NASA Cryocooler Technology Developments and Goals to Achieve Zero Boil-Off and to Liquefy Cryogenic Propellants for Space Exploration

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Background

- The history of Zero Boil-Off (ZBO) cryocooler integration to cryogenic propellant tanks is described to provide a context for distributed cooling and present cryocooler investments
  - History of ZBO
    - 1998, 2001, 2003 testing
    - Evolution of distributed cooling
      - Analysis at GRC
      - Analysis and testing at ARC
      - 2009 test at Ball
      - Trade study in 2011
      - Reduced boil-off tests in 2012
      - Zero boil-off tests in 2013
- Present ZBO requirements
  - ZBO is required for Nuclear Thermal Propulsion (NTP) concepts in support of human missions to Mars
  - ZBO is required for NASA's Mars Study Capabilities Team, for LOX production and in-space storage
- 20K cryocooler development
- 90K cryocooler development
- Related developments described
- Summary

1998 LH2 ZBO Test; 2001 ZBO Test

1998 test at GRC

- Condenser at tank top removed heat, along with copper leaves within MLI
- Thermal gradient btw cryocooler and tank was high--8K
- Heat removal relied on buoyancy of LH_2

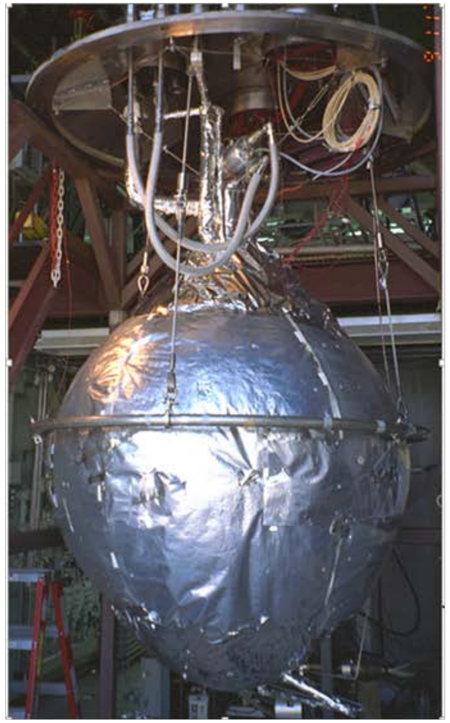


Figure 1. First LH2 ZBO test, 1998, NASA GRC.

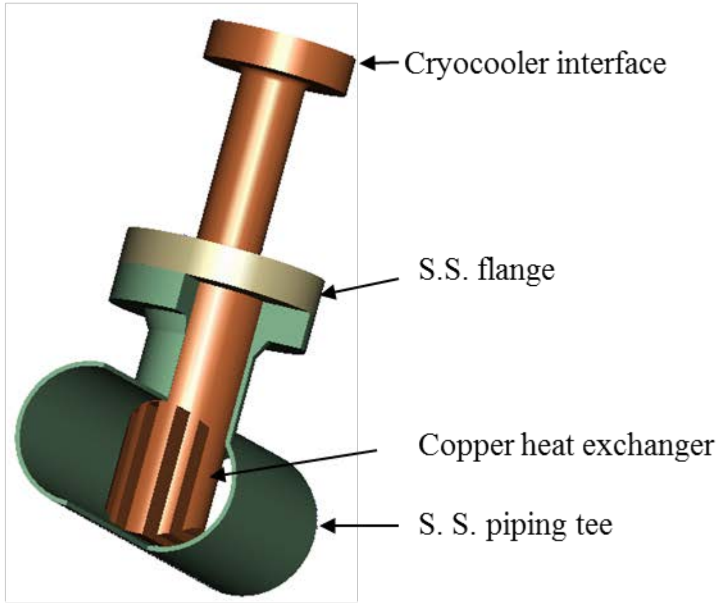


Figure 2. MSFC LH2 ZBO test heat exchanger design.

