Zero Boil Off System Testing

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Executive Summary

**Objectives**
- Advance technology to enable spaceflight systems capable of storing LOX in space with zero boil-off
  - Task funded by Space Technology Mission Directorate
- Conduct ground demonstration with active thermal control technologies to demonstrate ability to achieve LOX ZBO. Tank and structures (conductive heat paths) should be representative of designs for flight loads.
  - Validate design of tube-on-tank distributed cooling network at 95.6K

**Approach:**
- Integrate a reverse turbo-Brayton cycle cryocooler with a propellant tank to achieve zero-boil off LN2 storage (LOX surrogate) with low thermal and flow loss.
- Demonstrate ability to control tank pressure using active cooling system.

**Results:**
- An extensible and low-loss integrated design of distributed active cooling has been proven.
  - No loss propellant storage has been demonstrated with less than 4K thermal gradient, from top to bottom
  - Robust ability to control tank pressure demonstrated
Active Cooling Background/Definitions

- NASA’s future mission architecture’s cryogenic propellant based stages will require long duration in-space storage of LH₂ and LO₂
- Propellant losses due to solar insolation and planetary albedo for these long duration missions must be minimized to insure mission cost effectiveness and success
  - Analysis has shown that use of a cryocooler to “actively” cool the LO₂/LH₂ storage systems becomes the mass efficient approach for missions longer than a few weeks
- Following a NASA depot study, focus has been on Cryogenic Boil-Off Reduction System to cool large tank surface areas
  - 2007 study by Glenn and Ames
  - Bench testing at Ames
  - 2009 system test at Ball
  - 2011 trade study at Glenn
- Boil-off reduction is accomplished by distributed or broad area cooling (BAC)
  - A transport gas (typically neon or helium) is cooled by the cryocooler and then circulated through a tubing loop covering the outer surface area of the propellant tank
  - The transport gas efficiently distributes the cooling capacity of the cryocooler throughout the surface of propellant tank storage system
Objectives

• Three main objectives:
  – Demonstrate robust ZBO
    • Use the cryocooler to control tank pressure
    • Operate cryocooler over extended period of time
    • Use cryocooler to reduce tank pressure
    • Find if homogenous pressurization model can be accurately used
  – Eliminate boil-off at low fill levels
    • Condition will occur for in-space propellant depots and for multi-burn upper stages
    • Low fill level cryogenic tanks exacerbates tank stratification
  – Validate Scaling Study
    • Predicts ZBO inclusion reduces mass for loiter periods > week, when compared to MLI only, as used for cryogenic propellant storage
Facility and Hardware

