# DOE/NASA Advances in Liquid Hydrogen Storage Workshop

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## $LH_2$ Storage and Handling Demonstrations Using Active Refrigeration


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# Background

- In the 1950's and 1960's DoD 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 liquid hydrogen purchased during the shuttle program
- Some technology development work done with densified propellants but never incorporated by NASA


Image Credit : [1]

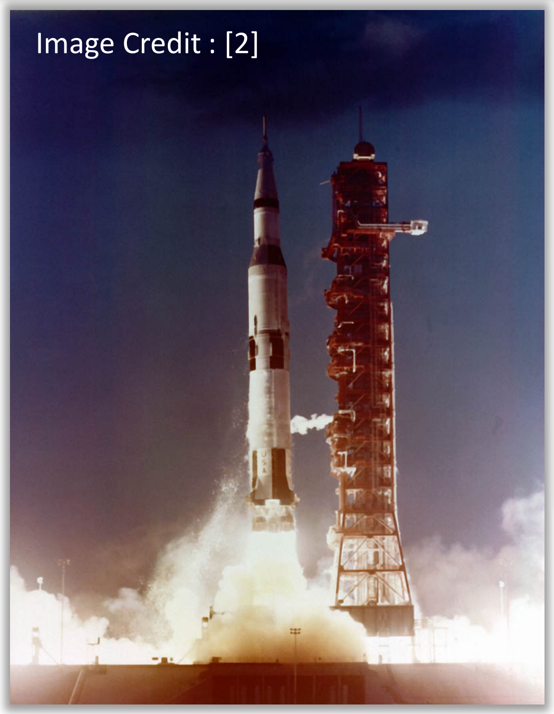
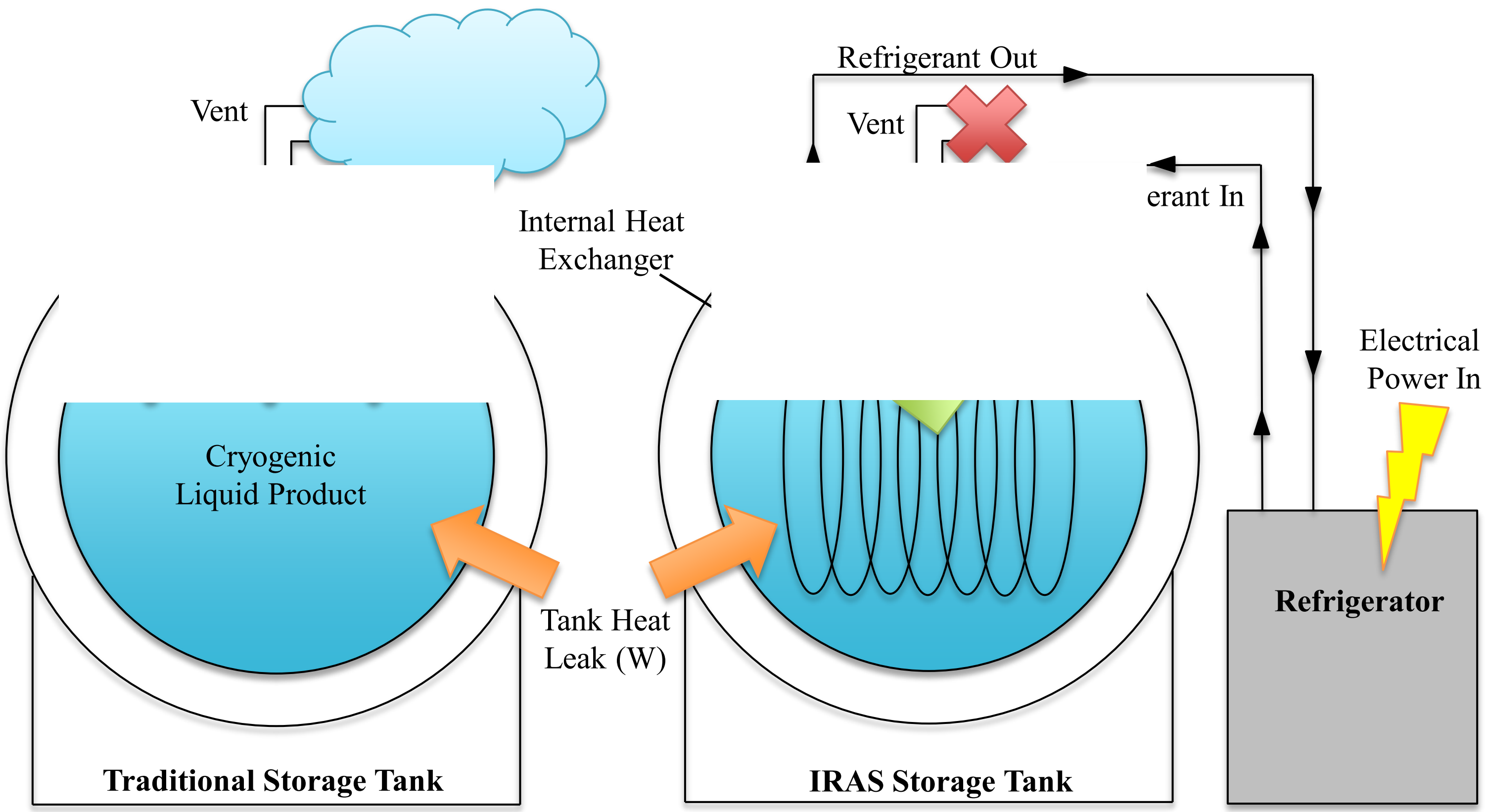


Image Credit : [2]

