KEA-144: Final Results of the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) Project

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• Questions
• In the 1950’s and 1960’s USAF and NASA requirements drove the development of large scale LH$_2$ systems
• Kennedy Space Center has not substantially changed its LH$_2$ hardware or processes since that time
• Inefficiencies lead to the loss of almost 50% of hydrogen purchased by SSC and KSC during the shuttle program
• Total Shuttle losses at KSC were calculated to be 24.6 M lbs of LH$_2$, or $59M based on 2016 prices
• Re-liquefiers have been proposed for LC-39 but never incorporated by KSC
• Some technology development work done with densified propellants but never incorporated by NASA
Zero Boil-Off (ZBO) History

- Zero boil off refers to the ability to store cryogens for indefinite periods with no losses.
- ZBO can be accomplished with re-liquefiers (use stored fluid as working fluid) or close cycle cryocoolers.
  - 1950’s: Industrial gas industry develops re-liquefiers for helium storage.
  - 1967: Air Products designs hydrogen re-liquefier for in-space use.
  - 1977: Martin Marietta proposes to incorporate a re-liquefier for use at LC-39 for upcoming Shuttle Program.
  - 1991: Energetics Inc proposes re-liquefier for LC-39 also capable of recovering tanker and chilldown losses.
  - 1999-2002: Space simulated ZBO testing at MSFC with commercial cryocooler, mixing pump, and axial jets.
  - 2000’s: Multiple trade studies and cryocooler development projects for in space ZBO.
  - 2002-06: ZBO testing using IRAS at Florida Solar Energy center.
  - 2004: ZBO testing at GRC using LN$_2$ and commercial cryocooler.
  - 2012-14: ZBO testing at GRC using flight like cryocooler and broad area cooling.
Densification History

- LH₂/LOX are the most energetic chemical propellants practical, but LH₂ suffers from low density and volumetric heat capacity.
- Hydrogen densification can be used to increase the liquid density and heat capacity.
- Densification can lead to a large increase in payload mass (15%).
- NASA/USAF has investigated use of densified LOX/LH₂ since the 1960’s:
  - 1960’s: National Bureau of Standards quantifies densified and slush hydrogen thermodynamic properties
  - 1977: Martin Marietta report on SSTO using densified LOX and LH₂
  - 1988-94: NASA X30 Slush Hydrogen Technology Program - large scale production, transfer and in-tank thermodynamics
  - 1995-97: LH₂ densification prototype system - 2 lb/sec rig tested at K-Site X33 RLV Precursor Demo
  - 1996: Hot fire ignition test of RL10B-2 engine with densified LH2 at Plum Brook B2
  - 1998: Demonstration of DLH₂ loading, hold and thermal stratification in a composite flight weight dual-lobe tank
  - 1997-2001: Design, build and test of large scale LOX & LH₂ propellant densification units for X-33/RLV flight
  - 2000: STA Tank Loading Tests w/GRC 30 lb/sec LOX PDU at GRC S40
  - 2001: LN₂ Performance Demo Tests w/GRC 8 lb/sec LH₂ PDU at GRC S40 (funding terminated before hydrogen testing)
  - 2001: Space shuttle performance enhancement study with propellant densification – 8 mo. multi-center effort
  - 2002-06: LH₂ densification to 15K using IRAS with Florida Solar Energy Center
  - 2002-03: 2nd GEN RLV Program -- funded three densification technology demonstrators (PHPK, Sierra Lobo, and LM/Praxair)
  - 2008: Design, fabrication & integration of a Cryogenic Propellant System capable of conditioning LCH₄ (GRC)
  - 2015: SpaceX using densified LOX, not to increase mass to LEO, but to enable reusability
Integrated Refrigeration and Storage (IRAS)

• Interface a cryogenic refrigerator to a liquid hydrogen storage tank via an internal heat exchanger
• Remove energy directly from the liquid to control bulk fluid
• Enables Zero Boil Off, Densification, and Liquefaction
• NASA and DoE funded small scale LH₂ IRAS proof of concept demonstration from 2002-06
• Exploration Technology Development Program funded IRAS Heat Exchanger characterization tests in 2008-09 as part of Cryogenic Fluid Management (CFM) Project
• Plans for ETDP large scale Integrated Refrigeration and Storage demonstration cancelled in FY10
GODU-LH2 Project