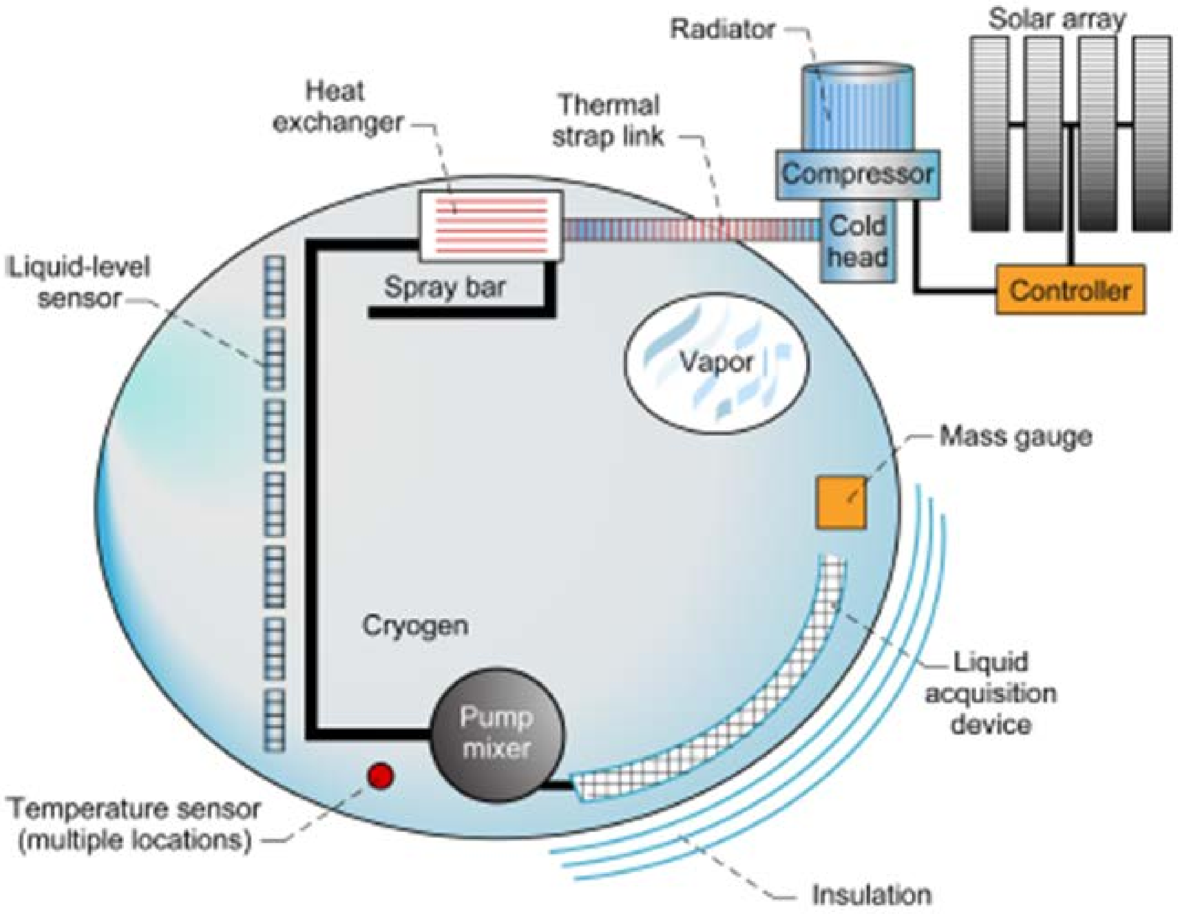
2001 test at MSFC

- Heat removed in recirculation loop at tank bottom
- While concept was not sensitive to gravity, integration issues were added heat of recirculation loop and heat from mixer, which required continuous operation

