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

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Background

• 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
  - 1962 National Bureau of Standards develops hydrogen re-liquefier
  - 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
  - 1993 Hydrogen Consultants Inc develops prototype closed cycle Joule-Thomson cryocooler for LC-39 zero boil off (SBIR Phase II)
  - 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 LN₂ 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 NASP 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 LN₃ 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 LH$_2$ 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 LH₂ 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 13th, 2014

November 2015

April 2014

January 2014
GODU-LH2 Functional Diagram

Liquid Hydrogen
- 33,000 gallons
- 95 psig MAWP

Liquid Nitrogen
- 5,600 Gallons
- 150 psig MAWP

Gaseous Hydrogen
- 100,000 scf
- 2400 psi

ACCU-MAX Refrigerator & RSX Compressor
- 8x40 ISO Container
- 8x20 ISO DOT Container
“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

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<th>End Date</th>
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<td>5/21/2015</td>
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<tr>
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<tr>
<td>Tanker 3 Offload</td>
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<tr>
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<td>5/6/2016</td>
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Zero-Loss Tank Childdown Test Results

- **Initial Conditions**
  - 99.95% GH\textsubscript{2} at 300 K and 40 psia.
  - Lock up tank and turn on refrigerator at T-0.
  - Add GH\textsubscript{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

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

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<th>PT2 (psia)</th>
<th>TT19 (K)</th>
<th>Q_L (W)</th>
<th>Q_V (W)</th>
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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
• 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

- GH$_2$ was controlled using a mass flow controller until the tank pressure remained constant.
- NOT optimized for liquefaction. GH$_2$ was fed in at ambient temperature.
- Using LN$_2$ pre-cooling, roughly 78 gal of LH$_2$ 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 ≈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°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{\( \approx 85 \text{ hrs} \)} \]

\[ \text{\( \approx 85 \text{ hrs} \)} \]

83% Tank LH\(_2\) Fill Level Test
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

$$\frac{SE}{SH} = \frac{(h_{fg} + c_p \Delta T) t}{T_f - T_c \eta t} \quad \text{electricity cost over hydrogen cost}$$
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?