- HEOMD recognized the need and called for “Efficient ground-based systems for cryogenic fluid storage and transfer” in the 2012 AES PRG
- GODU-LH2 combined with Autonomous Command and Control development to submit the Integrated Ground Operations Demonstration Units (IGODU) proposal
- Proposal scored a 92 during evaluations and was described as a “Strong effort of actual hardware development and highly relevant tasks”

**Project Goal**
“Demonstrate cost efficient cryogenic operations on a relevant scale that can be projected onto future Spaceport architecture”

**Primary Objectives**
1. Demonstrate zero loss storage and transfer of LH$_2$ at a large scale.
2. Demonstrate hydrogen densification in storage tank
3. Demonstrate in situ hydrogen liquefaction
Site Build-Up
Site Build-Up

January 9th, 2013
Site Build-Up

January 13\textsuperscript{th}, 2014

November 2015

April 2014

January 2014
“Bird’s-eye View” of GODU-LH2 Site
Test Matrix and Timeline

- Completed Test Readiness Review on February 12, 2015
- First tanker offload occurred May 21, 2015
- Refrigerator contamination from October 2015 until March 2016
- Compressed testing from March 2016 until October 2016

<table>
<thead>
<tr>
<th>Test</th>
<th>Start Date</th>
<th>End Date</th>
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<tbody>
<tr>
<td>Chilldown</td>
<td>4/9/2015</td>
<td>5/21/2015</td>
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<tr>
<td>Tanker 1 Offload</td>
<td>5/21/2015</td>
<td>5/29/2015</td>
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<tr>
<td>Tanker 3 Offload</td>
<td>8/3/2016</td>
<td>8/12/2016</td>
</tr>
<tr>
<td>33% Boil Off</td>
<td>5/29/2015</td>
<td>6/19/2015</td>
</tr>
<tr>
<td>66% Boil Off</td>
<td>5/6/2016</td>
<td>5/31/2016</td>
</tr>
<tr>
<td>100% Boil Off</td>
<td>8/14/2016</td>
<td>8/24/2016</td>
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<tr>
<td>33% ZBO (Press Control)</td>
<td>4/25/2016</td>
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<tr>
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<td>6/21/2016</td>
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<td>9/6/2016</td>
</tr>
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<td>33% ZBO (Temp Control)</td>
<td>6/23/2015</td>
<td>7/13/2015</td>
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<td>33% ZBO (Duty Cycle)</td>
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<td>33% Densification</td>
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<td>7/22/2016</td>
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Zero-Loss Tank Chilldown Test Results

- **Initial Conditions**
  - 99.95% GH\(_2\) at 300 K and 40 psia.
- Lock up tank and turn on refrigerator at T-0.
- Add GH\(_2\) as tank pressure decreases.
- **Final Conditions**
  - Tank near isothermal at 20.8K - 22.4 K and 14.7 psia
  - Saturated vapor with condensation on HX tubing
- Multiple lessons learned would decrease total timeline in the future

**Conclusion:** IRAS enables zero-loss chilldown of a large cryogenic vessel
Zero-Loss Tanker Offload Test Results

- Based on STS Program data, 13% of purchased LH$_2$ is lost due to transport and offload inefficiency
- Heat from transport and line chilldown can be removed by refrigerator, allowing no loss offload
- Zero-loss tanker offloads were achieved at 33%, 67%, and 100% fill levels

Conclusion: IRAS enables zero-loss tanker offloads at all fill levels
Boil-off Heat Leak Test Results

- Boil off testing to quantify heat leak was conducted at 3 fill levels
- Vented thru control valve and mass flow meter
- Pre-test analysis estimated 300 W

Conclusion: Tank heat leak was quantified at three fill levels and agreed closely with pretest estimates

\[ \dot{Q} = \dot{m} \times \left( h_{fg} + (h_{ullage} - h_{sat,vapor}) \right) \] [W]

<table>
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<tr>
<th>Level</th>
<th>MF3 (slm)</th>
<th>PT2 (psia)</th>
<th>TT19 (K)</th>
<th>( Q_L ) (W)</th>
<th>( Q_V ) (W)</th>
<th>( Q ) (W)</th>
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<td>120</td>
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<td>196</td>
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<td>100</td>
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<td>15.9</td>
<td>34.5</td>
<td>234</td>
<td>81</td>
<td>315</td>
</tr>
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ZBO Pressure Control Test Results

