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

Dr. William Notardonato[1], James Fesmire[1], Adam Swanger[2], Kevin Jumper[3], Wesley Johnson[4], and Thomas Tomsik[4]

[1]NASA Kennedy Space Center, Cryogenics Test Laboratory, UB-R1, KSC, FL 32899 USA
[2]NASA Kennedy Space Center, Cryogenics Test Laboratory, NE-M5, KSC, FL 32899 USA
[3]NASA Kennedy Space Center, Cryogenics Test Laboratory, NE-L1, KSC, FL 32899 USA
[4]NASA Glenn Research Center, Fluid and Cryogenic Systems Branch, LTF, GRC, OH 44135 USA

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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 LN_2 and commercial cryocooler
2012-14	ZBO testing at GRC using flight like cryocooler and broad area cooling

Densification History

- LH_2/LOX are the most energetic chemical propellants practical, but LH_2 suffers from low density and volumetric heat capacity.
- Hydrogen densification can be used to increase the liquid density and heat capacity
- Densification can lead the a large increase in payload mass (15%)
- NASA/USAF has investigated use of densified LOX/LH_2 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 LH_2
– 1988- 94	NASP X30 Slush Hydrogen Technology Program - large scale production, transfer and in-tank thermodynamics
– 1995- 97	LH_2 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 DLH_2 loading, hold and thermal stratification in a composite flight weight dual-lobe tank
– 1997- 2001	Design, build and test of large scale LOX & LH_2 propellant densification units for X-33/RLV flight
– 2000	STA Tank Loading Tests w/GRC 30 lb/sec LOX PDU at GRC S40
– 2001	LN_2 Performance Demo Tests w/GRC 8 lb/sec LH_2 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	LH_2 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

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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