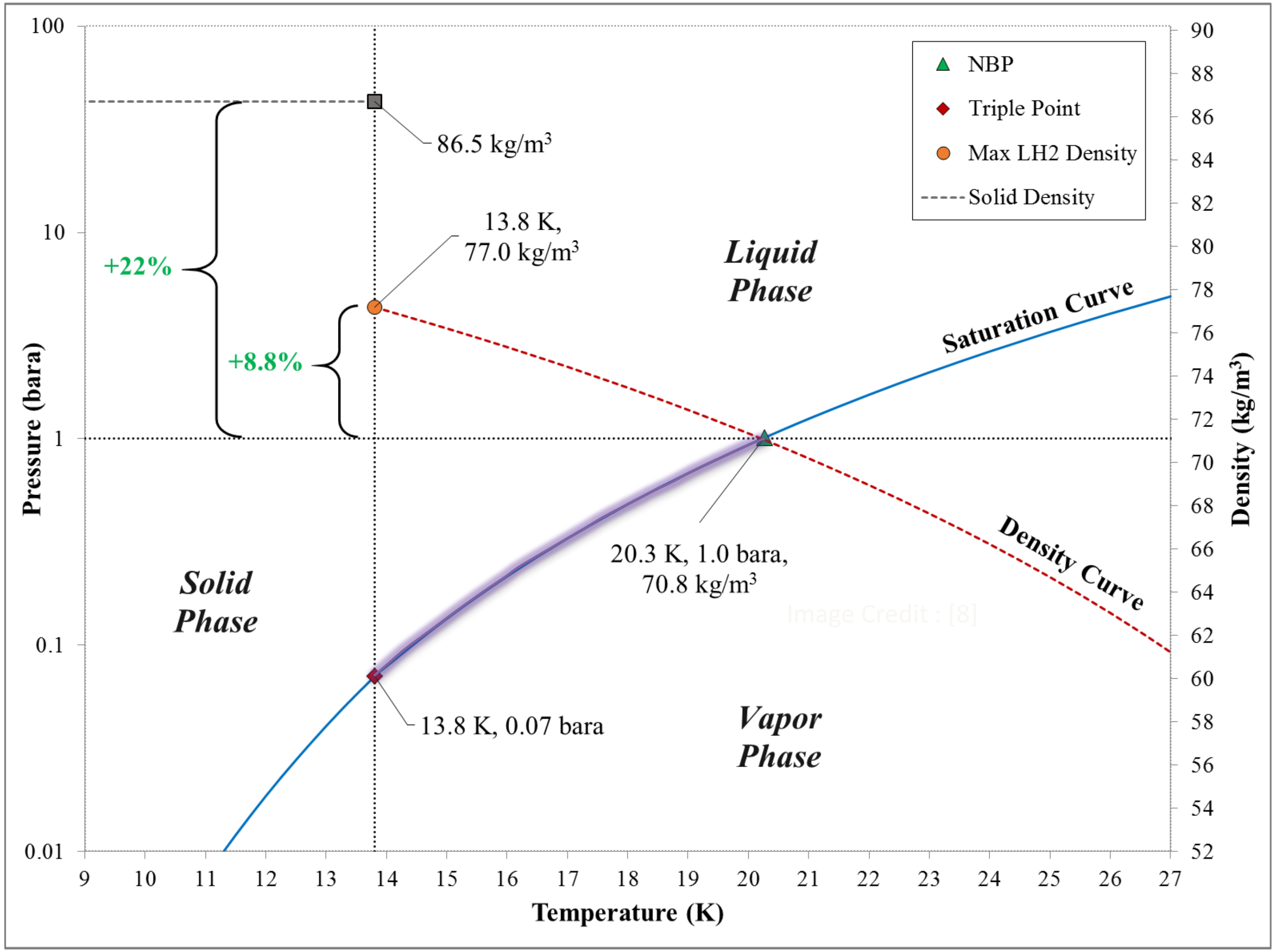

Image Credit : [3]

# 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 **Full Control Storage**, including Zero Boil-Off, Densification, and Liquefaction
- NASA and DoE funded small scale $LH_2$ IRAS proof of concept demonstration from 2002-2006
- NASA funded IRAS Heat Exchanger characterization tests in 2008-2009

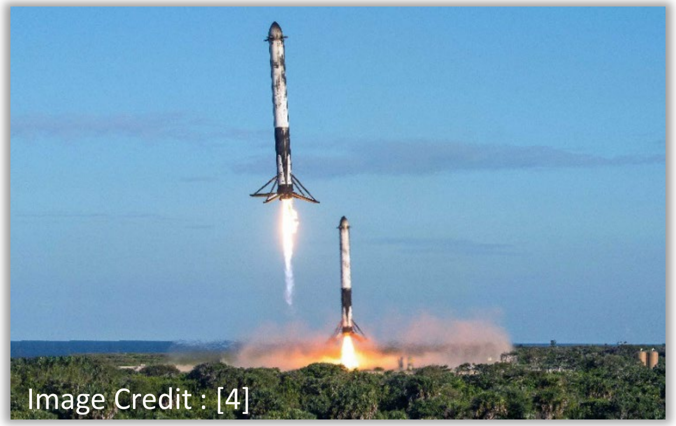


# Densification Benefits




Properties of para-hydrogen from RefProp Version 8

- Additional payload to orbit of 4.9% to 17.5% for liquid, up to 26% for slush
- Enables advanced capabilities such as reusability (SpaceX Falcon 9)




- Additional energy storage capacity and enthalpy margin

# GODU-LH2 Project

- Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) project ran from 2012 to 2016
- IRAS tech development and scale-up