- GODU-LH2 software controlled refrigerator to achieve and maintain IRAS tank pressure set-point.
- No LN$_2$ pre-cooling used
- Approach set points from above and below
- Pressure stability +/- 0.5% for all three fill levels
- Near isothermal temperature profile following saturation line

Conclusion: IRAS using tank pressure control achieves ZBO and provides complete control over the state of the fluid
ZBO Temperature Control Test Results

- Linde software controlled refrigerator to achieve and maintain constant helium supply temperature.
- No LN$_2$ pre-cooling used.
- Helium supply temperature response fast and accurate.
- But LH$_2$ takes long time period to reach equilibrium state.

Conclusion: IRAS using supply temperature control achieves ZBO but takes a long time to reach LH$_2$ equilibrium state.
ZBO Duty Cycle Test Results

- ZBO achieved in batch processes by turning on and off the refrigerator as required
- Testing was both accidental and purposeful
- Minimum electrical cost but depends on multiple start/stop cycles of cryogenic equipment
- Duty cycle varied from 1.13 (33%) to 1.16 (67%) to 3.6 (100%) on/off with no LN$_2$ precooling

**Conclusion:** IRAS using duty cycling of the refrigerator achieves ZBO with minimal energy but provides no control of LH$_2$ state
Liquefaction Test Results

- GH₂ was controlled using a mass flow controller until the tank pressure remained constant.
- NOT optimized for liquefaction. GH₂ was fed in at ambient temperature.
- Using LN₂ pre-cooling, roughly 78 gal of LH₂ was produced during the test.

Conclusion: Hydrogen liquefaction was achieved using IRAS, though the current system was not optimized for yield.
Densification Test Results

- System performance exceeded expectations! Min temp was expected to be $\approx 15$ K
- Fridge ran with LN$_2$ precooling, and densified 13,000 gallons of LH$_2$ for 14 days.
- LH$_2$ cooled below the triple point. Minimum temp recorded was 12.6 K ($-437^\circ$F)
- Estimated that 3,700 lb of hydrogen ice was formed during the course of testing; or about 5,100 gal

Conclusion: IRAS enables propellant densification down to the triple point
Slush Hydrogen Production

$\%\text{Tank LH}_2$ Fill Level Test

$H_2$ Ice Production $\approx 85$ hrs
Conclusions

• GODU-LH2 system has successfully met all test objectives at the 33%, 67%, and 100% tank fill level

• Complete control over the state of the fluid has been demonstrated using Integrated Refrigeration and Storage (IRAS).
  – Almost any desired point along the H₂ saturation curve can essentially be “dialed in” and maintained indefinitely.

• System can also be used to produce densified hydrogen in large quantities to the triple point

• Exploring multiple technology infusion paths
  – Studying implementation of IRAS technology into new LH₂ sphere for EM-2 at LC39B
  – Technical interchange also occurring with STMD, LSP, ULA, DoE, KIST, Kawasaki, Shell Oil, SpaceX, US Coast Guard, and Virgin Galactic
Proposing to GSDO to integrate the IRAS technology into a new 1.4M gallon LH2 sphere required for EM-2

- Analysis demonstrates that $0.15 in electricity saves $1.00 in hydrogen

Low risk – Failure of system just reverts back to business as usual

Working with A&E contractor to get cost, schedule and constructability impacts

\[
\frac{S_E}{S_H} = \frac{(h_{fg} + c_p \Delta T) t}{\frac{T_c}{T_h - T_c} \eta t} \quad \text{electricity cost} \quad \text{hydrogen cost}
\]
Densified Hydrogen Flight Tank Loading Demo

- Densified Hydrogen loading of a flight weight tank was a secondary objective that was not accomplished.
- Launch Services Program and United Launch Alliance want to partner with GODU LH2 to perform densified LH2 loading demonstrations with “Cryote III” tank.
- LSP will contribute modest funding and modeling support and ULA will provide Cryote III tank and supporting equipment.
- Plan to submit for possible future AES funding.
Questions?