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Site Build-Up

September 30th, 2012

October 14th, 2014

Site Build-Up

January 9th, 2013

Site Build-Up

January 13th, 2014

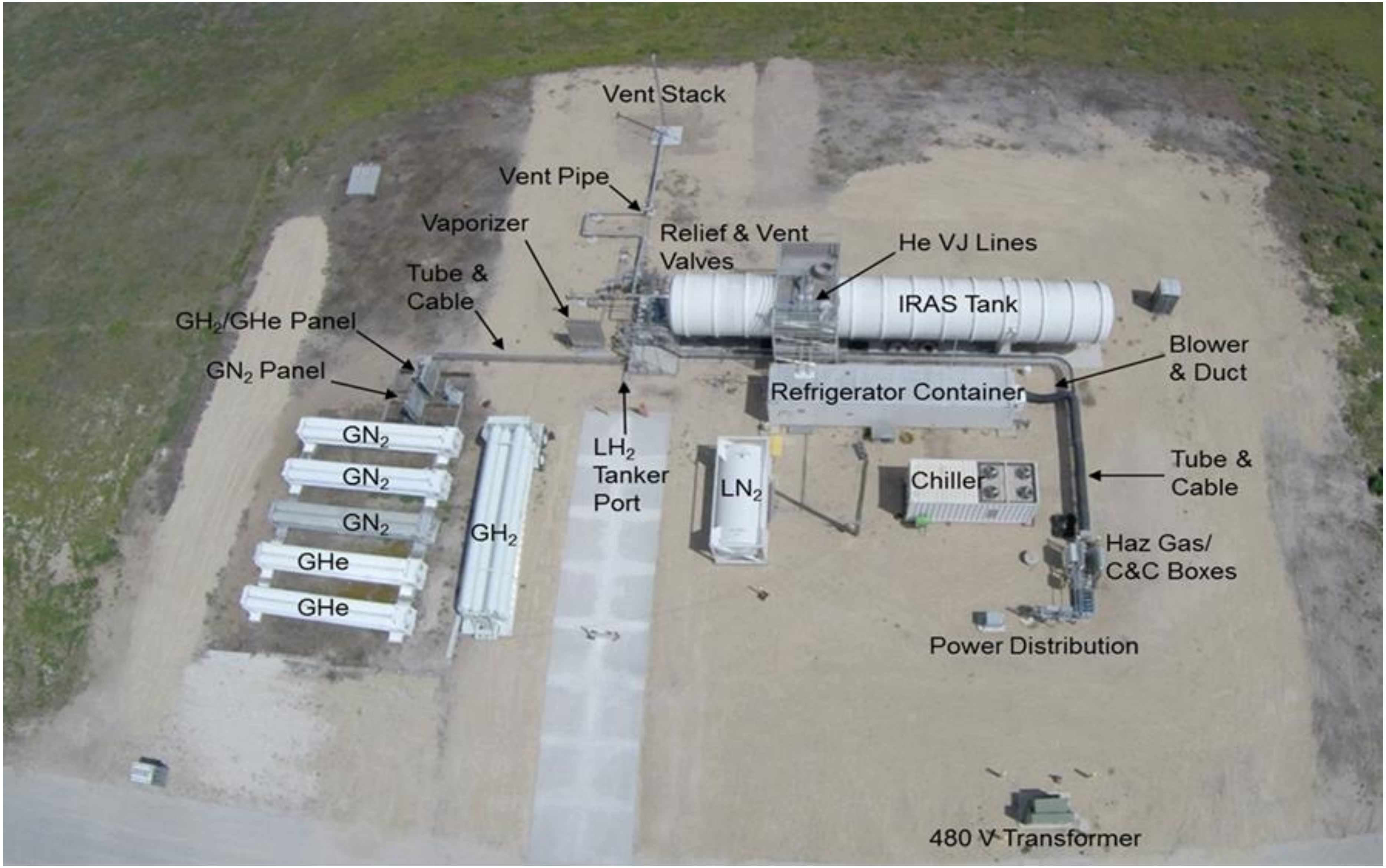

November 2015


January 2014


April 2014

GODU-LH2 Functional Diagram

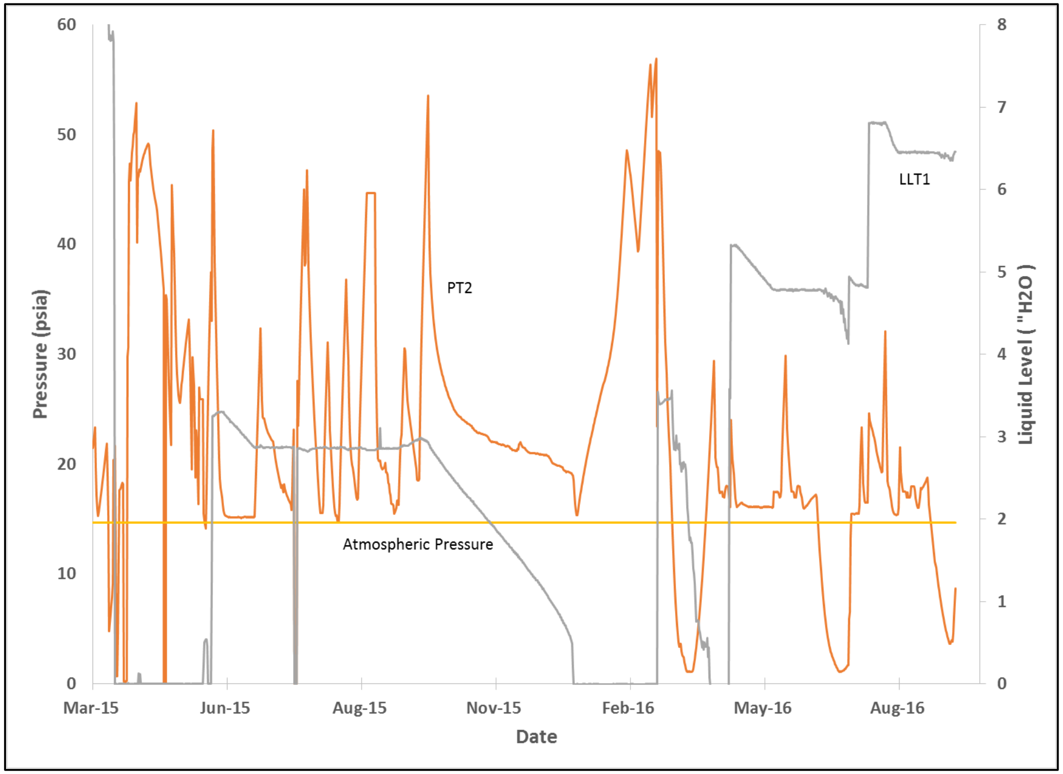
“Bird’s-eye View” of GODU-LH2 Site



Test Matrix and Timeline

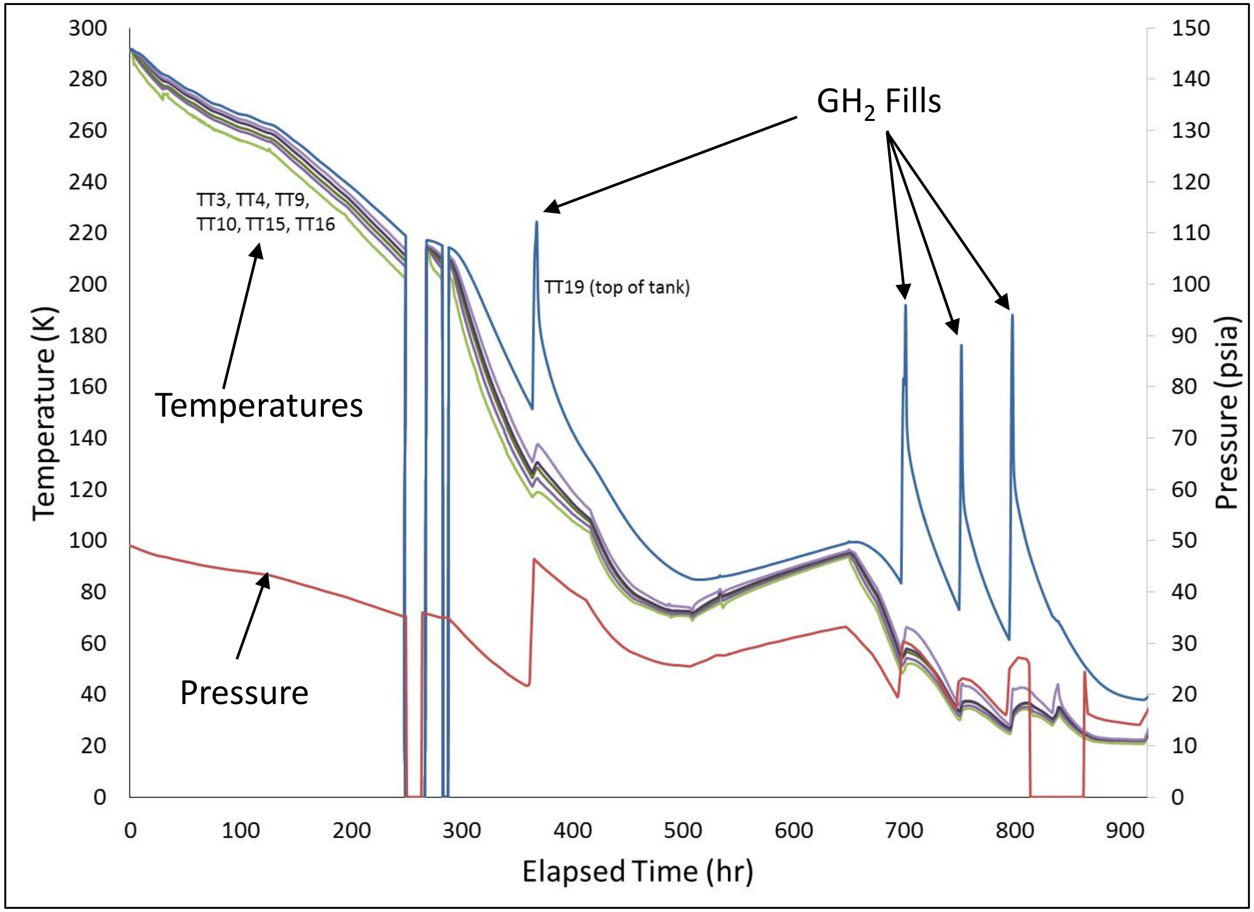
- Completed Test Readiness Review on February 12, 2015
- First tanker offload occurred May 21, 2015
- Refrigerator contamination from October 2015 until March 2016
- Compressed testing from March 2016 until October 2016