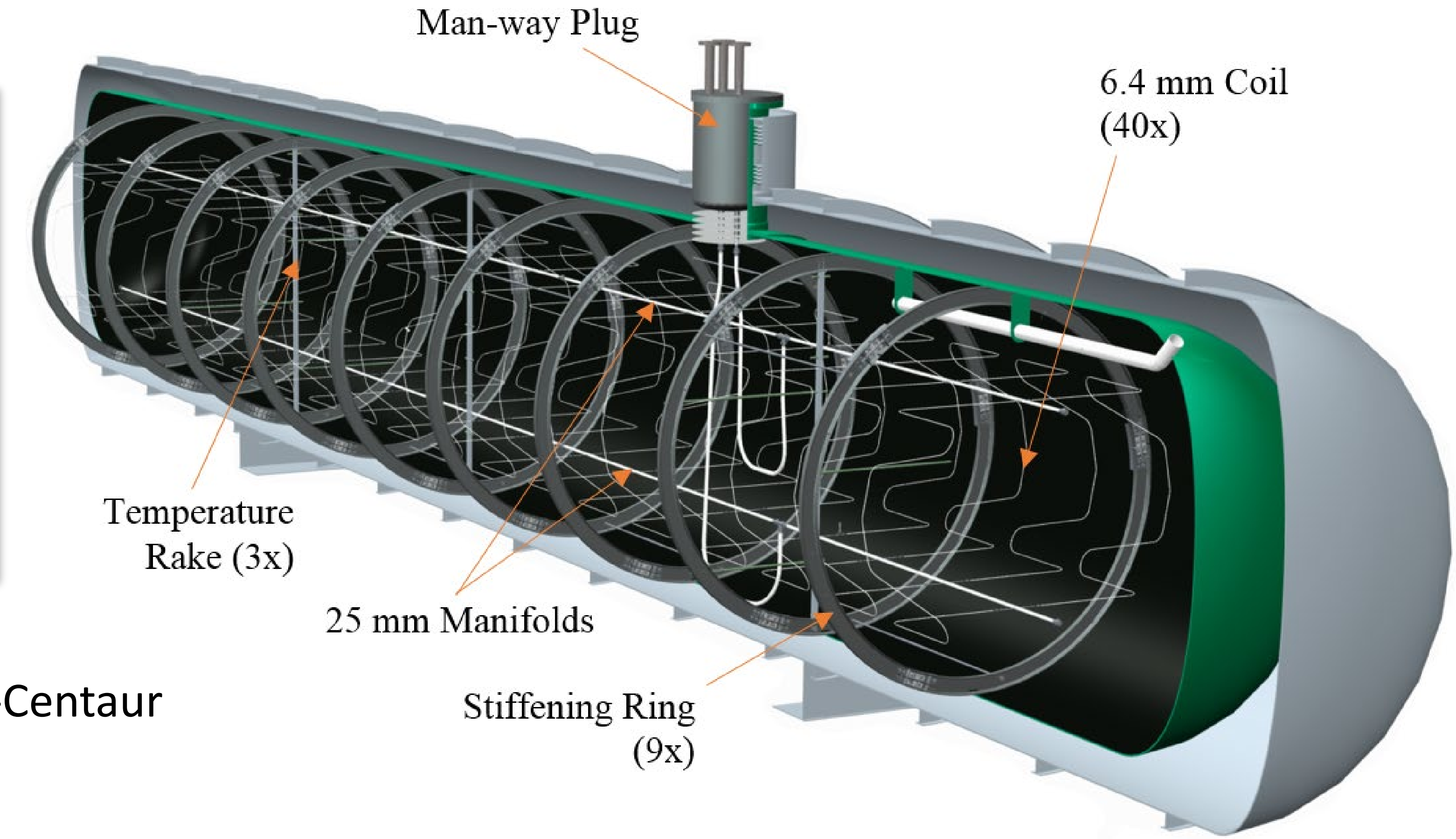
## Project Goal

Demonstrate cost efficient cryogenic operations using IRAS, on a relevant scale that can be projected onto future Spaceport architectures

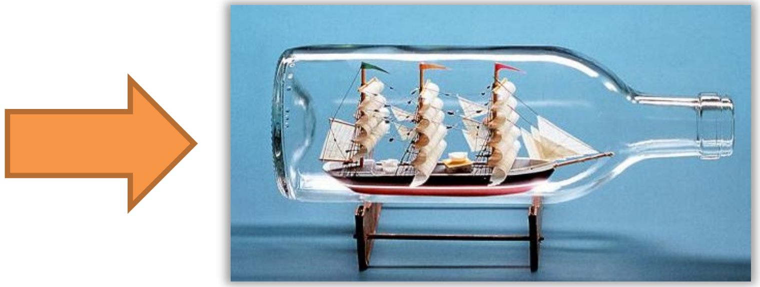
## Primary Technical Objectives

1. Demonstrate large scale zero loss storage and transfer of $LH_2$
2. Demonstrate hydrogen densification inside the storage tank
3. Demonstrate in situ hydrogen liquefaction

# IRAS Tank




- Originally constructed in 1991 for Titan-Centaur program
- 33,000 gallons (125, $m^3$) of NBP $LH_2$ storage
- Modified into an IRAS tank by incorporating an internal HX, stiffening rings, temperature rakes, and man-way feed-through



