temperature decreases, radiator size and mass increases, cryocooler efficiency increases (input power decreases).



20 W 20 K Cryocooler

- NASA awarded an SBIR Phase III to Creare LLC for development of a 20 W 20 K cryocooler.
- Anticipated acceptance and characterization testing in 2021
- Critical element to the development of a two-stage cooling system for NTP.
- Expected to be TRL-6 hardware in 2021 (electronics TRL-4).

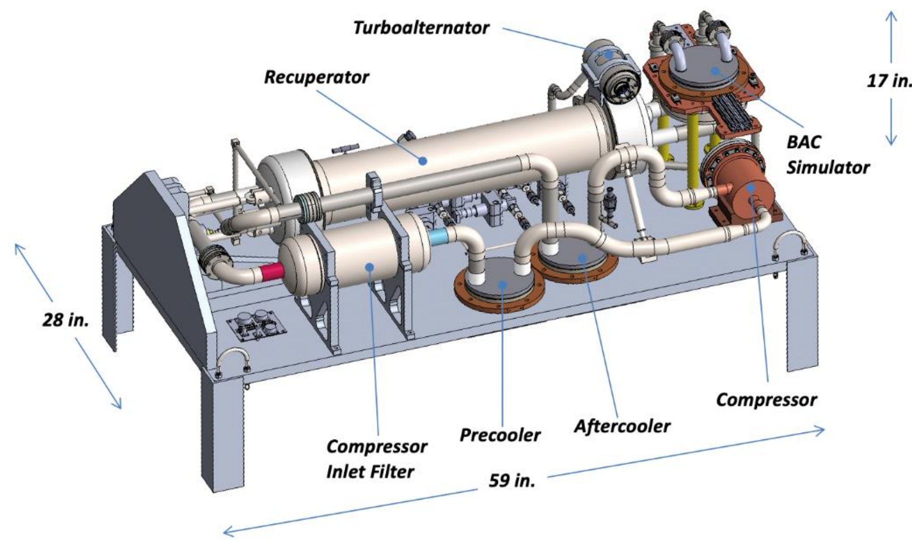
20W 20K Cryocooler in Creare's Clean Room

Parameter	State of the Art	Project Goal	Current Value
1) Lift Capacity (W)	1	20	19.1(1)
2) Specific Mass (kg/W)	18.7	4.4	5.3
3) Specific Power (W/W)	370	60	95(1)

Notes:
All parmeters assume a fully integrated cryocooler operating at an environmental temperature of 270 K and are established based on a 20K design point, and do not include the mass and inefficiency of the drive electronics.
(1) This value represents the as-delivered Engineering model. The flight model is predicted to be 20 W.
(2) This value represents the as-delivered Engineering model. The flight model is predicted to be 71 W/W.

150 W 90 K Cryocooler

- An engineering model Reverse Turbo-Brayton (RTB) Cycle cryocooler is currently under development for NASA via a SBIR contract with Creare, LLC.
- Applicable to lunar and Mars missions, In-Space stages, Propellant Depots, and the liquefaction of In-Situ produced propellants.
- Designed to operate over a range of temperatures for applicability to liquid oxygen, liquid methane, and liquid natural gas
  - May also be used for liquid hydrogen applications if two-stage cooling is implemented.
- Creare, LLC will demonstrate the performance of the cryocooler via characterization and vibration testing advancing the Technology Readiness Level to TRL 6.
- NASA will take delivery of the engineering model, then conduct further testing.

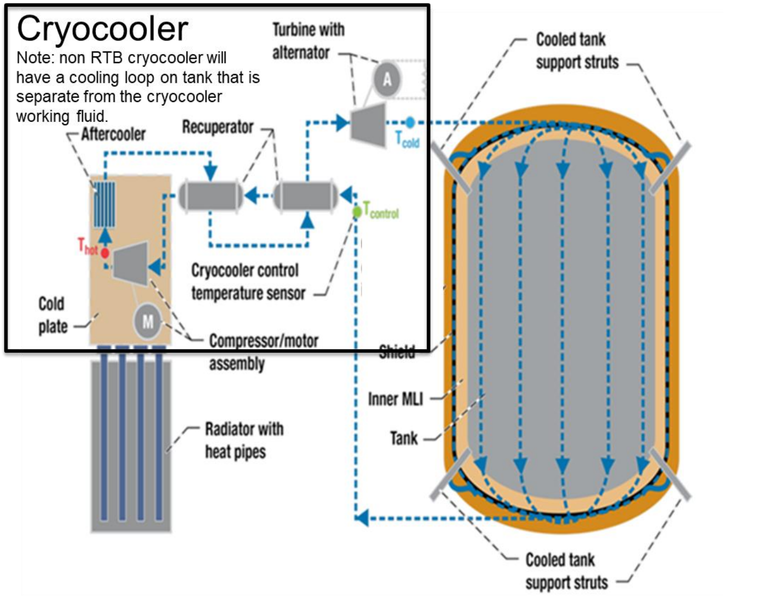


Creare's 150W/90K Reverse Turbo-Brayton Cycle Cryocooler

Key Performance Parameters				
Parameter	**Units**	**State of the Art (SOA)**	**Threshold Value**	**Project Goal**
1) Lift Capacity	Watts	20	120	150
2) Specific Mass	kg/Watt	1	0.8	0.4
3) Specific Power	Watt/Watt	15	15	8

Reverse Turbo-Brayton Cycle Cryocooler Electronics

- Mechanical Components ("Mechanical Side")
  - Turbo Alternator
  - Recuperator
  - Compressor
  - Aftercooler, Precooler, Recuperator (if needed)



Reverse Turbo-Brayton Cycle Cryocooler Integrated with Tube-On-Tank Broad Area Cooling

- Electronics and Software ("Electrical Side")
  - Drives the mechanical components
  - Controls the cryocooler

- Current development plans will advance the Reverse Turbo-Brayton cycle cryocooler "Mechanical Side" to a Technology Readiness Level of TRL 6, however the cryocooler "Electrical Side" remains at TRL 4.
- Similarly to the "Mechanical Side", a contract will be awarded to design, build and demonstrate an engineering model of the cryocooler electronics package.
- Demonstration will include Thermal-Vac and Vibration testing to advance the "Electrical Side" to TRL 6

Multiple Path Approach

- NASA realized that reliance on multiple companies for high capacity 90K cryocooler technology was prudent, and that there were large aerospace contractors who likely had the capability to develop these 150 W at 90 K cryocoolers.
- NASA proposed to contract with these companies for conceptual designs of such a system.
- Two awards were made in February 2019, one to Lockheed Martin (LM) and one to Northrop Grumman Aerospace Systems (NGAS).
  - Both LM and NGAS both proposed and then successfully completed Conceptual Design Review(s) in the October/November 2019 timeframe, based upon Pulse-Tube cryocoolers and technology.
  - Both LM and NGAS are presenting at least portions of their results at ICC.

Conclusions and Remaining Gaps

- NASA technologists have attempted to foresee NASA programmatic needs
- The current developments in progress cover a large majority of NASA's current needs, however a few opportunities remain:
  - Combined cycle oxygen/hydrogen liquefaction systems.
  - ISRU Liquefaction of hydrogen will require higher capacity 20 K class cryocoolers.
  - Alternative solutions at 20 K and 90 K class cryocoolers, both faster development approaches and multi-path approaches.
  - 150 K class cryocoolers (both pre-cooling for liquefaction and CO2 separation on Mars).

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