Test	Start Date	End Date
Chilldown	4/9/2015	5/21/2015
Tanker 1 Offload	5/21/2015	5/29/2015
Tanker 2 Offload	5/3/2016	5/6/2016
Tanker 3 Offload	8/3/2016	8/12/2016
33% Boil Off	5/29/2015	6/19/2015
66% Boil Off	5/6/2016	5/31/2016
100% Boil Off	8/14/2016	8/24/2016
33% ZBO (Press Control)	4/25/2016	5/3/2016
66% ZBO (Press Control)	6/12/2016	6/21/2016
100% ZBO (Press Control)	8/25/2016	9/6/2016
33% ZBO (Temp Control)	6/23/2015	7/13/2015
66% ZBO (Temp Control)	6/21/2016	6/29/2016
100% ZBO (Temp Control)	9/6/2016	9/12/2016
33% ZBO (Duty Cycle)	8/4/2015	8/11/2015
66% ZBO (Duty Cycle)	6/5/2016	6/13/2016
100% ZBO (Duty Cycle)	8/12/2016	8/16/2016
33% Densification	3/24/2016	4/21/2016
66% Densification	6/29/2016	7/23/2016
100% Densification	9/12/2016	10/5/2016
0% Liquefaction	4/9/2015	5/21/2015
33% Liquefaction	9/23/2015	10/8/2015
66% Liquefaction	7/22/2016	8/2/2016



Zero-Loss Tank Chilldown Test Results

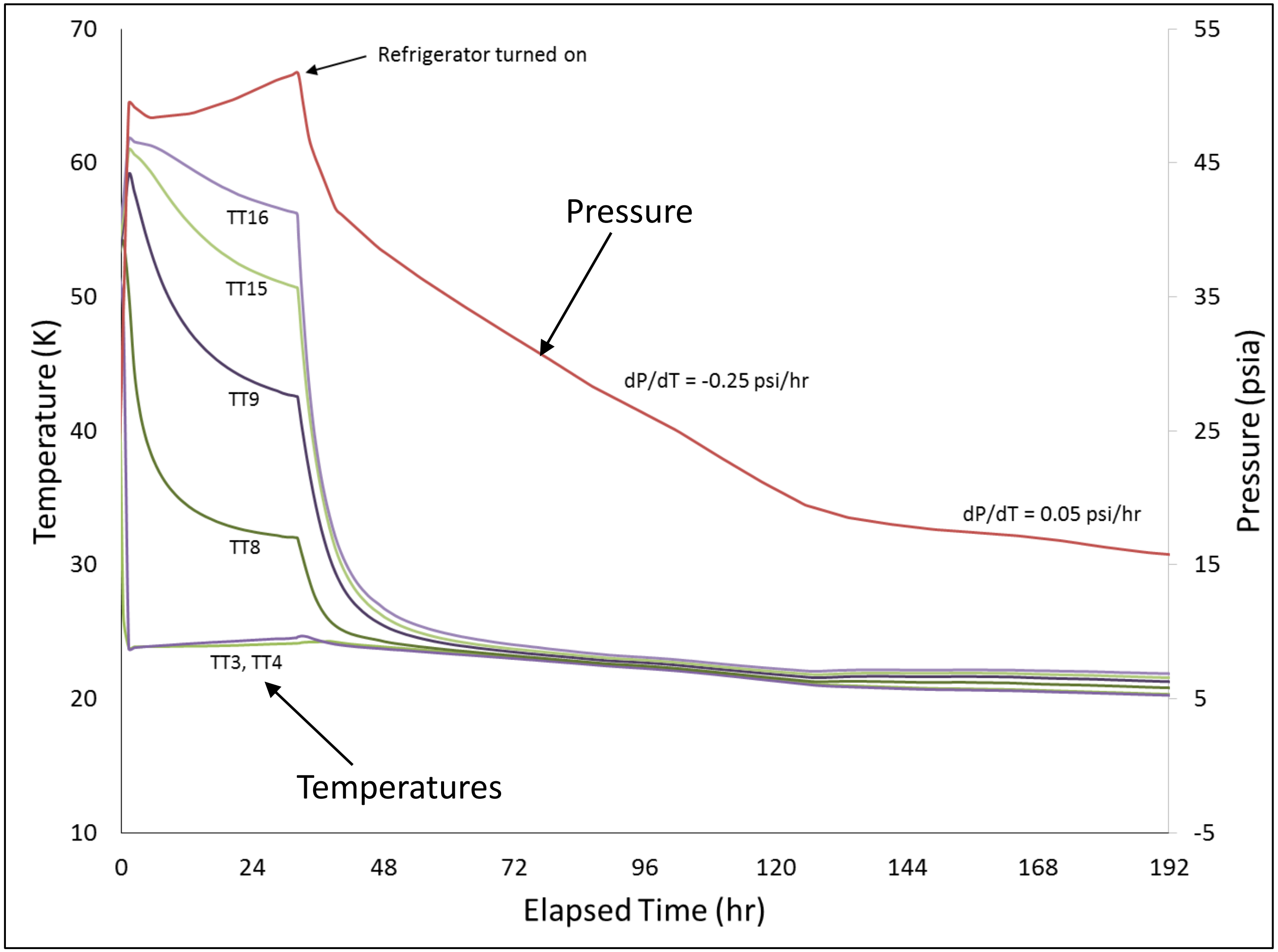
- Initial Conditions
  - 99.95% GH_2 at 300 K and 40 psia.
- Lock up tank and turn on refrigerator at T-0.
- Add GH_2 as tank pressure decreases
- Final Conditions
  - Tank near isothermal at 20.8K - 22.4 K and 14.7 psia
  - Saturated vapor with condensation on HX tubing
- Multiple lessons learned would decrease total timeline in the future



