Reduced Boil-Off System Sizing

Monica C. Guzik, Glenn Research Center
David W. Plachta, Glenn Research Center
Jeffrey R. Feller, Ames Research Center

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Introduction

• NASA is developing capabilities to take exploration crews beyond Low Earth orbit (LEO)
  – Liquid hydrogen (LH2) and liquid oxygen (LOX) propellants provide highest efficiencies
  – Increased exploration necessitates longer mission durations
  – Due to its low boiling point, LH2 is difficult to store over long duration missions
Cryogenic Boil-Off Reduction Systems

• To increase mission duration capability, distributed cooling systems can be applied to intercept heat entering the propellant to achieve Reduced Boil-Off (RBO) or Zero Boil-Off (ZBO)

• RBO and ZBO can be achieved by utilizing a Broad Area Cooling (BAC) network of distributed tubing
  – For LH$_2$ RBO, a tube-on-shield approach is used, in which the BAC tubing is installed on a shield within the MLI
  – For LH$_2$ ZBO, a tube-on-tank approach is used with the BAC tubing installed directly on the tank surface
    • Due to the low efficiency and technical readiness of 20 K stage cryocoolers required for LH2 ZBO, the tube-on-shield concept is the lowest mass approach
NASA GRC Reduced Boil-Off Efforts

- Cryogenic Boil-Off Reduction System Testing occurred in 2012-2013 at NASA GRC
  - A 90 K stage Reverse Turbo-Brayton Cycle (RTBC) cryocooler was used in combination with a BAC network installed on a shield within the tank’s MLI layers
  - Two versions of MLI were tested beneath the BAC shield: traditional MLI, and self-supporting MLI (SSMLI)
  - Penetration elements were also cooled by the use of conductive cooling straps linked to the BAC tubing

Cryogenic Boil-Off Reduction System Concept

- Aftercooler
- Recuperator
- Cryocooler control temperature sensor
- Compressor/motor assembly
- Radiator with heat pipes
- Turbine with alternator
- Cooled tank support struts
- Outer MLI (multilayer insulation)
- Shield
- Inner MLI
- Tank
- Cold plate

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• In 2012, NASA performed an Active Thermal Control Scaling Study\(^2\) to determine how current ZBO and RBO thermal control concepts scale up to large applications

• Focus was on scaling the Cryogenic Boil-Off Reduction System Concept for the 2012/2013 testing to future missions

• Preliminary results were reported, but not linked to most recent test results

Potential Mission Savings with RBO

- For a large 8.4m diameter LH2 tank, it was shown that active thermal control begins to have a positive impact on mission mass savings after a loiter period of several weeks, with significant savings after 6 months\(^2\)
Sizing an RBO System for LH$_2$ Storage

- **Problem:** Present model iterates on RBO sizing, as part of a two stage cooling concept
  - No direct calculation of RBO stage was attempted
  - Data from RBO testing was used for validation
    - Broad Area Cooling shield data
    - Discrete cooling strap performance data
      - Conductive heat into the propellant tank liquid is intercepted at tank supports, piping and electrical penetrations
      - High conductivity straps from these tank penetrations are attached to BAC shield

- **Solution** enables mission designers to perform conceptual RBO design early in design process (prior to Mission Concept Review)
  - Requires ability to quickly size a system based on lowest number of mission-specific variables
  - A conductance-based model allows for rapid determination of heat leak and performance benefits without a detailed CAD geometry and thermal analysis
  - Sizing parameters for the RTBC cryocooler can be narrowed down to fractional pressure drop of the coolant loop and required heat lift
  - Heat leak entering tank can be used to directly size a 20K stage for ZBO
Heat enters the system primarily through the MLI and the penetrations, which include both structural and plumbing elements.

Heat leak entering the 90 K stage is a result of heat intercepted by the BAC shield within the MLI layers and heat entering the BAC tubing via cooling straps to the penetrations.

\[
Q_{90K} = Q_{mli,1} - Q_{mli,0} - Q_{stand-offs} + Q_{parasitic} + \sum_i Q_{pen,strap,i}
\]

\[
Q_{tank} = Q_{mli,0} + Q_{stand-offs} + \sum_i Q_{pen,0,i} + Q_{other}
\]
Quantifying MLI Heat Leak

- The Lockheed equation $4.55^3$ is well established as the baseline for calculating heat flux through an MLI blanket.
- Scale factors, which adjust the Lockheed Equation for inefficiencies in the MLI such as seams and installation defects, are an input to model.
- For MLI outside of BAC shield, Lockheed scale factor of 3.5 is assumed:
  - CBRS I and II had Lockheed scale factors of 4 and 3 for outer MLI.
  - LOX ZBO testing has Lockheed scale factor of 4, with 220 K shroud.
  - MLSTC testing had Lockheed scale factor of 5.2 with 250 K shroud.
- Due to the need to support the BAC shield as well as the MLI above it, self-supporting MLI (SSMLI) was selected for use between the shield and the tank:
  - It is simpler to predict SSMLI heat flux using a layer-by-layer model due to its uniformity between layers.
  - CBRS testing shows that, for SSMLI supporting a BAC shield, a scale factor of 3.0 should be applied to the heat flux:
    - Test results for “passive” had scale factor of 2.
    - Test results for “active” had scale factor of 5.5; Mylar emissivity is likely the problem.
      - Follow on MLI calorimeter work from 20-90K will better understand emissivity issue.