- *These tests provided a foundation for future developments*

2003 Advanced Development Test

- Figure shows schematic representation of preferred flight ZBO concept in 2003
- 2003 test at GRC
  - Flight-type cryocooler integrated with heat pipe
  - Cryocooler located close to tank at top
  - Issues were:
    - High thermal gradient between tank top and cooler (6.9K); expected to increase when cooler placed further from tank, as expected
    - Pump operation added heat



Distributed Cooling

- GRC design of distributed cooling began in 2007
  - Concept uses gas circulated across cryocooler heat exchanger and plumbed around tank and within MLI
- Ames analysis and bench testing proved heat exchanger designs
- 2009 test at Ball using broad area cooled shield, shown at right. Results showed:
  - High heat exchanger effectiveness
  - Insensitivity to slight flow imbalance in tubes
  - Temperature gradients between tubes were less than design indicated
    - MLI helped distribute cooling

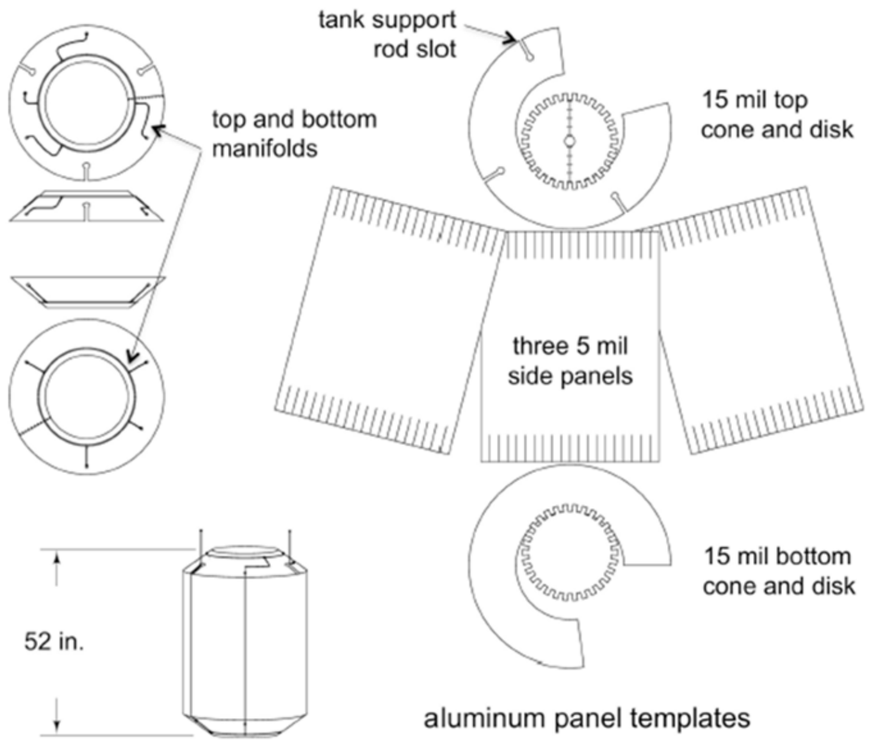


Figure 4. The broad area cooled shield, constructed from 1100 aluminum panels and cooled with three ¼" tubes.

Distributed Cooling Trade Study

- Following Ball test, NASA pursued comprehensive trade study of cryocoolers and circulators for:
  - LOX ZBO/liquid hydrogen RBO demonstration under CPST
  - Extensibility for flight via scaling/sizing
- Reverse turbo-Brayton cycle (RTBC) was selected
  - Working fluid could be used to directly cool tank
  - Cryocooler specific mass and power improves with larger lifts, critical to ZBO application
  - RTBC includes very efficient circulator
    - Circulator options considered (see table)
    - Heat leak to fluid and anticipated heat exchanger loss from integration of cold finger to circulator were important factors