Conclusion: IRAS enables zero-loss chilldown of a large cryogenic vessel

Zero-Loss Tanker Offload Test Results

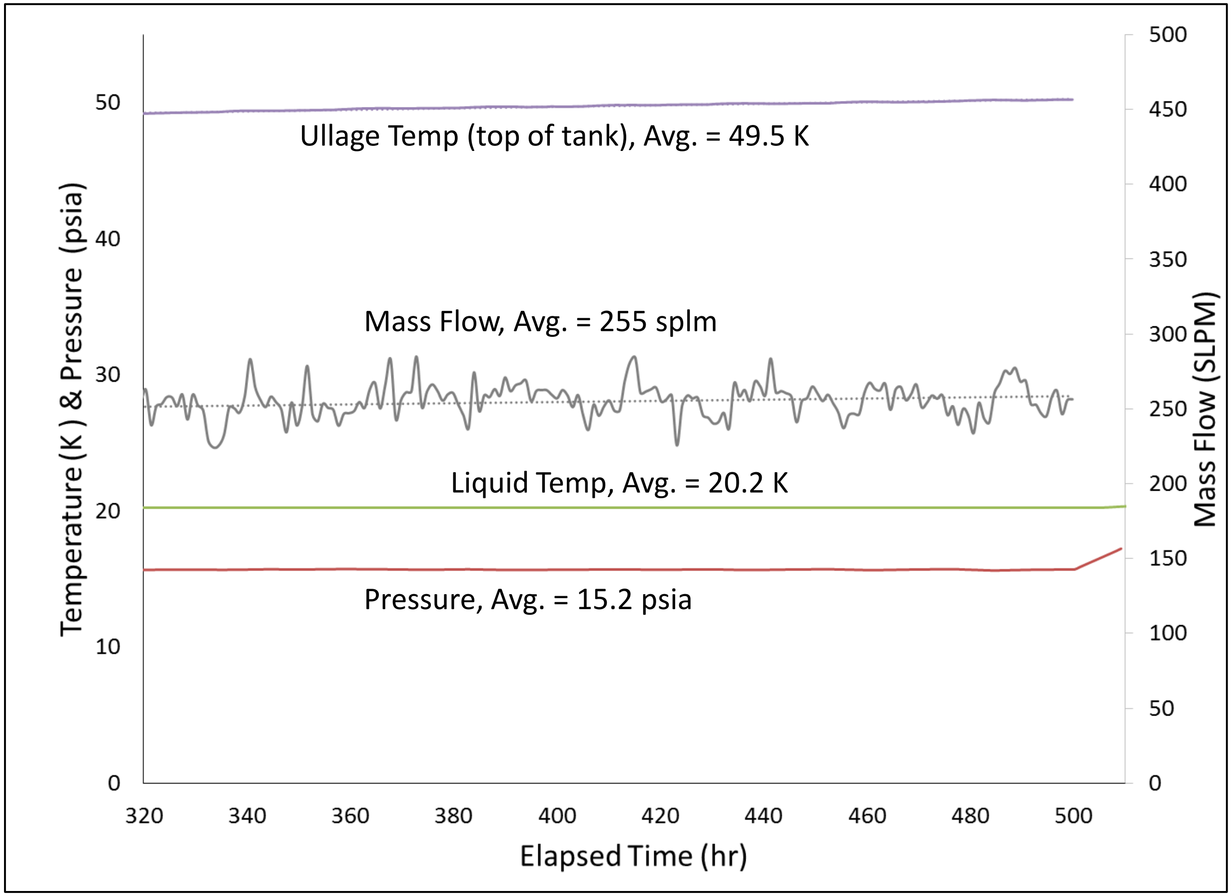
- Based on STS Program data, 13% of purchased LH_2 is lost due to transport and offload inefficiency
- Heat from transport and line chilldown can be removed by refrigerator, allowing no loss offload
- Zero-loss tanker offloads were achieved at 33%, 67%, and 100% fill levels



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

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

Level %	MF3 (slm)	PT2 (psia)	TT19 (K)	Q_L (W)	Q_V (W)	Q (W)
33	255	15.2	49.5	170	120	290
67	295	16.6	41.3	196	100	296
100	351	15.9	34.5	234	81	315

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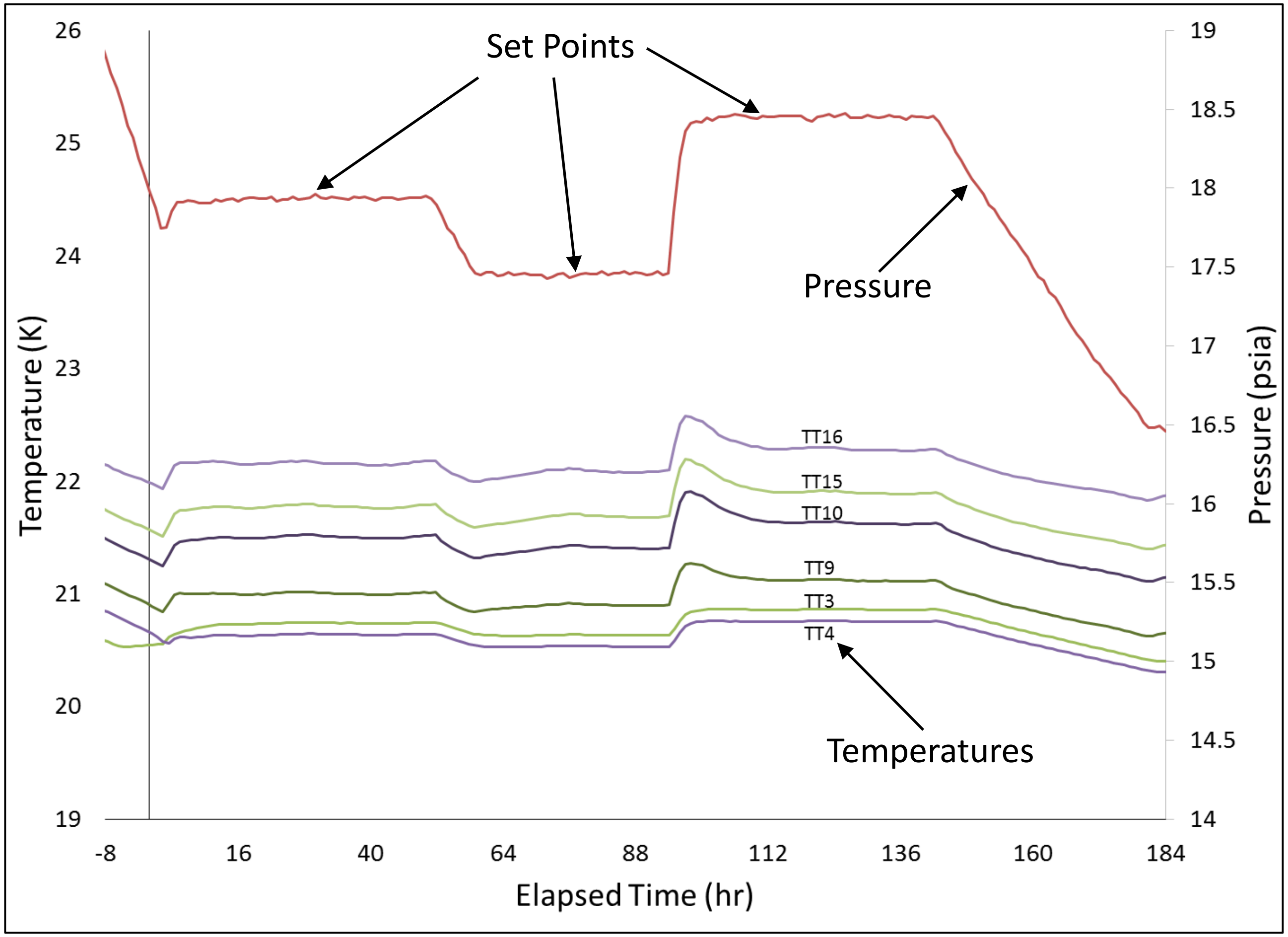
ZBO Pressure Control Test Results