- NASA GRC’s SMiRF
  - Low Earth Orbit thermal environment
    - Cryoshroud use to create 220 K background temperature
    - Diffusion pumps create average hard vacuum of $1 \times 10^{-6}$ torr
  - $\text{LN}_2$ as LOX surrogate
    - Assumed LOX propulsion requirement at 25 psi, 95.6 K
    - Pressurized $\text{LN}_2$ to 82 psi, 95.6 K
- Test article assembled to vacuum chamber lid
  - Ring supported from lid
    - Cryocooler, radiator, and tank supported from ring
  - Tank diameter 1.2 m, volume 1.2 m$^3$
  - Tank struts 0.38 m long, wall thickness 0.8 mm (.032”)
  - Radiator aluminum panel 4 mm thick, loop heat pipe design
<table>
<thead>
<tr>
<th>Location</th>
<th>Count</th>
<th>SD/TC</th>
<th>Notes – Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode Rake</td>
<td>8</td>
<td>8/0</td>
<td>Liquid temperature and liquid level indication. Key sensors at 96.9, 87.2, and 28.4 % full.</td>
</tr>
<tr>
<td>Tank Wall</td>
<td>13</td>
<td>12/1</td>
<td>Exterior tank temperatures at top, bottom, and between cooling loops.</td>
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<tr>
<td>BAC System</td>
<td>28</td>
<td>21/7</td>
<td>Measure BAC system temperatures (cooling tubes, manifolds, and thermal strap)</td>
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<tr>
<td>Penetrations</td>
<td>16</td>
<td>6/10</td>
<td>Two at warm and two at cold end of vent, fill/drain, and cap probe. Used for heat leak calc’s</td>
</tr>
<tr>
<td>Struts</td>
<td>26</td>
<td>2/24</td>
<td>Two at warm and two at cold ends. Heat leak calculations.</td>
</tr>
<tr>
<td>Radiator</td>
<td>25</td>
<td>0/25</td>
<td>Map radiator performance.</td>
</tr>
<tr>
<td>MLI</td>
<td>11</td>
<td>0/11</td>
<td>Determine MLI temperature profile.</td>
</tr>
<tr>
<td>Supports/cabling</td>
<td>12</td>
<td>0/12</td>
<td>Used to find misc. heat leak through wire bundles &amp; suspension hardware.</td>
</tr>
<tr>
<td>Cryoshroud</td>
<td>18</td>
<td>0/18</td>
<td>Boundary temperature definition and control.</td>
</tr>
<tr>
<td>Tank Pressure</td>
<td>2</td>
<td>NA</td>
<td>Measure and control tank pressure. Range of sensors were 0-50 and 0-100 psia.</td>
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<tr>
<td>Boil-off Flow</td>
<td>4</td>
<td>NA</td>
<td>Mass flowmeters used to measure boil-off rates</td>
</tr>
<tr>
<td>Tank/Strut Heaters</td>
<td>14</td>
<td>NA</td>
<td>Warm up tank, warm liquid, and set warm boundary temperature on struts</td>
</tr>
</tbody>
</table>

**Cryocooler Instrumentation:**

![Cryocooler Instrumentation Diagram]
Cryocooler and MLI

• Cryocooler: Creare reverse turbo Brayton cycle
  – Flight like design, based on the NICMOS cryocooler flown on Hubble
  – Integrated circulator for distributed cooling of neon at 2 g/sec, 2 atm
  – Capacity 15 W at 77 K

• Tank MLI
  – 75 layers of double aluminized Mylar
    • Traditional MLI design, 2 blankets 38 layers each
    • Seems butted and stich taped every 5th layer
  – 2 sheets of Dacron netting between Mylar layers
  – 1% perforations in outer 2-mil cloth reinforced Mylar
  – Layer density 24 layers/cm
Broad Area Cooling System

- Tube-on-tank design
  - ¼” tubes spot welded every foot
  - Tubes epoxied down length
  - Supply and return manifolds used at tank top to feed cooling loops
    - 5 loops run down tank wall
    - Spacing every 36 degrees around tank
    - No trim valves or orifices used
  - 4.2 m line length on tank
    - Cryocooler supply and return hoses 1 m long
    - 0.25 psi pressure drop
<table>
<thead>
<tr>
<th>Test</th>
<th>Fill Level</th>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>95%</td>
<td>Passive boil-off</td>
<td>Find tank heat leak</td>
</tr>
<tr>
<td>Test 2</td>
<td>95%</td>
<td>Passive Pressurization</td>
<td>Find tank pressure rise rate</td>
</tr>
<tr>
<td>Test 3</td>
<td>95%</td>
<td>ZBO</td>
<td>Achieve ZBO; collect data</td>
</tr>
<tr>
<td>Test 4</td>
<td>95%</td>
<td>ZBO high power</td>
<td>Find robustness of ZBO system</td>
</tr>
<tr>
<td>Test 5</td>
<td>95%</td>
<td>ZBO low power</td>
<td>More data to map pressurization rate with cooler power</td>
</tr>
<tr>
<td>Test 6</td>
<td>95%</td>
<td>ZBO destratification</td>
<td>Find tank pressure rise rate with tank heat added while at ZBO</td>
</tr>
<tr>
<td>Test 7</td>
<td>95%</td>
<td>ZBO high power 2</td>
<td>More data to map pressurization rate with cooler power</td>
</tr>
<tr>
<td>Test 8</td>
<td>25%</td>
<td>ZBO</td>
<td>Achieve ZBO; collect data</td>
</tr>
<tr>
<td>Test 9</td>
<td>25%</td>
<td>ZBO high power</td>
<td>More data to map pressurization rate with cooler power</td>
</tr>
<tr>
<td>Test 10</td>
<td>95%</td>
<td>Passive boil-off with cryoshroud set to 300K</td>
<td>Additional MLI data point for tank applied system</td>
</tr>
</tbody>
</table>
Component Results

