Liquid Acquisition Device Hydrogen Outflow Testing on the Cryogenic Propellant Storage and Transfer Engineering Design Unit

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Cryogenic Propellant Storage and Transfer (CPST) mission and the EDU

- CPST was being developed by NASA under the Space Technology Mission Directorate to demonstrate cryogenic fluid management technologies (storage, liquid acquisition, transfer, gauging) in space for up to 3 months.
- An Engineering Development Unit (EDU) was built to provide a “Proof of Manufacturability” for the Flight Article.
- The Flight article was not built due to reformulation of the project at the direction of the STMD office.
- Ground based LH2 testing of the EDU was completed.
- This talk focuses on the liquid acquisition device data.
Screen channel Liquid Acquisition Device

• Construction
  - U-shaped channel; open side is covered with stainless steel screen
  - Screen side faces tank wall
  - Wetted screen pores allow liquid to pass through, but prevent vapor ingestion up to the bubble point pressure, $\Delta P_{BP}$

  \[
  \Delta P_{BP} = \frac{4\gamma}{D_P}
  \]

  $\gamma$, surface tension
  $D_P$, effective pore diameter

• Advantages
  - Screen channel LAD’s support higher flow rates
  - More robust against adverse accelerations (spacecraft maneuvers)
  - Can be characterized to some degree in 1g

• Disadvantages
  - Complex construction
  - LAD channel not easily refilled in presence of non-condensable pressurant gas

Dutch twill weave, 325 x 2300 weaves/inch
EDU test article

Aluminum tank 67” x 91”

- LH2 testing conducted at MSFC TS-300
- 20 days of testing to quantify performance of various subsystems (6/12/14 – 7/1/14)
EDU liquid acquisition device (LAD) design

- 325 x 2300 screen channel gallery arms (based on seam welding capability)
- LAD arms extended only to the top of the storage tank barrel
- Three (3) different LAD configurations to determine the best method for mitigating heat transfer into LAD arms
  - Bare LAD; +TVS conditioning (did not function); + Foam insulation
In 1g, the screen channel LAD can support a liquid filled vertical column up to some height, $H_{\text{max}}$

$$H_{\text{max}} = \frac{\Delta P_{BP}}{(\rho_L - \rho_V)g} = \frac{4\gamma}{(\rho_L - \rho_V)gD_P}$$

For the 325x2300 screen mesh used in these tests, $D_P = 14.0$ microns

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$\gamma/\Delta \rho$ (m$^3$/s$^2$)</th>
<th>$H_{\text{max}}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>2.77 E-5</td>
<td>0.81</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1.16 E-5</td>
<td>0.34</td>
</tr>
<tr>
<td>Methane</td>
<td>3.16 E-5</td>
<td>0.92</td>
</tr>
</tbody>
</table>

• LAD screen “breakdown” happens when the pressure exceeds the bubble-point pressure (e.g., $H > H_{\text{max}}$) and vapor is ingested.

• Fluid flow creates additional pressure drop (decreasing H)
LAD Manufacturing

Curved Arm Perforated Plate/Screen Assembly

Screen Side – LAD Straight Sections

Back Side – LAD Straight Sections

LAD’s were bubble-point tested to 0.8 psid in IPA prior to integration.
LAD assembly and installation

Connection to tank outlet

Integrated into tank shell
Tank fill/drain operation

- The excerpt from the CPST EDU Schematic Rev B below shows the fill/drain flow path.
- All storage tank fill and drain operations are through the LADs. There is not an alternate path for either fill or drain operations.
LAD silicon diode sensors (Temperature, wet-dry)

LAD Arm 2

- **Screen Diode** D4437
- **Internal Diode** D4441

LAD Arm 3

- **Internal Diode** D4438
- **Screen Diode** D4440

LAD Arm 4

- **External Diode** D4439
- **Screen Diode** D4442

Diode Not Functional for LH2 Test

Diodes Shown in Picture

<table>
<thead>
<tr>
<th>Station Level</th>
<th>Fill Level</th>
<th>Distance from Tank Bottom</th>
<th>180 Degree Arm</th>
<th>90 Degree Arm</th>
<th>0 Degree Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td>68.7%</td>
<td>85.2&quot;</td>
<td>D4413</td>
<td>D4414</td>
<td>D4415</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>66.7%</td>
<td>80.2&quot;</td>
<td>D4416</td>
<td>D4417</td>
<td>D4418</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>58.3%</td>
<td>77.3&quot;</td>
<td>D4419**</td>
<td>D4420</td>
<td>D4421</td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>43.7%</td>
<td>76.4&quot;</td>
<td>D4422</td>
<td>D4423</td>
<td>D4424</td>
</tr>
</tbody>
</table>
LAD testing and “breakdown”