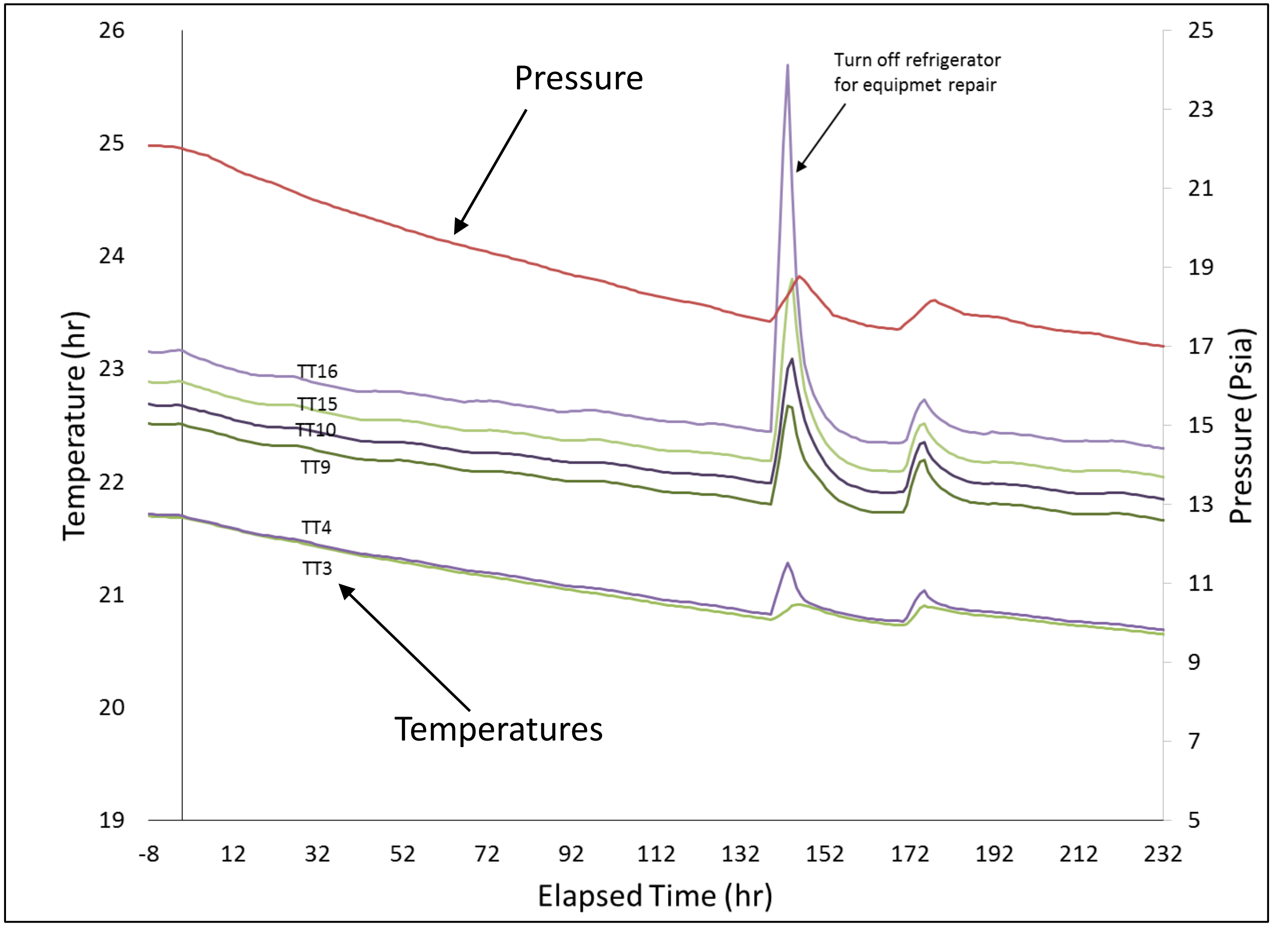
- GODU-LH2 software controlled refrigerator to achieve and maintain IRAS tank pressure set-point.
- No LN_2 pre-cooling used
- Approach set points from above and below
- Pressure stability +/- 0.5% for all three fill levels
- Near isothermal temperature profile following saturation line