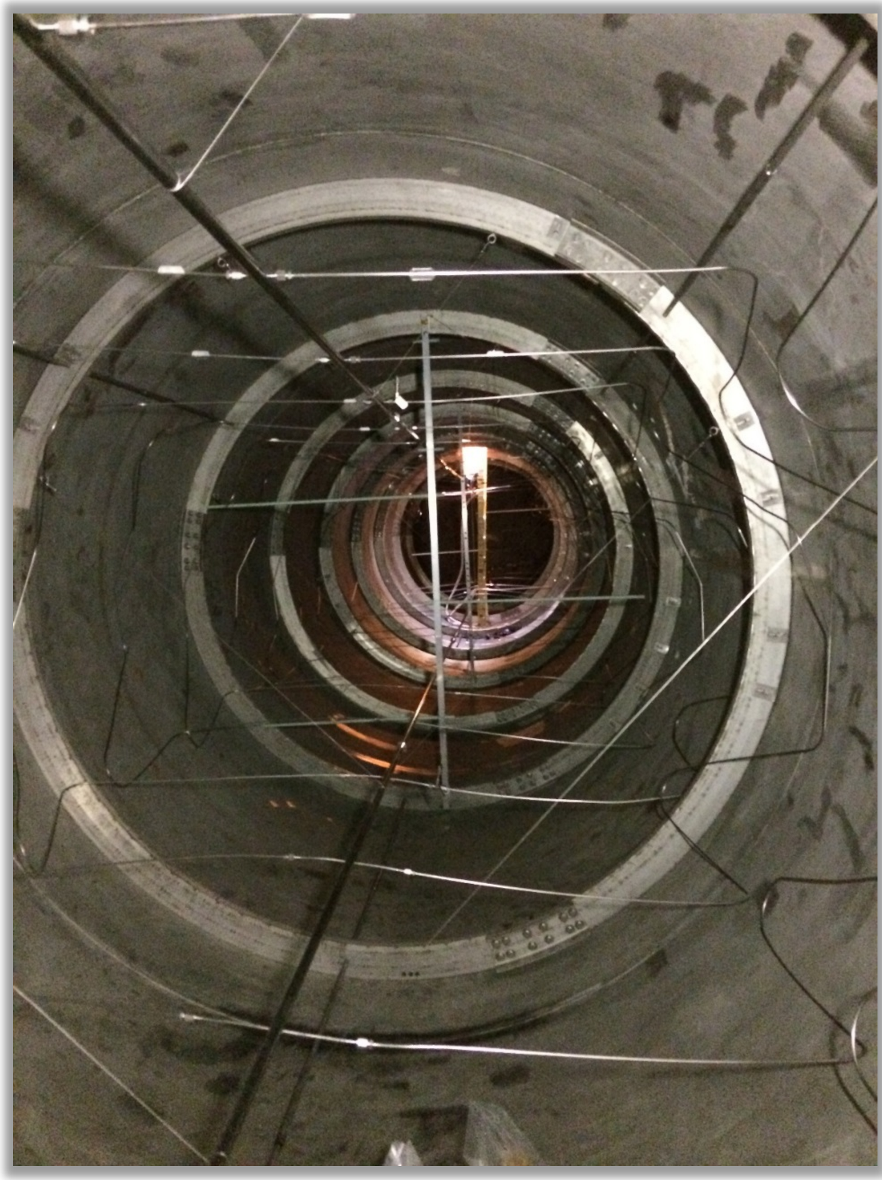
# Site Build-Up

September 14th, 2012

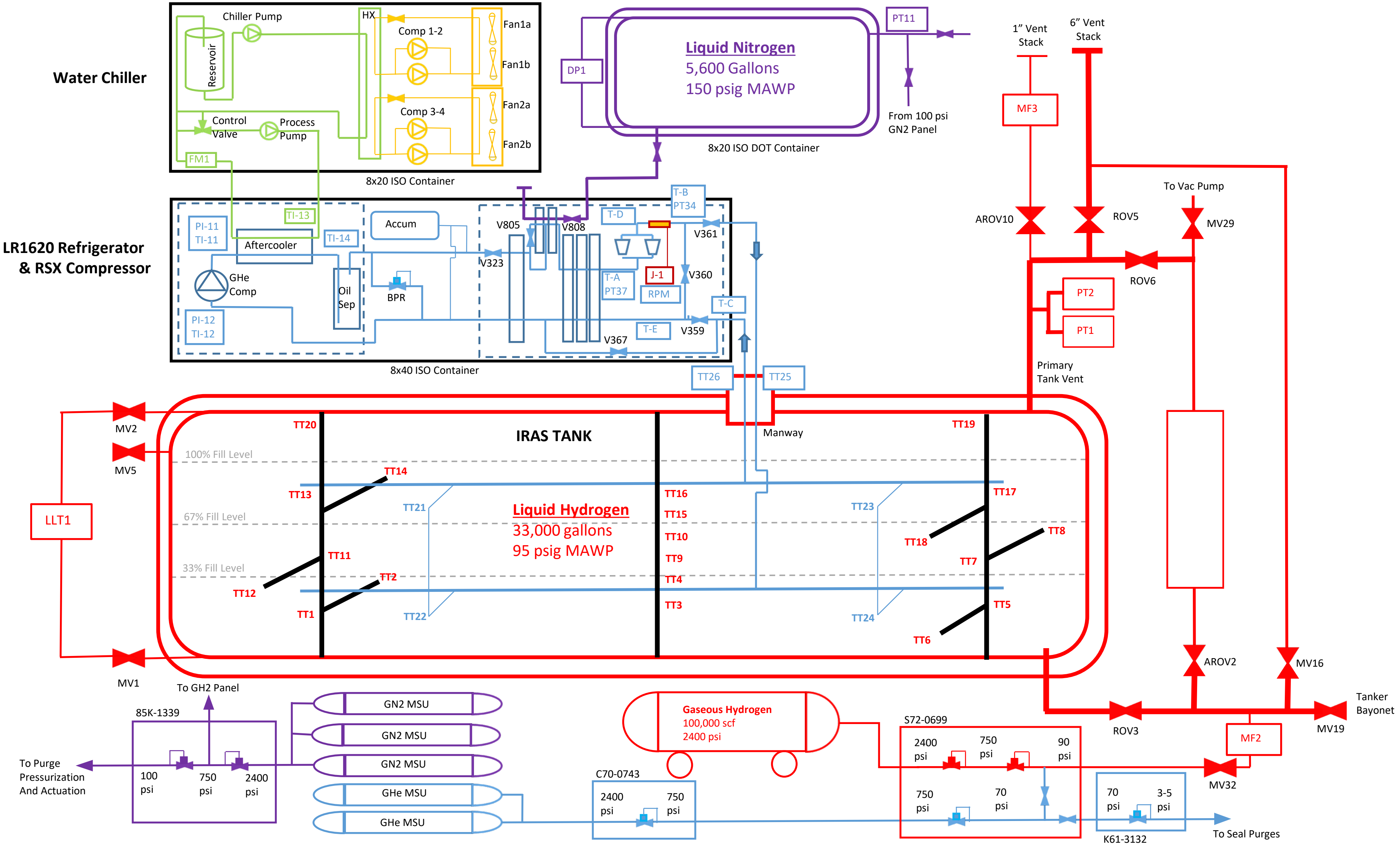
# Site Build-Up

October 30th, 2014

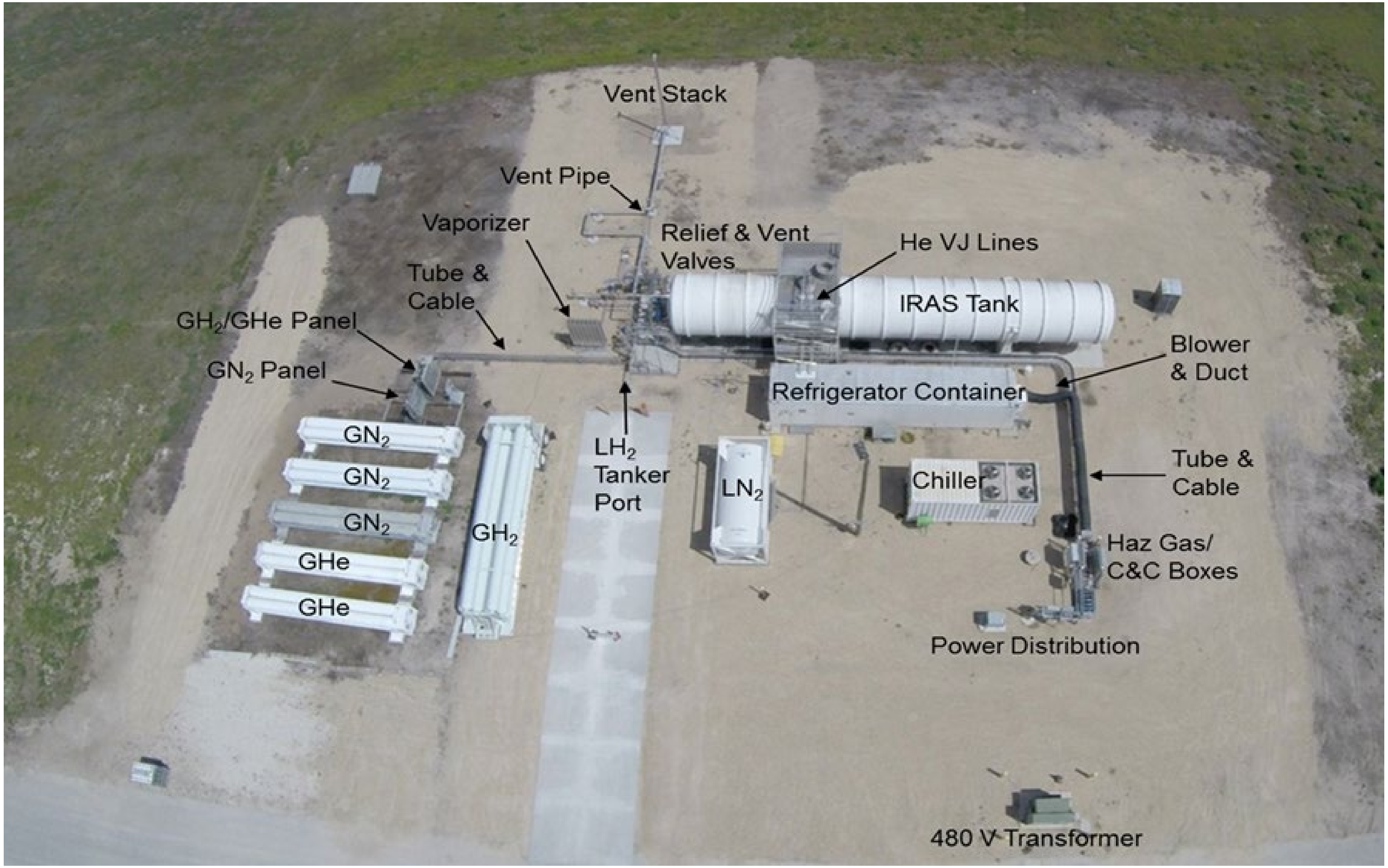
# Site Build-Up




# GODU-LH2 Functional Diagram



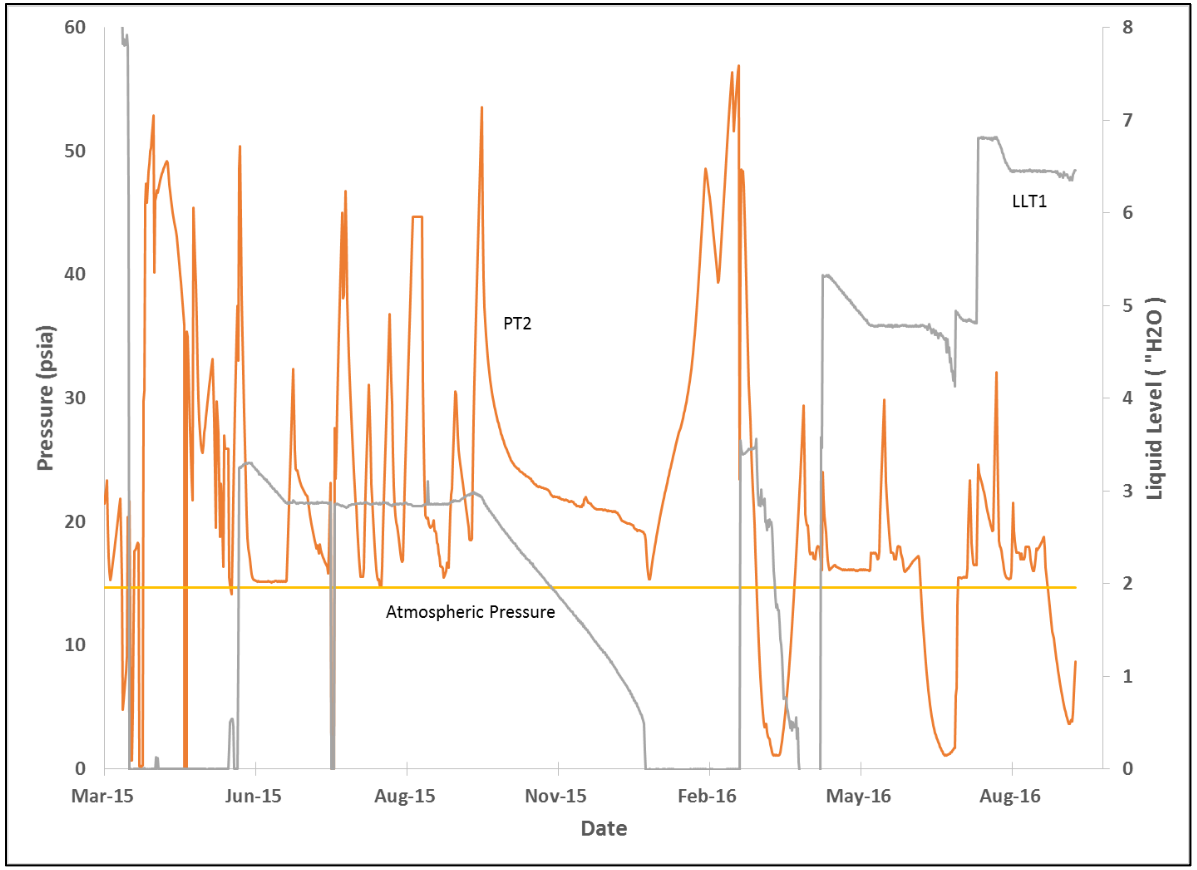
