Cryogenic Boil-Off Reduction System Testing

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Introduction

• Liquid hydrogen (LH$_2$) and oxygen (LO$_2$) are highly efficient propellants
  – Upper stages utilizing LH$_2$ and LO$_2$ are competitive in mission architecture studies for upper stages and depots
  – Low LH$_2$ and LO$_2$ boiling points, however, mean they boil-off propellant in low Earth orbit
    • Extra propellant must be tanked and launched from Earth

• Reducing boil-off requires good insulation
  – Multi-layer Insulation (MLI) used

• For long duration missions, however, active refrigeration of propellant tanks is being considered
Potential NASA Uses for Boil-Off Reduction System

**NASA** is developing capabilities to take exploration crews beyond low Earth orbit (LEO).
Needs and Goals

• Need:
  • Enable long-term cryogen storage for future exploration missions beyond Earth’s orbit
  • Validate cryogenic boil-off reduction system (CBRS) scaling study that predicts this system reduces mass after just several weeks loiter in low Earth orbit

• Goal:
  – Efficiently reduce or eliminate tank boil-off
    • Determine integrated system performance
    • Validate system model
Cryogenic Boil-Off Reduction System

- Uses a cryocooler to transfer heat from propellant tank to reduce or eliminate cryogen boil-off
  - Primary application is LH$_2$ and LO$_2$ storage
- Incorporating existing 90 K cryocoolers that can substantially reduce propellant boil-off
  - Similar to a vapor cooled shield, but coupled with a cryocooler
  - Cool struts and plumbing in addition to insulation system
- Lack of large scale 20 K class cryocoolers limits current availability to achieve zero boil-off with liquid hydrogen

LH$_2$ tank show with integrated reduced boil-off system
CBRS Background/Definitions

- NASA has been developing two approaches
  - For LH2 Reduced Boil Off (RBO) propellant storage applications,
    • A tube-on-shield approach is used where a tubing loop is attached to a aluminum sheet embedded in the propellant tank Multi-Layer Insulation (MLI)
    • Integrates existing flight-type warmer temperature cryocoolers (e.g. 90K) to intercept some of the heat before it reaches the tank
  - For LH2 Zero Boil Off (ZBO) propellant storage applications,
    • A tube-on-tank approach is used with the tubing loop attached directly to the outer tank wall of the propellant tank.
    • Unfortunately, at this time there are no flight-type cryocoolers available that remove heat at 20K with sufficient heat removal capacity to be useful for LH2 Zero Boil Off (ZBO) propellant storage applications
  - For LO2 ZBO tube-on-tank approach integrating existing flight-type warmer temperature cryocoolers can be used
Key Technology Developments

- Demonstrate the low loss integration of a reverse turbo-Brayton cycle cryocooler with a propellant tank to reduce and eliminate boil-off
  - Demonstrate ability to control tank pressure using active cooling system.
- Determine the tank applied self-supporting multi-layer insulation (SS-MLI) performance
  - Uses polymer spacers to maintain layer separation
  - Can reduce heat leak through the insulation system
- Its advantages over conventional MLI include:
  - Improved thermal performance per layer
  - Estimated lower fabrication and installation cost
  - More predictable and repeatable performance
RTBC Cryocooler Layout

- Turbo Alternator
- Recuperators
- Compressor
- Aftercooler
- Aluminum mounting structure
- Radiator mounting plate

Flight heritage cryocooler design, evolved from NICMOS.
Test Program

- Tests conducted at NASA Glenn SMiRF in vacuum chamber with cryoshroud providing LEO temperature.
- Three test series, all with 1.2 m dia 1.4m³ tank, with same reverse turbo-Brayton cycle cryocooler and heat pipe radiator