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

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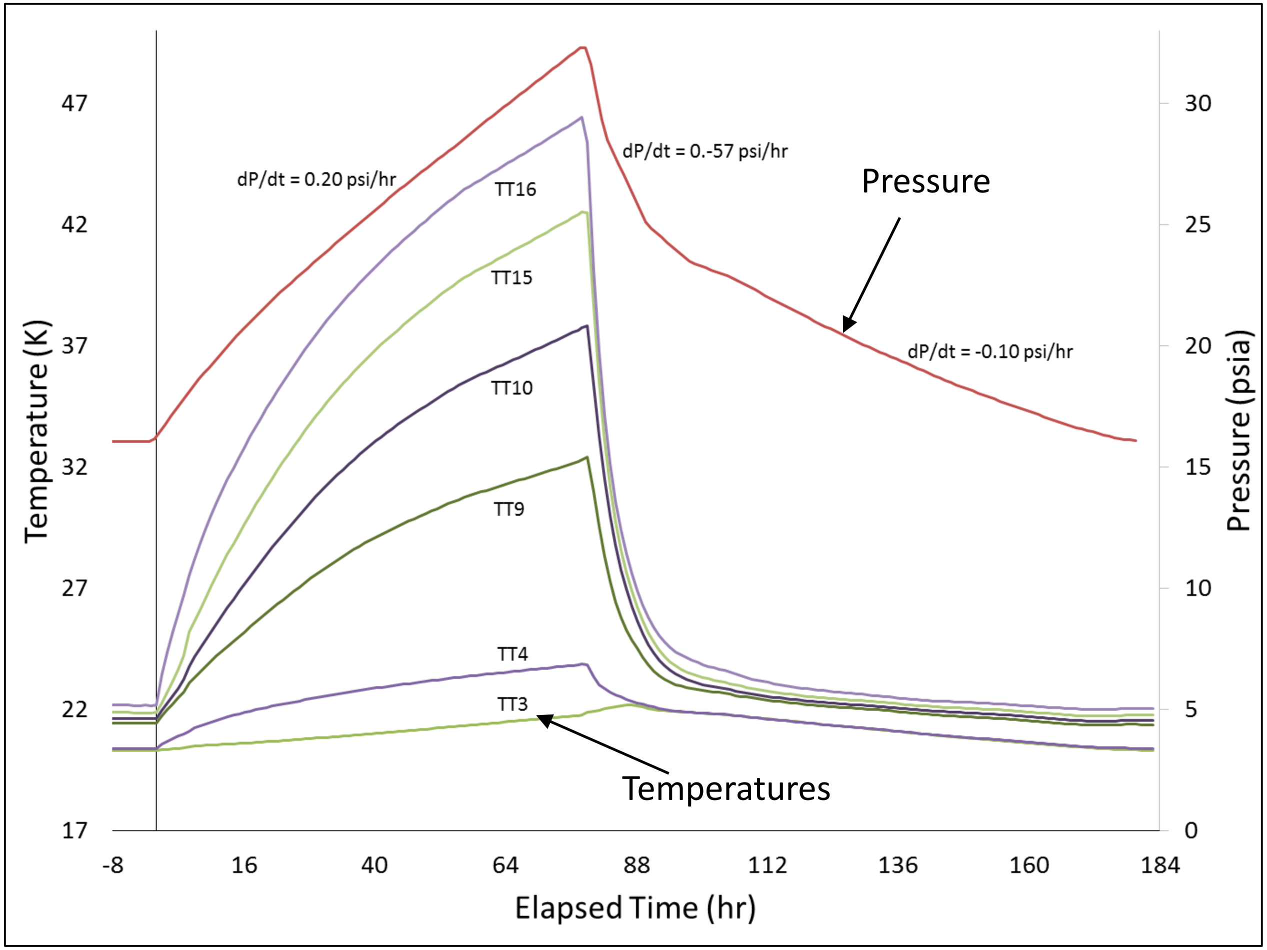
ZBO Duty Cycle Test Results

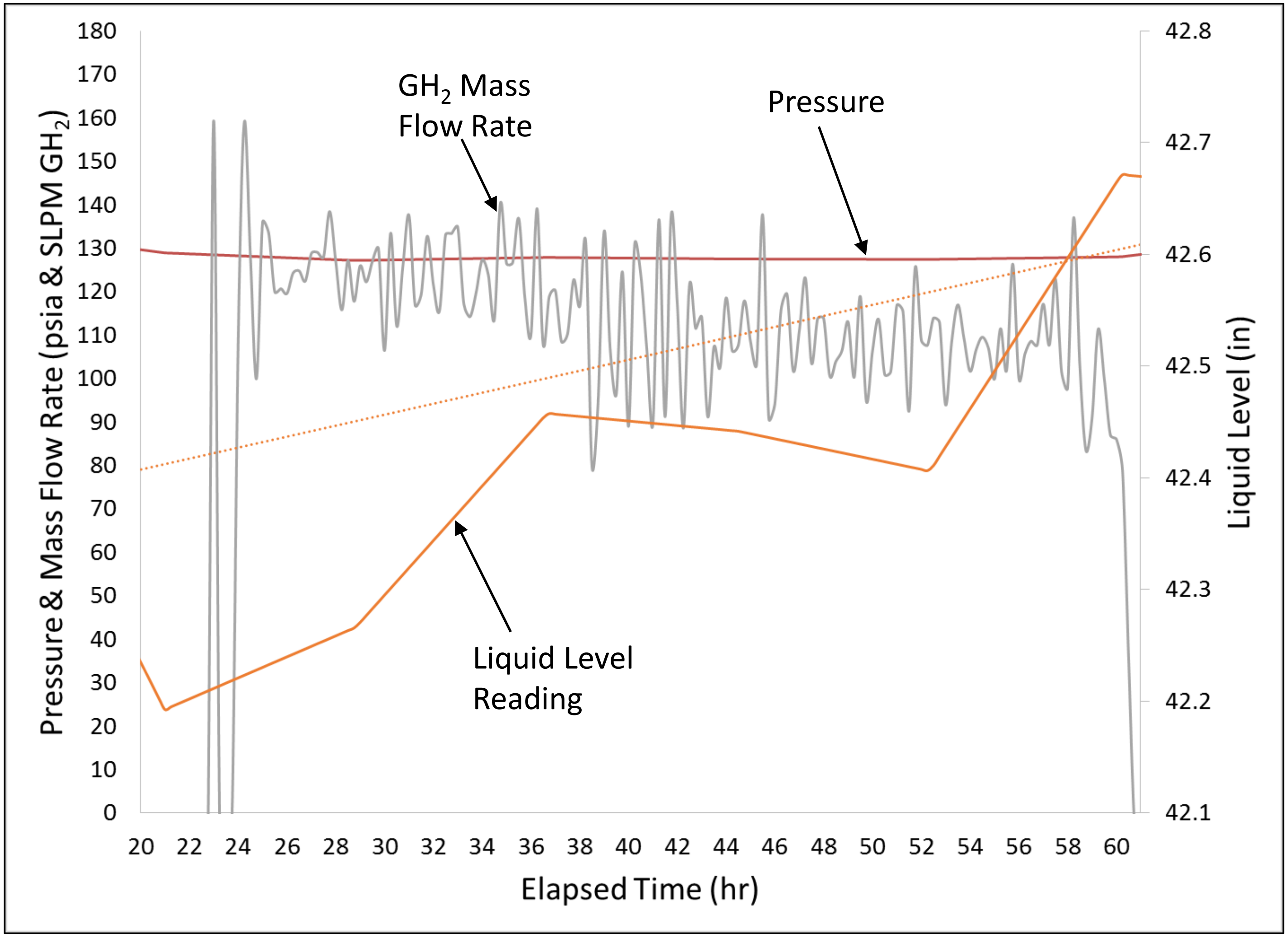
- ZBO achieved in batch processes by turning on and off the refrigerator as required
- Testing was both accidental and purposeful
- Minimum electrical cost but depends on multiple start/stop cycles of cryogenic equipment
- Duty cycle varied from 1.13 (33%) to 1.16 (67%) to 3.6 (100%) on/off with no LN_2 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