# "Bird's-eye View" of GODU-LH2 Site



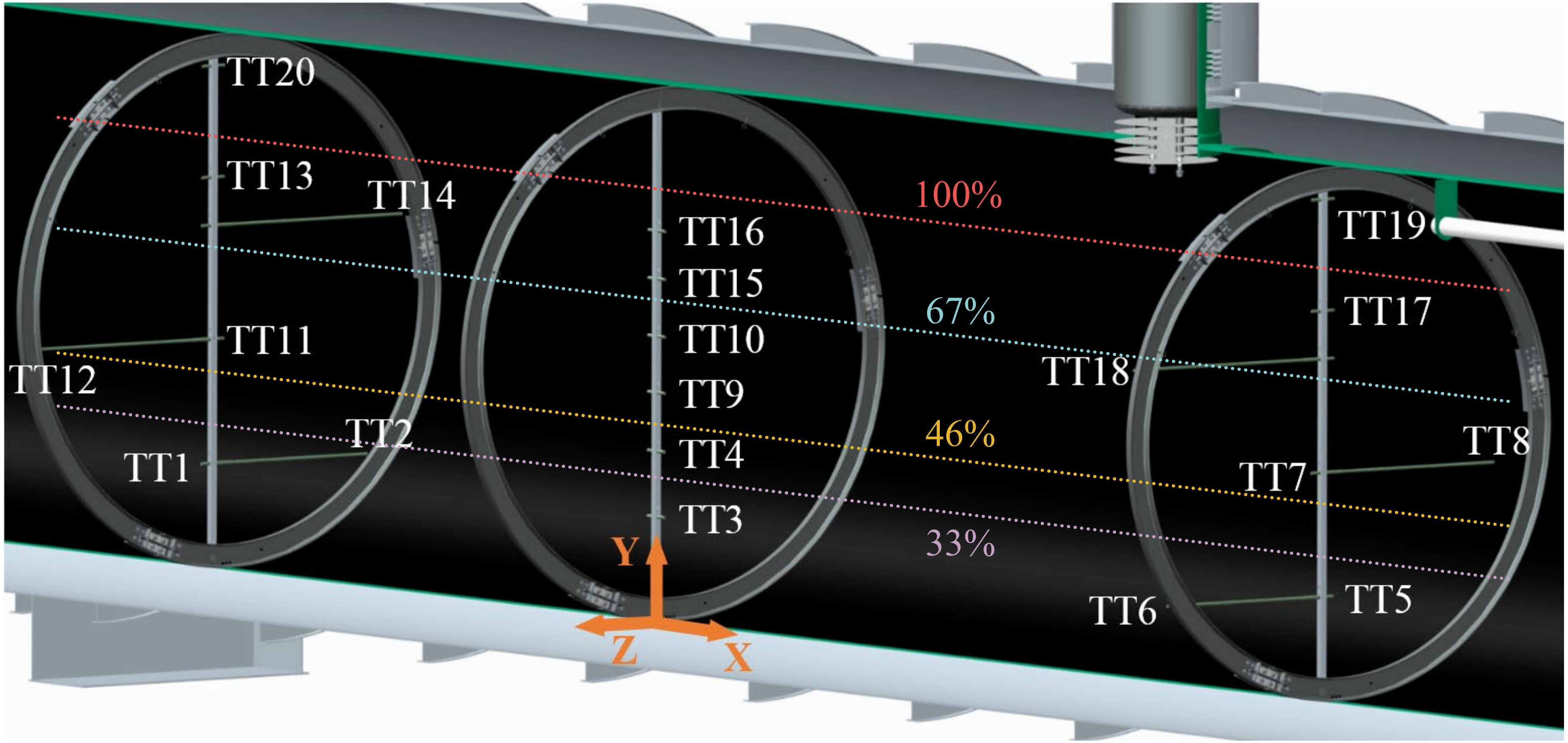
# Test Matrix and Timeline

- 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 |



# Inner Tank Instrumentation



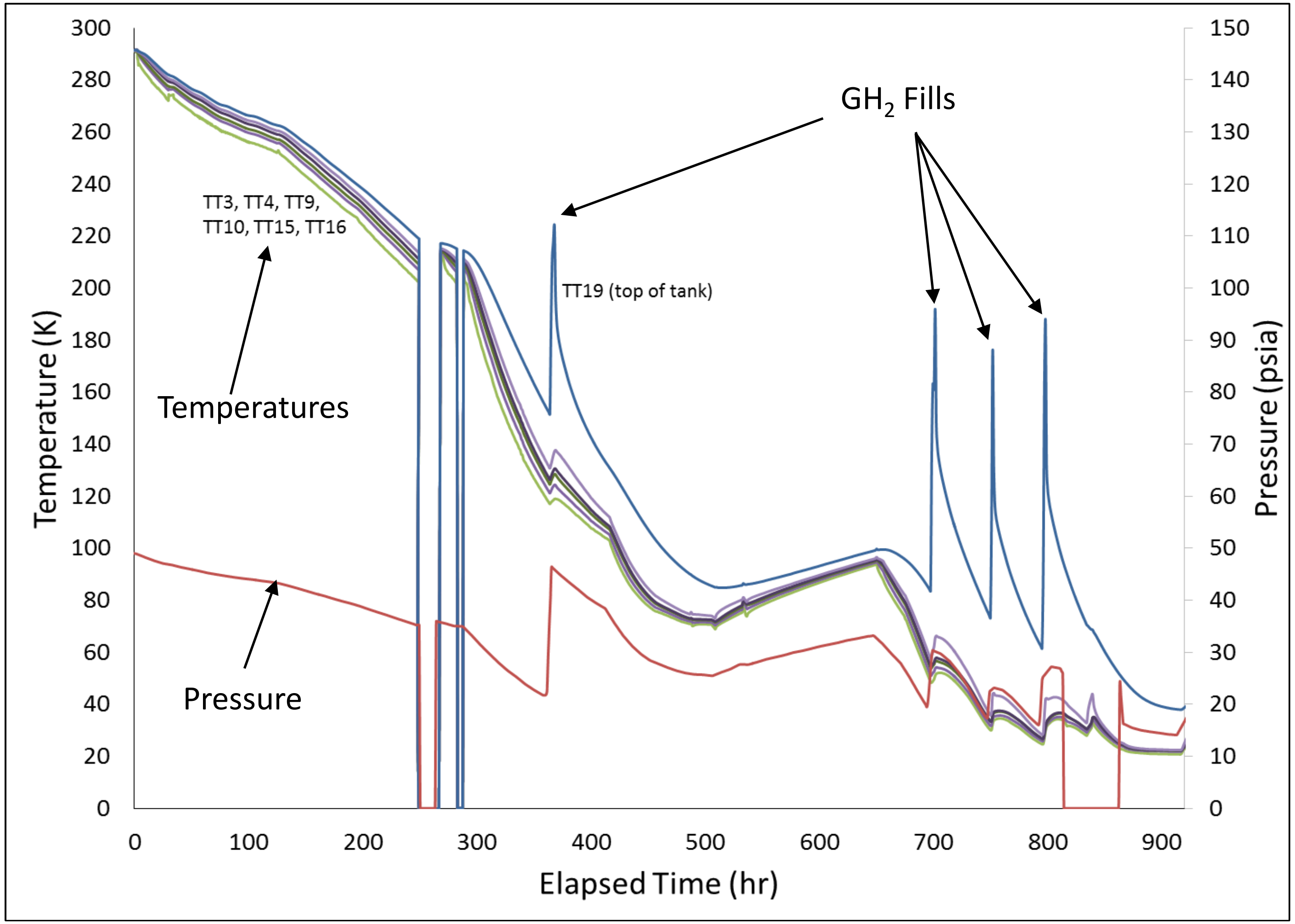

Accuracies