Manufacturer	Mass, kg	TRL[a]	Input power, W	Heat Leak to fluid, W	Fluid	Phase, Φ	Motor temp., K	Flow, g/s	Press., atm
CryoZone Ciezo	N/A	5	N/A	4	He	Gas (cold)	85	0.6	21
Sierra Lobo He blower	1	4	0.28	.14	He	Gas (cold)	85	.57	20
Creare NICMOS circulator	1	9	.89	.6	Ne	Gas (cold)	80	.75	3
CryoZone Noordenwind CryoFan	N/A	5	.6	N/A	He	Gas (hot)	300	.57	21
Aerojet He gas circulator	3.5	5	2.8	2.0	He	Gas (cold)	150	.8	20
Barber-Nichols	N/A	4	71	44.9	He	Gas (cold)	90	41.8	27
Sierra Lobo piston	1	3	.01	.001	N_2	Liquid (2-Φ)	85	.13	2
Lawrence Lab bellows linear	4.5	3	16.5	5.0	He	Liquid (2-Φ)	4.5	40	4
Mikrosysteme 2-phase	N/A	4	.1	.0	Ar	Liquid (2-Φ)	120	.3	12

[a]Technology readiness level.

Reduced Boil-Off Tests (RBO) Conducted

- Using Creare RTBC cryocooler with distributed cooling on tank, NASA MSFC, Ames, and GRC combined efforts to complete Reduced Boil-Off LH2 tests and ZBO LN2 tests
  - Tube on shield heat exchanger used
  - Where cooled was used, boil-off was reduced 60%
  - MLI heat leak under 90K shield was higher than expected
    - Cause of issue remains unsolved
  - Penetration conduction (plumbing and struts) heat was reduced by 67%

Figure 5. The NASA SMiRF test rig used in RBO and ZBO testing.

Zero Boil-Off (ZBO) Tests Conducted

- Same cryocooler was used to achieve robust tank pressure control of LN_2 without venting
- Tube-on-tank heat exchange used
- RTBC Cryocooler cycle is shown on right
- Cryocooler achieve ZBO at high and low fill levels
- Cryocooler (at ZBO condition) dropped thermal gradient in fluid from 10.2 to 3.8K
- As power to cryocooler was increase, cryocooler decreased tank pressure
  - Graph shows that pressure rise/decay rates vs. net heat
  - Data agrees with homogenous model, showing distributed cooling effectively de-stratified cryogen
  - Testing validated Cryo Analysis Tool and Scaling Study