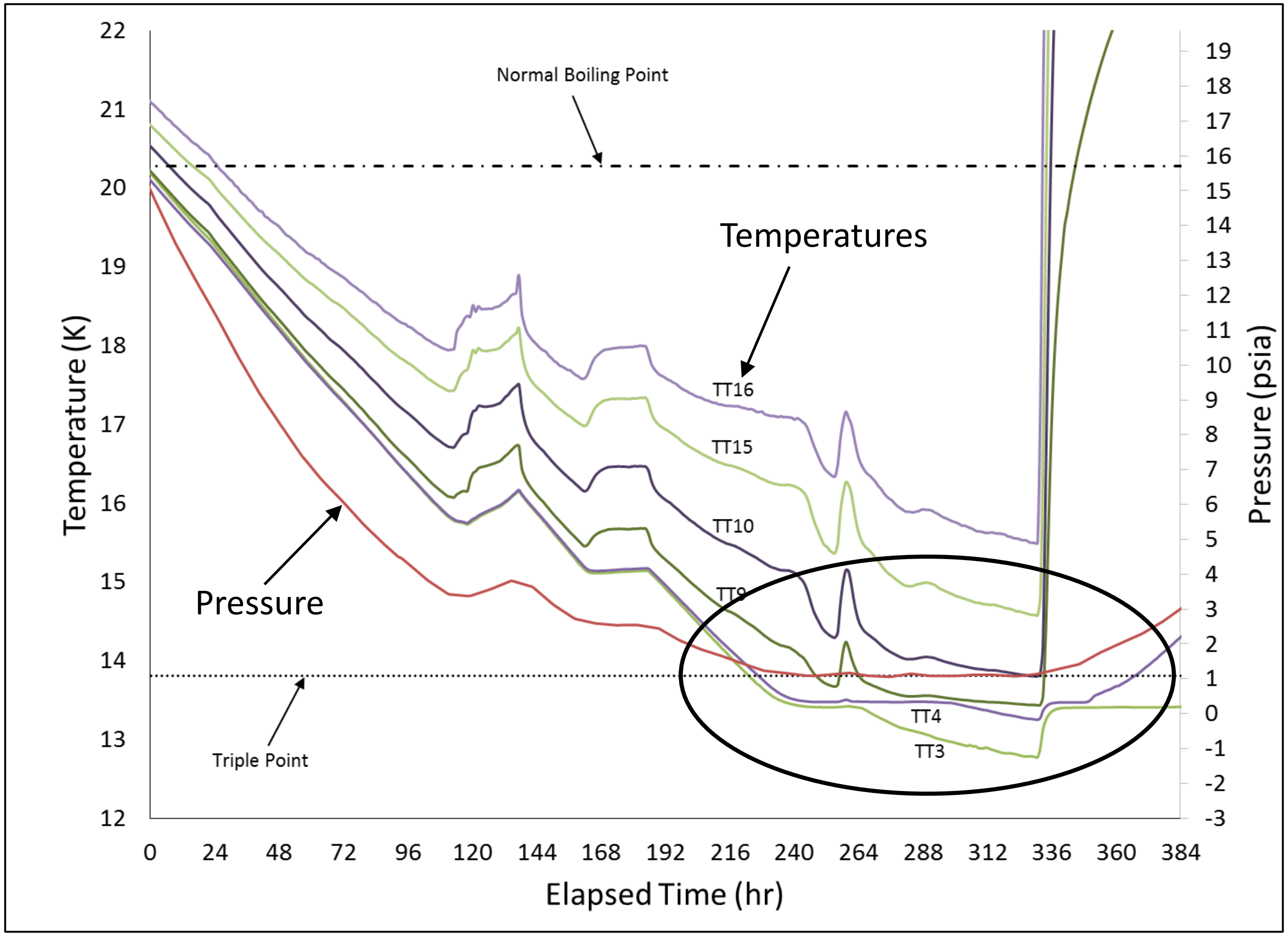
- GH_2 was controlled using a mass flow controller until the tank pressure remained constant.
- NOT optimized for liquefaction. GH_2 was fed in at ambient temperature.
- Using LN_2 pre-cooling, roughly 78 gal of LH_2 was produced during the test.