Diodes: ±0.5 K from 450 K to 25 K, and ±0.1 K from 25 K to 1.5 K

Pressure Transducers: ±6.89 kPa (1% of full scale)

# Zero-Loss Tank Chilldown Test Results

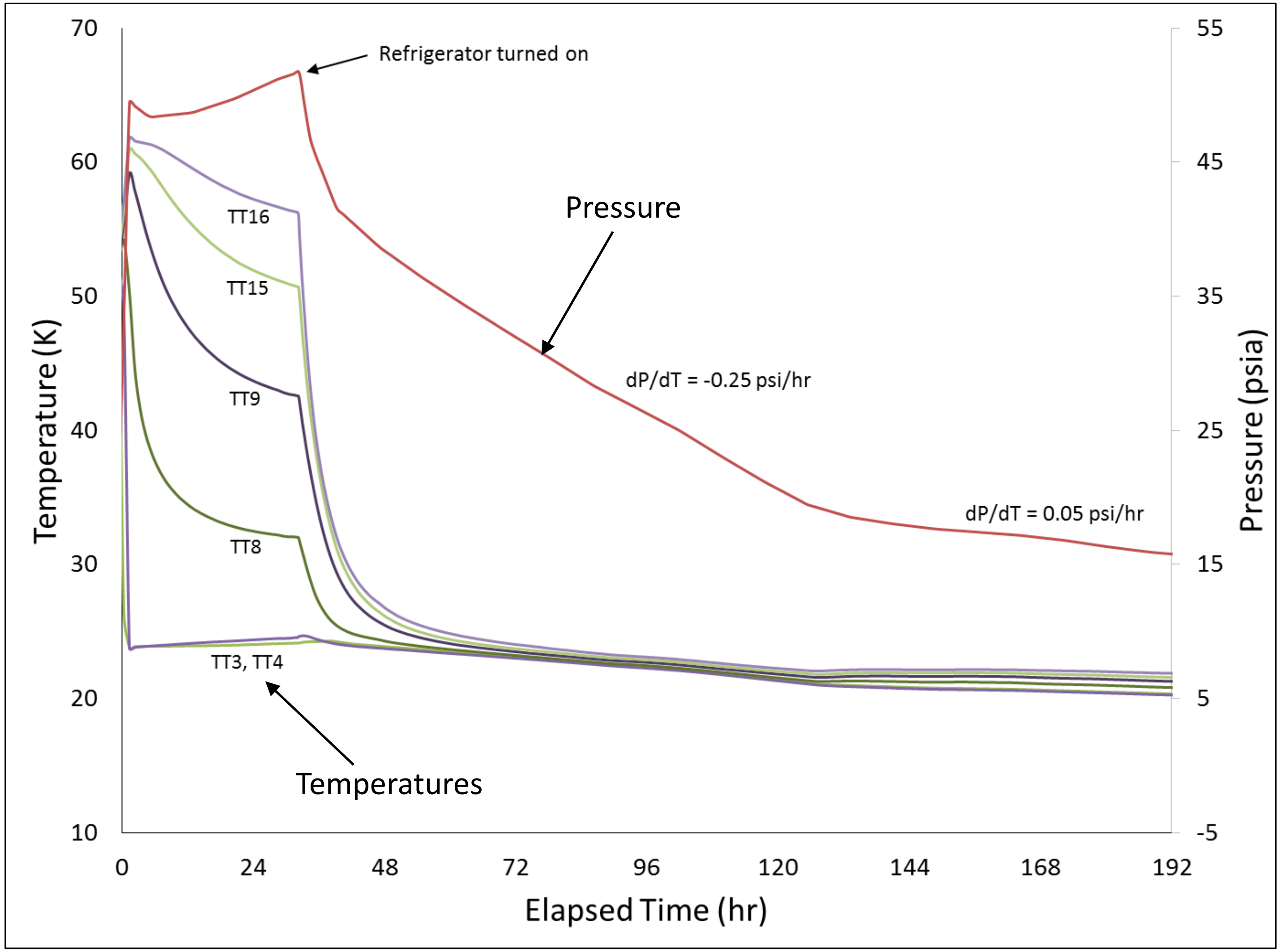
- Initial Conditions
  - 99.95% $GH_2$ at 300 K and 40 psia.
- Lock up tank and turn on refrigerator at T-0.
- Add $GH_2$ as tank pressure decreases
- Final Conditions
  - Tank near isothermal at 20.8K - 22.4 K and 14.7 psia
  - Saturated vapor with condensation on HX tubing
- Multiple lessons learned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