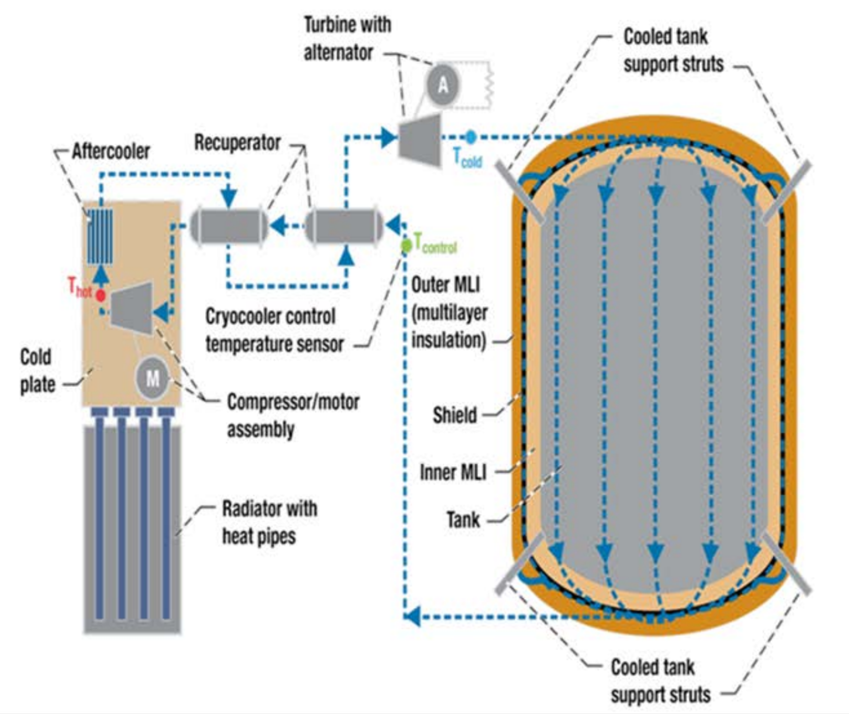


Figure 6. Schematic of the reverse turbo-Brayton cycle cryocooler