**Test Series 1**
- LH₂ test with 60 layers of traditional MLI used
- Cooled shield located after 30 layers of MLI

**Test Series 2**
- LH₂ test with 30 layers of traditional MLI over shield
- Inner MLI was 18 layers of SS-MLI

**Test Series 3**
- ZBO tube-on-tank test with 75 layers of traditional MLI

Cross-sectional view of Test Series 2 insulation
Key Components and Heat Paths

Q_{inlet} = \text{inlet line heat path}

Q_{outlet} = \text{outlet line heat path}

Q_{man,inlet} = \text{inlet manifold heat path}

Q_{man,outlet} = \text{outlet manifold heat path}

Q_{struts} = \text{strut heat path}

Q_{strap} = \text{strap heat path}

Q_{fill} = \text{fill line heat path}

Q_{vent} = \text{vent line heat path}

Q_{nipple} = \text{instrumentation nipple heat path}

Q_{heater} = \text{tank wall heater heat path}

Q_{bac} = \text{BAC line heat path}

Q_{probe} = \text{capacitance probe heat path}

Q_{wires} = \text{instrumentation wiring heat path}

Q_{rake} = \text{diode rake heat path}

Not shown:
- MLI \( Q_{MLI} \)
- diode rake \( Q_{rake} \)
- capacitance probe \( Q_{probe} \)
- instrumentation wiring \( Q_{wires} \)
- cryocooler \( Q_{cc} \)

• penetration heat leak
  \[ Q_{pen} = Q_{vent} + Q_{fill} + Q_{struts} + Q_{nipple} \]

• instrumentation heat leak
  \[ Q_{instr} = Q_{rake} + Q_{wires} + Q_{probe} \]

• total heat load on tank (tank thermal balance)
  \[ Q_{tank} = Q_{MLI} + Q_{pen} + Q_{instr} + Q_{heater} - Q_{bac} \]

• total heat load on cryocooler (cryocooler thermal balance)
  \[ Q_{cc} = Q_{bac} + Q_{strap} + Q_{par} \]

• parasitic heat load on cooling loop
  \[ Q_{par} = Q_{inlet} + Q_{man,inlet} + Q_{man,outlet} + Q_{outlet} \]

\[ Q_{man} = Q_{man,inlet} + Q_{man,outlet} \]
## Test Data

<table>
<thead>
<tr>
<th></th>
<th>CBRS I</th>
<th>CBRS II</th>
<th>ZBO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cooler Off</td>
<td>Cooler On</td>
<td>Heat or Boil-Off (%) Reduction</td>
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<tr>
<td>BO*</td>
<td>3.87</td>
<td>2.03</td>
<td>48%</td>
</tr>
<tr>
<td>MLI</td>
<td>2.04</td>
<td>0.79</td>
<td>61%</td>
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<tr>
<td>Vent</td>
<td>0.09</td>
<td>0.11</td>
<td>-22%</td>
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<tr>
<td>Fill</td>
<td>0.38</td>
<td>0.19</td>
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<tr>
<td>Struts</td>
<td>0.604</td>
<td>0.23</td>
<td>62%</td>
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<tr>
<td>Capacitance Probe</td>
<td>0.21</td>
<td>0.21</td>
<td>0%</td>
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<tr>
<td>Penetration Integration</td>
<td>0.34</td>
<td>0.34</td>
<td>0%</td>
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<tr>
<td>Standoffs</td>
<td>0.12</td>
<td>0.05</td>
<td>58%</td>
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<tr>
<td>Instrumentation</td>
<td>0.1</td>
<td>0.1</td>
<td>0%</td>
</tr>
<tr>
<td>Instr. port</td>
<td>0.13</td>
<td>0.13</td>
<td>0%</td>
</tr>
<tr>
<td>non-cooled heat</td>
<td>0.65</td>
<td>0.65</td>
<td>0%</td>
</tr>
<tr>
<td>Cooled items</td>
<td><strong>3.114</strong></td>
<td><strong>1.32</strong></td>
<td><strong>58%</strong></td>
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<tr>
<td>Q lift</td>
<td>13.2</td>
<td></td>
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<tr>
<td>Q BAC</td>
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<tr>
<td>Q struts</td>
<td>1.21</td>
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<tr>
<td>Q parasitic</td>
<td>6.17</td>
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<td>Q compressor</td>
<td>245</td>
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</table>

*Thermal acoustic oscillation heat removed*
Summary of Results

- First of its kind demonstration of flight heritage reverse turbo-Brayton cycle cryocooler integrated with broad area cooled shield to reduce boil-off of a LH2 storage tank
- Cooling loop flow and BAC shield thermal losses were lower than expected
- Boil-off % reduction was less than expected (48% measured vs. 60% predicted for test 1)
  - Where cooling was used, tank heat leak was reduced by 60%
  - Model configuration differed slightly from as-built test
- Inner MLI heat leak was reduced with SS-MLI, but still higher than expected
  - Low warm (90K) temp boundary conditions of both inner MLI concepts had higher than expected heat
  - Models do not work over this temperature range
  - Very little MLI data exists at these temps
  - Improved models require additional data
- Experienced Thermo-Acoustic Oscillations in hydrogen tank
Test Series 2- SS-MLI Performance

