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 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 LH₂

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
• 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 3/4” tubes.
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

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Mass, kg</th>
<th>TRL</th>
<th>Input power, W</th>
<th>Heat Leak to fluid, W</th>
<th>Fluid</th>
<th>Phase, ( \Phi )</th>
<th>Motor temp., K</th>
<th>Flow, g/s</th>
<th>Press., atm</th>
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<tbody>
<tr>
<td>CryoZone Ciezo</td>
<td>N/A</td>
<td>5</td>
<td>N/A</td>
<td>4</td>
<td>He</td>
<td>Gas (cold)</td>
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<td>Creare NICMOS circulator</td>
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<tr>
<td>Aerojet He gas circulator</td>
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<td>5</td>
<td>2.8</td>
<td>2.0</td>
<td>He</td>
<td>Gas (cold)</td>
<td>150</td>
<td>0.8</td>
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<td>Barber-Nichols</td>
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<td>71</td>
<td>44.9</td>
<td>He</td>
<td>Gas (cold)</td>
<td>90</td>
<td>41.8</td>
<td>27</td>
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<tr>
<td>Sierra Lobo piston</td>
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<td>0.01</td>
<td>0.001</td>
<td>N(_2)</td>
<td>Liquid (2-(\Phi))</td>
<td>85</td>
<td>0.13</td>
<td>2</td>
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<tr>
<td>Lawrence Lab bellows linear</td>
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<td>3</td>
<td>16.5</td>
<td>5.0</td>
<td>He</td>
<td>Liquid (2-(\Phi))</td>
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<td>40</td>
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<tr>
<td>Mikrosysteme 2-phase</td>
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<td>0.1</td>
<td>0</td>
<td>Ar</td>
<td>Liquid (2-(\Phi))</td>
<td>120</td>
<td>0.3</td>
<td>12</td>
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*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 LN₂ 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.
• 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, LO₂ and LCH₄
  • Liquefaction of LO₂ 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

![20K-20W Diagram](image)

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

<table>
<thead>
<tr>
<th>Key Performance Parameter</th>
<th>State-Of-The-Art</th>
<th>Contract Threshold</th>
<th>Contract Goal</th>
<th>As-Delivered</th>
<th>Flight</th>
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<tr>
<td>Cryocooler Lift at 20 K</td>
<td>1 W</td>
<td>17 W</td>
<td>20 W</td>
<td>20 W</td>
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<td>Compressor Speed</td>
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<tr>
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<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Specific Power</td>
<td>370 W/W</td>
<td>80 W/W</td>
<td>60 W/W</td>
<td>90 W/W</td>
<td>71 W/W</td>
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<tr>
<td>Cryocooler Mass (flight like)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>106 kg</td>
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<tr>
<td>Specific Mass (flight like)</td>
<td>18.7 kg/W</td>
<td>5.5 kg/W</td>
<td>4.4 kg/W</td>
<td>N/A</td>
<td>5.3 kg/W</td>
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</tbody>
</table>
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
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.