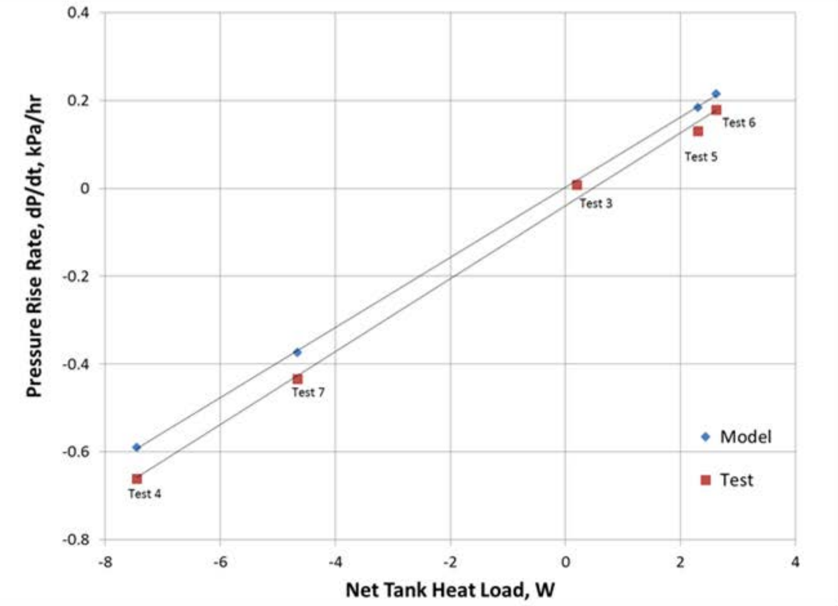
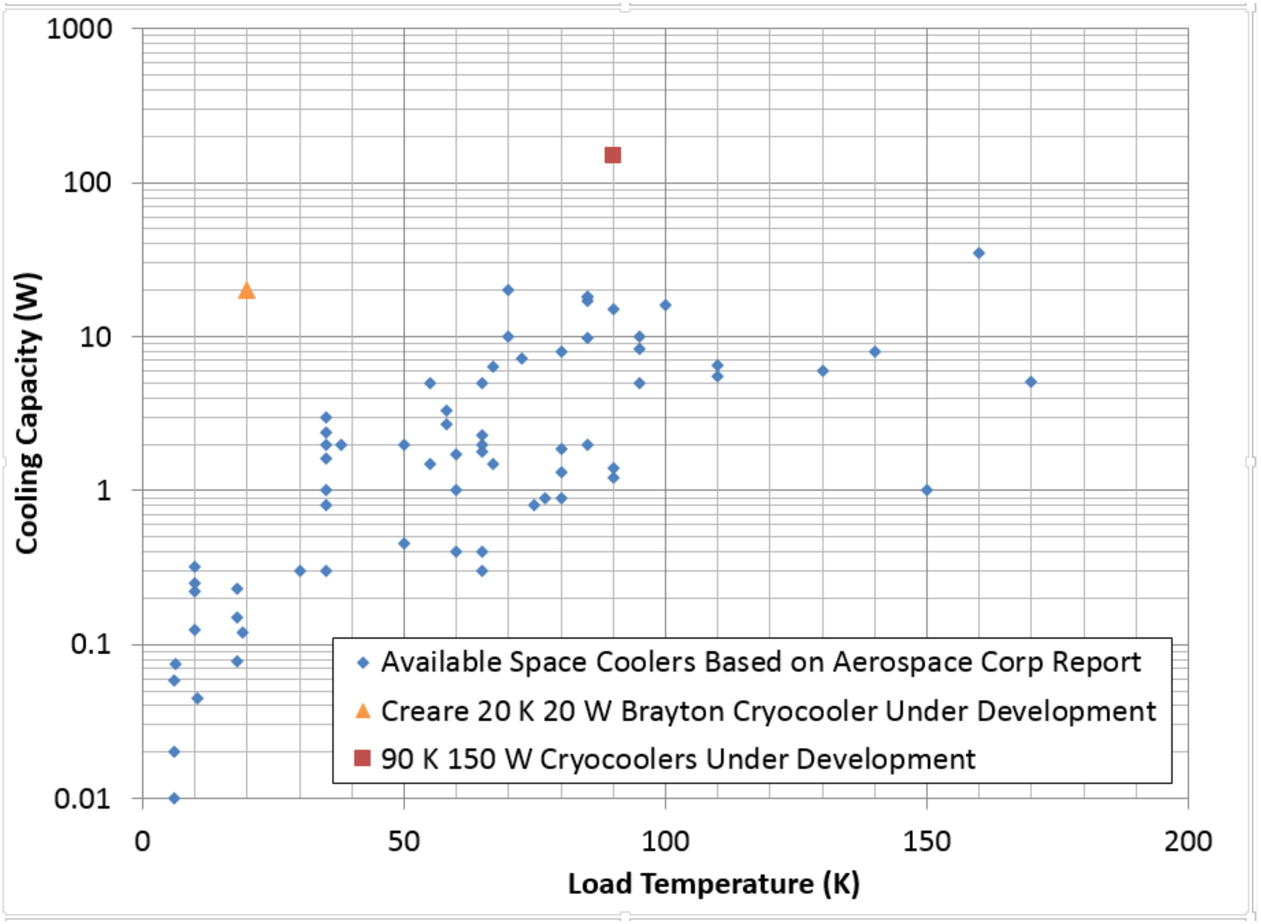