- Tank is initially filled above 75% fill, completely submerging the LAD
- Tank level decreases due to boil-off and outflow tests
- LAD diodes are monitored to determine when gas has been ingested (“breakdown”)
- Tank is refilled to conduct more tests

- 68.7% internal LAD diode – when this diode goes dry, LAD is considered broken down.
- TBD minute hold at TBD% fill
- Predicted isothermal no-flow break down at 32% fill ($\Delta h = 0.81$ m), based on 325 mesh bubble-point data.
Silicon diodes are run “hot” (30 mA) when in wet-dry mode.

- The T reading during wet-dry mode is obviously not accurate. It is based on an DT-670 voltage vs T table (valid for 10 µA) extrapolated to negative temperatures.

- Different offsets in the transition value are due to lead resistance.

- This did not affect the analysis, which was done manually.
LAD test events

- Data was analyzed from the following test events:
  - Day 13, LAD outflow #1
  - Day 19, LAD outflow #2-4
  - Day 20, LAD outflow #5, 6

Day 19; Outflow tests 2-4
All three LAD arms break down between 44% - 46% fill level
Ullage temperature near LAD is 22.4K
(Top of LAD is at 75%; predicted isothermal, static breakdown is at 32% fill)
All three LAD arms break down between 67% - 70% fill level (foam-insulated LAD is last to breakdown)
Ullage temperature near LAD is 35 – 40 K
(Top of LAD is at 75%; predicted isothermal breakdown is at 32% fill)
LAD outflow tests #3 and #6, warm helium, shows similar result
All three LAD arms break down between 55% - 56% fill level (approaching and during the no-flow hold)
Ullage temperature near LAD is 23.5 K
(Top of LAD is at 75%; predicted isothermal, static breakdown is at 32% fill)
All three LAD arms break down between 45% - 47% fill level
Ullage temperature near LAD is 22.0K
<table>
<thead>
<tr>
<th>Test Day</th>
<th>Event</th>
<th>Liquid Level (%)</th>
<th>Holds</th>
<th>Pressure Source</th>
<th>Ullage Temp (K)</th>
<th>Ullage Pressure (psia)</th>
<th>Flow rate (GPM)</th>
<th>Column height at breakdown (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>LAD Outflow #1</td>
<td>45</td>
<td>N/A</td>
<td>AFT</td>
<td>22</td>
<td>32</td>
<td>9.7</td>
<td>57</td>
</tr>
<tr>
<td>19</td>
<td>LAD Outflow #2</td>
<td>68</td>
<td>N/A</td>
<td>FWD</td>
<td>35-40</td>
<td>32</td>
<td>12.4</td>
<td>13</td>
</tr>
<tr>
<td>19</td>
<td>LAD Outflow #3</td>
<td>67</td>
<td>N/A</td>
<td>FWD</td>
<td>35-40</td>
<td>32</td>
<td>12.5</td>
<td>15</td>
</tr>
<tr>
<td>19</td>
<td>LAD Outflow #4</td>
<td>55</td>
<td>5m @63% 5m@55%</td>
<td>AFT</td>
<td>24</td>
<td>32</td>
<td>9.8 to 0</td>
<td>38</td>
</tr>
<tr>
<td>20</td>
<td>LAD Outflow #5</td>
<td>45</td>
<td>30m@65% 5m@56%</td>
<td>AFT</td>
<td>22</td>
<td>23</td>
<td>7.3</td>
<td>57</td>
</tr>
<tr>
<td>20</td>
<td>LAD Outflow #6</td>
<td>68</td>
<td>N/A</td>
<td>FWD</td>
<td>32</td>
<td>23</td>
<td>7.9</td>
<td>13</td>
</tr>
</tbody>
</table>

- Warmer ullage temperature has adverse effect on breakdown height
- Warmer fluid at screen affects local surface tension

\[ H_{\text{max}} = \frac{\Delta P_{BP}}{(\rho_L - \rho_V)g} = \frac{4\gamma}{(\rho_L - \rho_V)gD_p} \]

- Flow through the screen also creates a pressure drop, which would further decrease the column height at breakdown (forward work)
- Warm pressurant may be OK if accompanied by a large reduction in \( g \)
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