• SS-MLI reduced tank heat
  - Passive MLI heat was 1.46 W, reduced by 28% from Test I
  - Active MLI heat was 0.65 W
    • Improvement of 18% from RBO I
    • Both values were improvements over traditional MLI

• SS-MLI adequately supported the BAC shield
  - No movement or shifting of BAC noticed
  - Velcro supports were held intact on shield and tank foam
Test Series 3--Robust ZBO Demonstrated

- ZBO was easily achieved
- Robust tank pressure control using cryocooler system also demonstrated
- Testing established the pressurization rates vs net heat load into or out of the tank
  - With Cryocooler power increased 33% over that for ZBO, tank pressure dropped 1.4 psi over 22 hr period
- Model correlations show active system pressurization rates compare well with that of an isothermal system
- Tube-on-Tank system effectively prevented thermal stratifications within the tank while:
  - Being external to tank
  - Introducing minimal parasitic heat loads to tank with cooler off
Use of test data to help size propellant storage cryocoolers

- Goal: Find system Coefficient of Performance (COP) for tank applied broad area cooling systems
  - With improved insulation on cryocooler to BAC supply lines and on the manifold, \( Q_{\text{parastic}} = 1.5 \) W
    - This represents an 18% parasitic loss for active cooling of propellant tanks
      - 1.5 W/8.5W lift is 18% of cryocooler lift
    - Assume parasitic loss of 18% for integration of cryocoolers into propellant tanks
  - The system coefficient of performance is defined as:
    - \( \text{COP}_{\text{sys}} = \frac{Q_{\text{useful}}}{P_{\text{comp}}} \)
    - Find \( \text{COP}_{\text{sys}} \) for variety of LOX ZBO tank heat leaks by combining test data, CAT analysis, and that from Contract NNG12LN29P

<table>
<thead>
<tr>
<th>Tank Heat Leak</th>
<th>8.5 W</th>
<th>100 W</th>
<th>300 W</th>
<th>500 W</th>
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<tbody>
<tr>
<td>( Q_{\text{par}} )</td>
<td>1.5</td>
<td>18</td>
<td>54</td>
<td>90</td>
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<tr>
<td>( Q_{\text{useful}} )</td>
<td>7</td>
<td>82</td>
<td>246</td>
<td>410</td>
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<tr>
<td>( P_{\text{comp}} )</td>
<td>145</td>
<td>1046</td>
<td>2946</td>
<td>4810</td>
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<tr>
<td>COP system</td>
<td>4.8%</td>
<td>7.8%</td>
<td>8.4%</td>
<td>8.5%</td>
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</table>
Scalability

Updates based on cryocooler system data generated from LO$_2$ ZBO and LH$_2$ RBO testing have been integrated into NASA’s Cryogenic Analysis Tool

- Revisions from RBO testing were incorporated in tool and scaling study results last year
  - Updates were done on the radiator-cryocooler interface plate, cooling strap, cryocooler parasitics, and MLI below 90K
  - Impact: a slight increase in active cooling system mass is noted and shown in the figure, which moves the mission duration break even point for including LO$_2$ ZBO less than a day*

*Note, this is a simplified analysis and a more detailed analysis would be required to assist in the decision to include a LO$_2$ ZBO system in a future mission.

Conclusions

• Cryocooler and cryocooler integration hardware have been tested in first large surface area thermal test in simulated low-Earth orbit environment
  – Reverse turbo-Brayton cycle cryocooler performance was outstanding
    • Integrated circulation system had minimal losses
  – End-to-end system test was successful
    • Component performances were as expected except inner MLI
      – Reasons are not clear, however--
        » Little development work has been done for low-temperature (20-90K) MLI
        » MLI designs are straightforward and solutions are possible

• SS-MLI offers promise for space flight applications

• First successful test of distributed cooling system used to achieve ZBO
  – Controlled tank pressure using active cooling system.
  – Decreased tank pressure at controlled rate with cryocooler system operating at 33% excess capacity.
  – Testing indicates that internal tank mixer operation and its associated heat and risk may not be needed while operating ZBO systems

• ZBO Scaling Study effort was updated
  – Simplified approach for ZBO cryocooler sizing has been presented
  – Projected mass savings of RBO/ZBO has been confirmed
Questions?