Figure 7. Tank pressurization sensitivity to net tank heat.

Extension to NASA's Missions

- NASA's Mars Study Capabilities Team is studying propulsion options for human missions to Mars
- Applications for ZBO are:
  - Nuclear Thermal Propulsion Stages
  - In-space chemical propulsion stages, LO_2 and LCH_4
  - Liquefaction of LO_2 on Mars surface from In-Situ Resources
- Cryocooler requirements are over 20W at 20K and ~150W at 90K
  - Both requirements are substantially greater than that available
  - NASA is directing technology investments to advance the state-of-art through the SBIR program



20K-20W Program

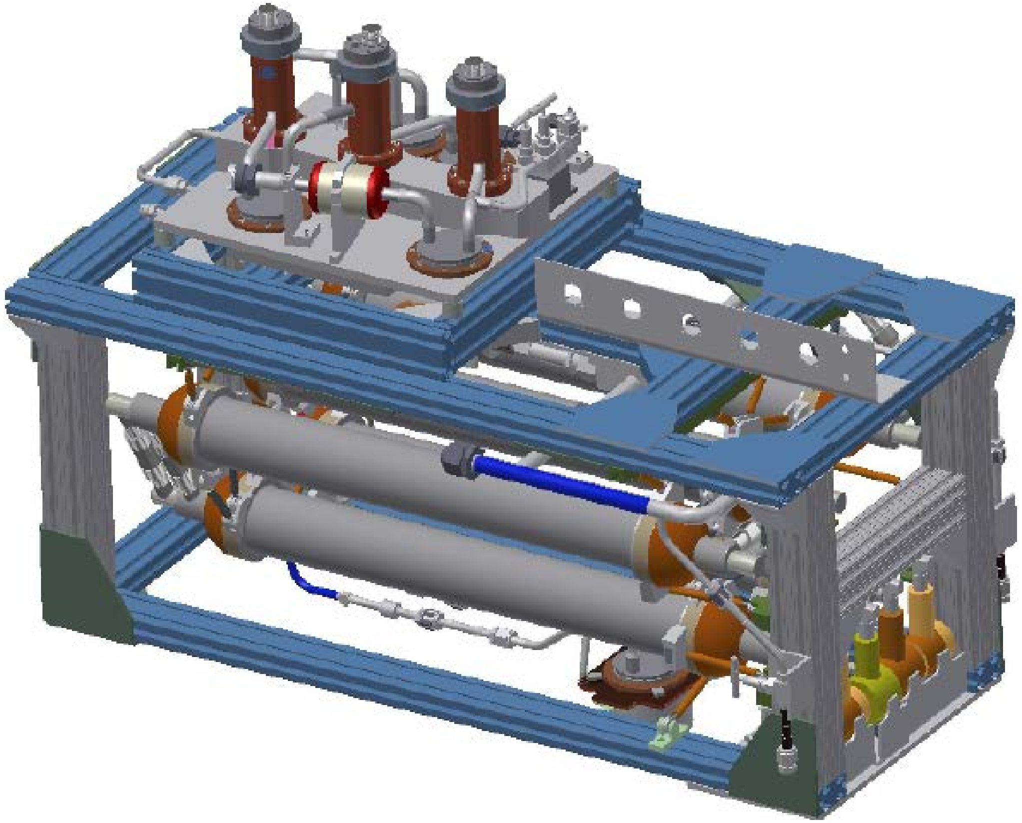


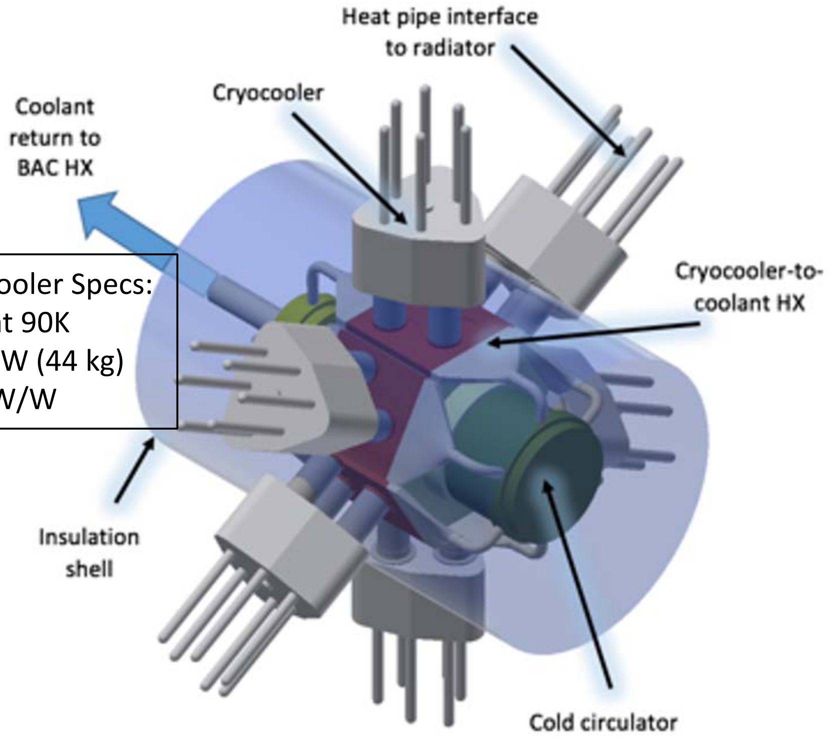
Figure 9. The assembled 20K-20W cryocooler installed into the bottom section of the vacuum bell jar, in preparation for testing.