Quantifying Strap Resistance

- A conductive strap can be used to intercept heat from a penetration element and direct it into the BAC system manifold.
- Based on CBRS testing, a strap resistance of 10 K/W is recommended:
  - Testing showed a strap resistance between 4.5 and 12.0 K/W, dominated by the contact resistance at the tank attachment points.
  - With further bench testing and better controlled clamp attachment procedures, 5 K/W is assumed for each clamp to get an overall strap resistance of 10 K/W.

\[
Q_{pen,1} = \left(\frac{A}{L}\right)_{pen} \times k_{pen} \times (T_2 - T_1)
\]

\[
Q_{pen,0} = \left(\frac{A}{L}\right)_{pen} \times k_{pen} \times (T_1 - T_0)
\]

\[
Q_{strap,pen} = \frac{(T_1 - T_{BAC})}{R_{strap,pen}}
\]

\[
Q_{strap,pen} = Q_{pen,0} - Q_{pen,1}
\]
Modeling Validation

- Results were compared to CBRS II test data results
- Recommended conductance values and scaling factors were used in place of actual test design

<table>
<thead>
<tr>
<th></th>
<th>Multi-Layer Insulation</th>
<th>Strut Supports (6 total)</th>
<th>Vent Line*</th>
<th>Fill/Drain Line</th>
<th>Totals**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model Results</td>
<td>Test Data</td>
<td>Model Results</td>
<td>Test Data</td>
<td>Model Results</td>
</tr>
<tr>
<td><strong>Heat leak Entering Intercept (W)</strong></td>
<td>4.44</td>
<td>4.26</td>
<td>1.10</td>
<td>0.96</td>
<td>2.03</td>
</tr>
<tr>
<td><strong>Heat Leak Entering BAC System (W)</strong></td>
<td>4.02</td>
<td>3.61</td>
<td>0.98</td>
<td>0.76</td>
<td>1.596</td>
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<tr>
<td><strong>Heat Leak Entering Tank (W)</strong></td>
<td>0.42</td>
<td>0.65</td>
<td>0.12</td>
<td>0.20</td>
<td>0.43</td>
</tr>
</tbody>
</table>

*The vent line was much colder than anticipated during test operation due to constant venting of cold GH2 vapor.

**Totals reflect only the components shown in the table, and do not include various heat sources such as instrumentation leads.
Sizing a 90K RTBC Cryocooler Stage

- Following a contracted study with Creare, Inc, general sizing correlations were developed for an RTBC cryocooler system
  - The 90 K cryocooler stage can be sized based on fractional pressure drop and required heat lift
  - For general sizing estimates where fractional pressure drop is unknown, a value of 0.01 is recommended.

\[
P_{input,DC} = 7.0667 \frac{\Delta p_{BAC}}{p_{inlet}} + 8.435Q_{BAC} - 14.83
\]
Sizing a 90K RTBC Cryocooler Stage

- Cryocooler system mass is the sum of the control electronics, cryocooler hardware, and structural support masses

\[ m_{\text{total}} = m_{\text{electronics}} + m_{\text{cooler}} + m_{\text{support}} \]

\[ m_{\text{cooler}} = 0.1773Q_{BAC} + 14.223 \]

\[ m_{\text{electronics}} = 0.0011Q_{BAC} + 6.3577 \]

\[ m_{\text{support}} = 0.0493(m_{\text{electronics}} + m_{\text{cooler}}) - 0.492 \]
Sample Results

- Results are shown for the CBRS test tank with recommended strap conductance and MLI scaling factors and a next-generation RTBC cryocooler. The fractional pressure drop is 0.01.

<table>
<thead>
<tr>
<th></th>
<th>No Active Cooling</th>
<th>Cooling With 90 K Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Leak Entering Tank (W)</td>
<td>4.72</td>
<td>1.17</td>
</tr>
<tr>
<td>Boil-Off Rate (kg/day)</td>
<td>0.93</td>
<td>0.23</td>
</tr>
<tr>
<td>Heat Leak Entering Cooler (W)</td>
<td>0</td>
<td>8.06</td>
</tr>
<tr>
<td>Cooler Input Power (W)</td>
<td>0</td>
<td>123.8</td>
</tr>
<tr>
<td>Cryocooler Mass (kg)</td>
<td>0</td>
<td>22.8</td>
</tr>
<tr>
<td>Heat Rejection Required (W)</td>
<td>0</td>
<td>132.1</td>
</tr>
</tbody>
</table>
Conclusions

• Using CBRS test data, BAC and discrete cooling heat exchanger relationships were developed
• From those relationships, a conductance model was created for a mission designer to size a 90 K active thermal control stage
• For extended duration missions, the addition of a 90 K active thermal control stage may significantly reduce propellant tank boil-off losses
• Use of a 90 K stage greatly reduces the burden of heat lift--and associated power and mass--for the less efficient 20 K stage in the case of LH2 ZBO