• Broad Area Cooling
  – Dropped temperature gradient between tank top to tank bottom
    • Test 1—Passive—gradient was 10.2 K
    • Test 3 gradient was 3.8 K
  – Tube-to-tank thermal gradient was 0.5 K
    • More than expected, but heat exchanger effectiveness was 0.9
    • Loss caused ~ 0.5 W increase in cryocooler input power
  – Tube-to-tube gradient was insignificant
    • No noticeable change in 5 BAC tube temperatures
  – Structural and thermal optimization of tube-on-tank configuration is required for flight

• Cryocooler
  – Thermally, the cryocooler performed same as bench test
  – % of Carnot ranged from 10.6 for Test 3 and 12 for Test 4.
  – High power settings dropped tank pressure
    • Tank pressure changes were akin to a battery for storing cryocooler power
  – Integration and control remain a challenge
    • Control of power setting and pressure feedback loop required

• Parasitics
  – No design or model before test; average loss was 4.2 W
  – Poor performing Mylar tape on return manifold
    • Improved insulation projected to reduce parasitic to ~1.2 to 1.5 W
  – Flight configuration needed to design and model parasitic loss realistically
Revisiting Test Objectives

Objective 1: Demonstrate robust ZBO
- Cryocooler temperature setting used to control tank pressure to within +/- 0.1 psi
- Cryocooler operated over 19 day period
  - Cryo stored without venting
- High power settings used successfully to reduce tank pressure
  - Tank pressure dropped at rate consistent with uniform temperature pressurization model
- Tank pressurization rate dropped 88% with active cooling
  - Test 2 tank pressure increased 36.2 kPa (4.6 W heat)
  - Test 6 tank pressure increased 1.3 kPa (2.6 W heat added to ZBO tank via heaters)
    » \( \frac{dP}{dt}/W \) of tank heat leak dropped 88%

Objective 2: ZBO at low fill level
- High degree of stratification at low fill level did not affect cryocooler operation
  - Tank top temperature increased from 98.7 to 98.9 K
    » Much lower than Test 1, 105.2 K
  - Cryocooler input power slightly increased (0.6%) from full tank ZBO power level to achieve ZBO
Revisiting Test Objectives

- Objective 3: Validation of Scaling Study (Cryogenics, D. Plachta, 2014)
  
  - In study, in-space loiter time break even point determined
    - Break even point is duration when Passive mass, MLI + boil-off, equals Active mass, MLI + cryocooler + radiator + solar array
      - For LOX with 7.5 m tank, 186 m³, 318 tank heat loiter period break even point was 7.3 days
  
  - Many assumptions in study
    - Test data used to update Cryogenic Analysis Tool (CAT)
      - Most significant update was for parasitic loss
    - Dry mass increased 6.5%
      - Shifted break even point from 7.3 to 8 days
  
  - Test data confirms and validates predictions of scaling study
Summary

- First of its kind demonstration of robust tank pressure control using cryocooler system
  - No venting, no mixing
- Tank stratification was cut dramatically
  - Unvented/unmixed tank pressurization rate was cut, per Watt heat leak, by 88%
  - Homogenous tank pressurization model validated
  - Tank lid to tank bottom temperature gradient dropped from 10.2 to 3.8 K
    - Tank mixer not required when active cooling system is operational
- Full ability of cryocooler system demonstrated
  - Tank pressure controlled to +/- 0.1 psi
  - Cryocooler decrease tank pressure at controlled rates at different levels of excess capacity
    - High power cryocooler operation to drop tank pressure could eliminate or reduce in-space battery requirement
- Test has validated Scaling Study, predicting large mass savings for applying ZBO to cryo upper stages
- Test series advance technology readiness level
- Test has reduced risk for future flight projects