Key Performance Parameter	State-Of-The-Art	Contract Threshold	Contract Goal	As-Delivered	Flight
Cryocooler Lift at 20 K	1 W	17 W	20 W	20 W	20 W
Compressor Speed	N/A	N/A	N/A	6,600 rev/s	6,380 rev/s
Cryocooler Input Power	N/A	N/A	N/A	1,800 W	1,420 W
Specific Power	370 W/W	80 W/W	60 W/W	90 W/W	71 W/W
Cryocooler Mass (flight like)	N/A	N/A	N/A	N/A	106 kg
Specific Mass (flight like)	18.7 kg/W	5.5 kg/W	4.4 kg/W	N/A	5.3 kg/W

90K-150W Program

- Two Phase II SBIRs are underway
  - Converter Source
  - Creare
- Results of Phase I concept development

Converter Source Cryocooler Specs:
- 180W Refrigeration at 90K
- Specific Mass .31 kg/W (44 kg)
- Specific Power 10.3 W/W



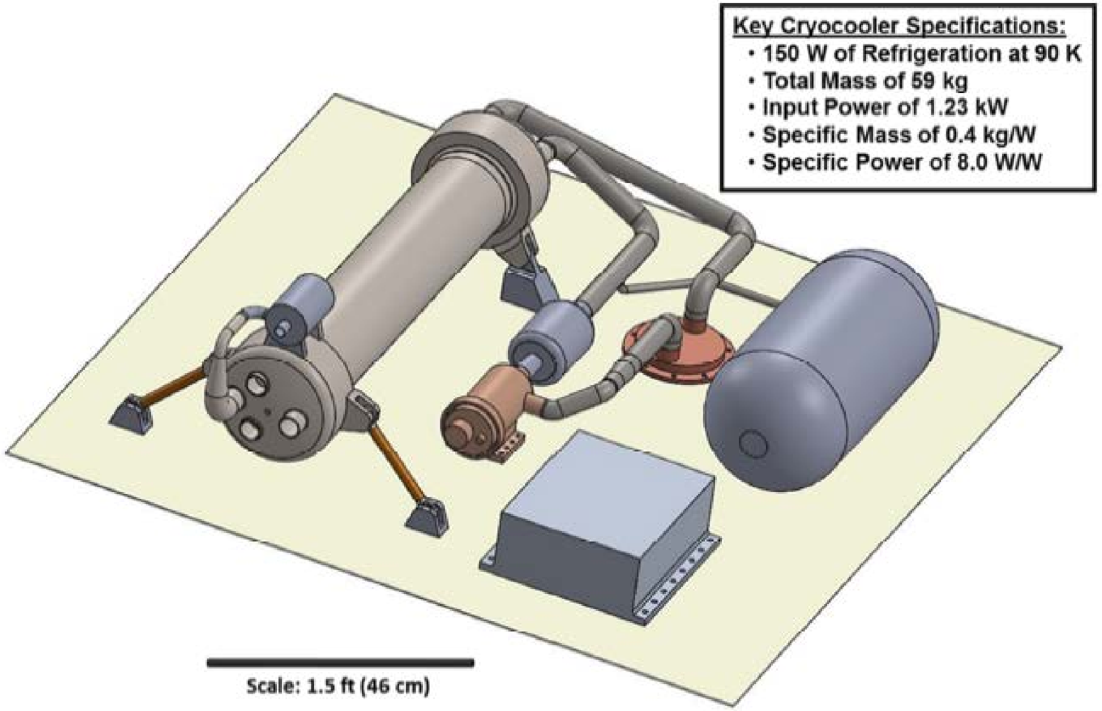


Figure 2. Creare's Preliminary Design of a 90 K, 150 W Cryocooler for Liquid Oxygen Storage

Recommended Related Developments

- Optimized thermal/structural design of NTP stage
  - Structural heat leak for tank skirt remains unknown
  - Fluid system design must be configured, sized, and heat loads estimated
- Further development of high capacity 90 K cryocoolers
- Additional testing:
  - NASA characterization and endurance test of 20K-20W Cooler
  - Vibration testing of 20K-20W
  - LH2 ZBO test with two stages of cooling
- Summary—NASA developments in ZBO technologies has evolved, with focus on distributed cooling, 20K and 90K coolers, and optimized vehicle design.