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

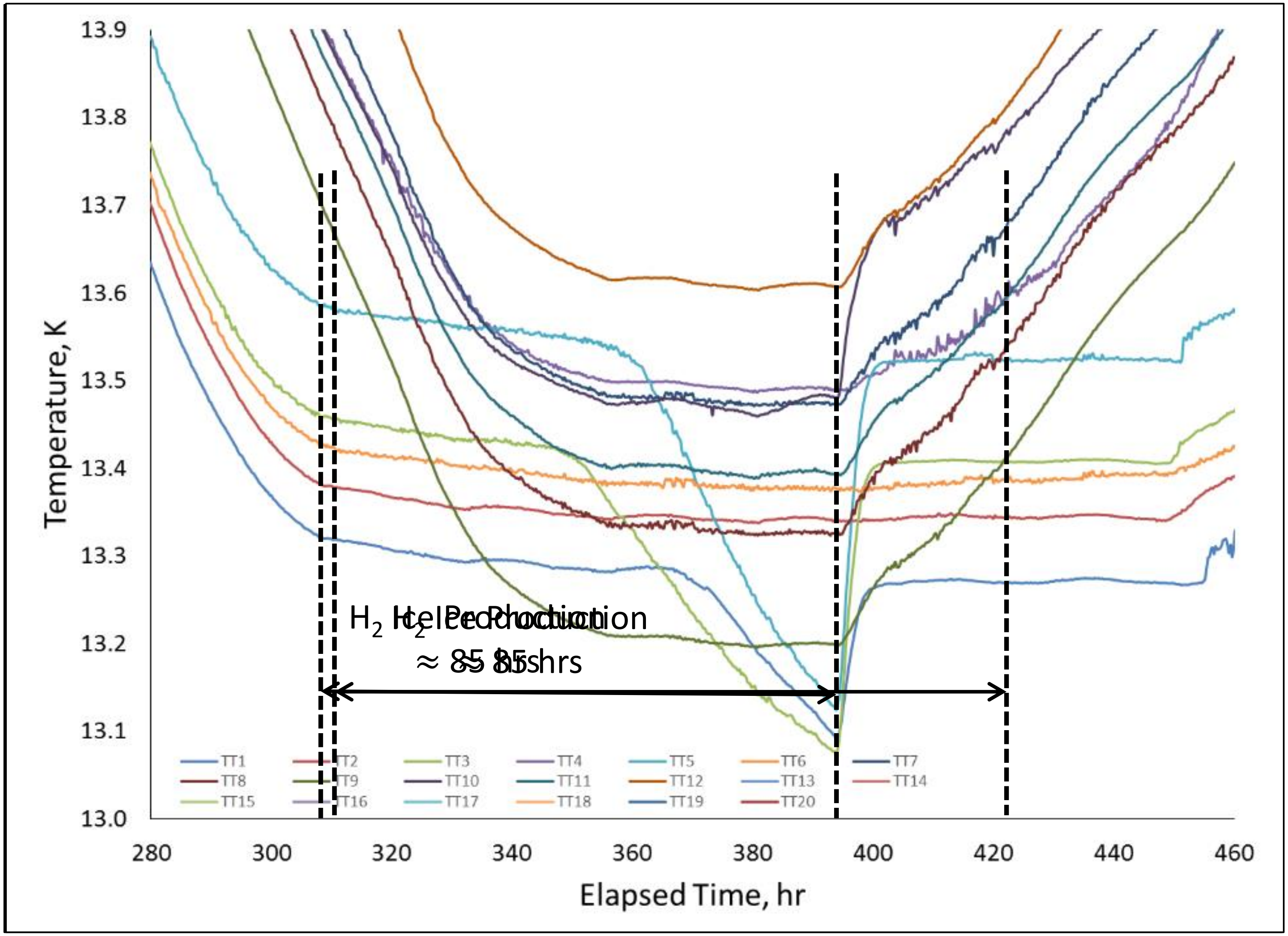
Densification Test Results

- System performance <u>exceeded expectations</u>! 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 <u>below the triple point</u>. 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



63% Tank LH_2 Fill Level Test

37% Tank LH_2 Fill Level Test

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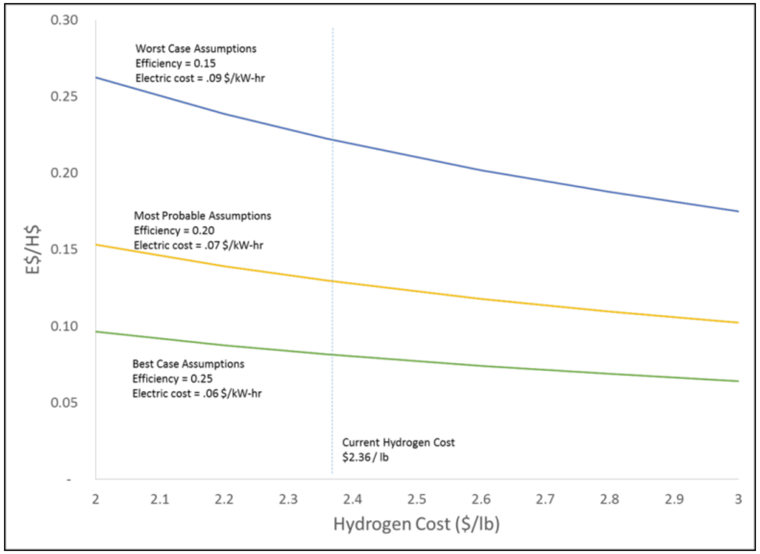
Conclusions

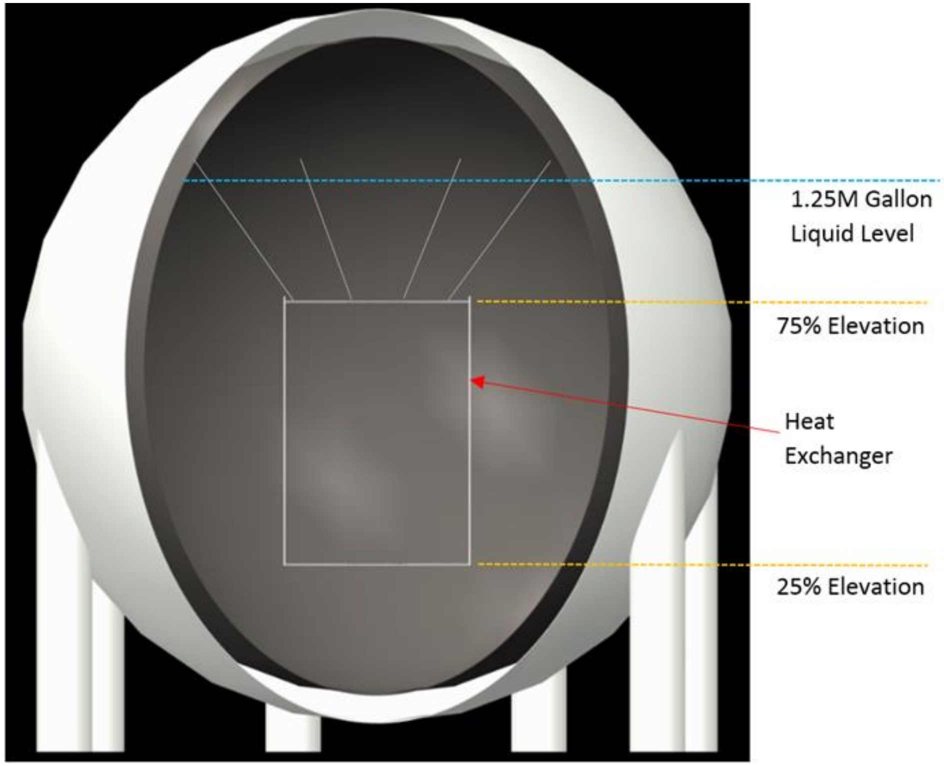
- **GODU-LH2 system has successfully met all test objectives at the 33%, 67%, and 100% tank fill level**
- **Complete control over the state of the fluid has been demonstrated using Integrated Refrigeration and Storage (IRAS).**
  - Almost any desired point along the H_2 saturation curve can essentially 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 LH_2 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

Ground Systems Development & Operations

- 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

$$\frac{\$_E}{\$_H} = \frac{(h_{fg} + c_p \Delta T)\, t}{\frac{T_c}{T_h - T_c} \eta\, t} \qquad \frac{\mathit{electricity\ cost}}{\mathit{hydrogen\ cost}}$$





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?