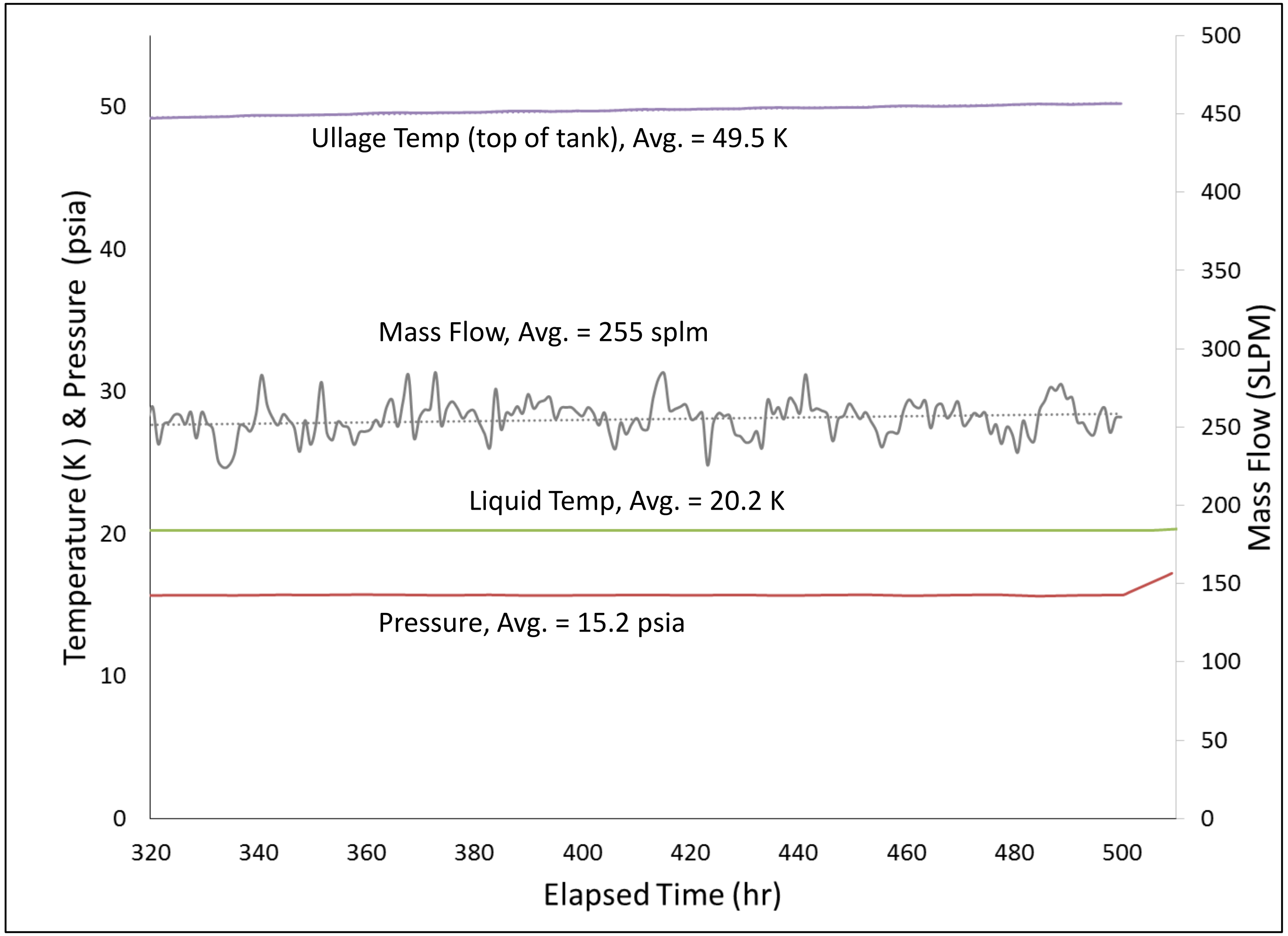

**Conclusion: IRAS enables zero-loss tanker offloads at all fill levels**

# 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

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

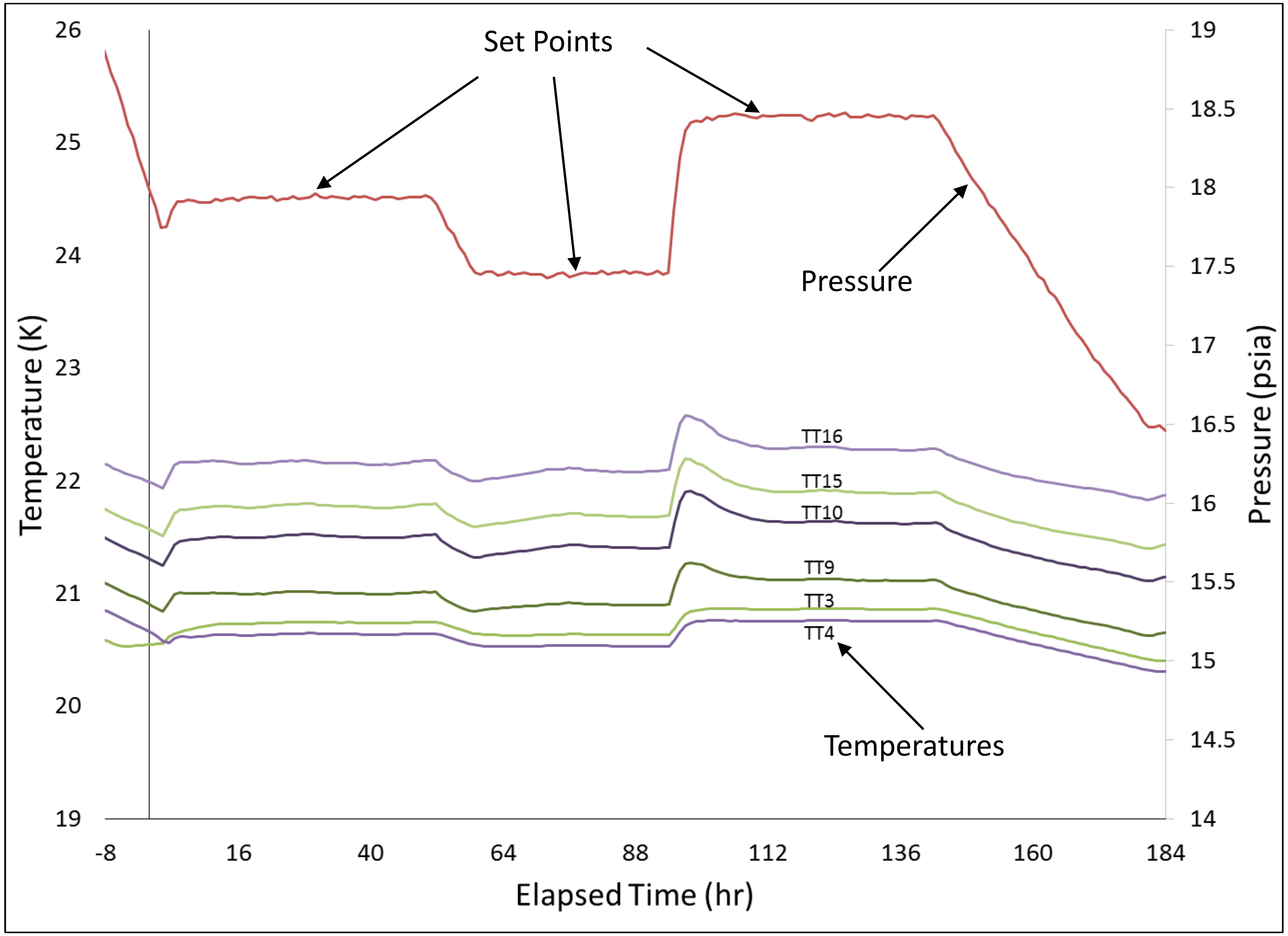
| Level % | MF3 (slm) | PT2 (psia) | TT19 (K) | $Q_L$ (W) | $Q_V$ (W) | Q (W) |
|---|---|---|---|---|---|---|
| 33 | 255 | 15.2 | 49.5 | 170 | 120 | 290 |
| 67 | 295 | 16.6 | 41.3 | 196 | 100 | 296 |
| 100 | 351 | 15.9 | 34.5 | 234 | 81 | 315 |




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

# ZBO Pressure Control Test Results

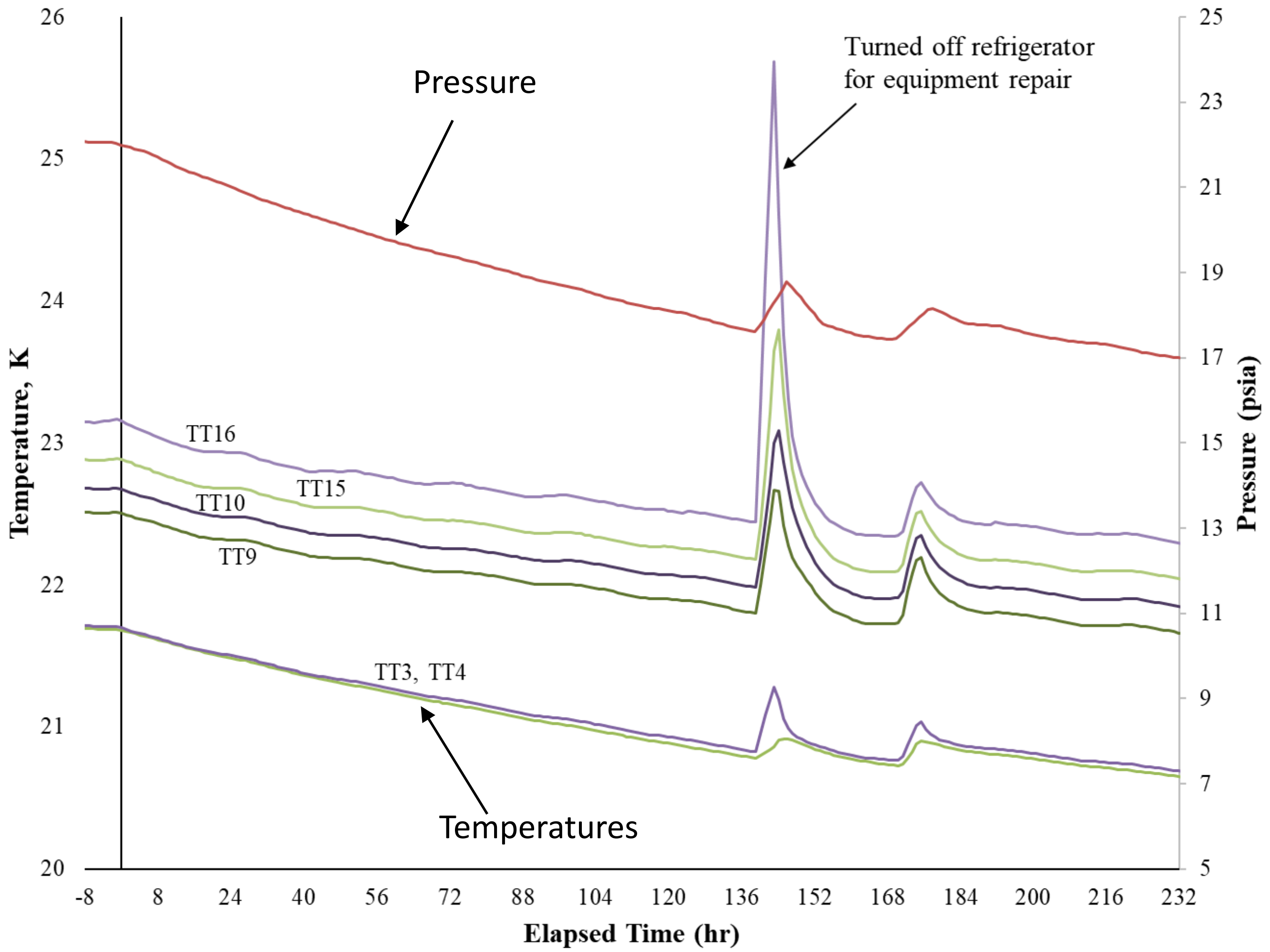
- GODU-LH2 software controlled refrigerator to achieve and maintain IRAS tank pressure set-point.
- No $LN_2$ pre-cooling used
- Approach set points from above and below
- Pressure stability +/- 0.5% for all three fill levels
- Near isothermal temperature profile following saturation line




**Conclusion: IRAS using tank pressure control achieves ZBO and provides complete control over the state of the fluid**

# ZBO Temperature Control Test Results

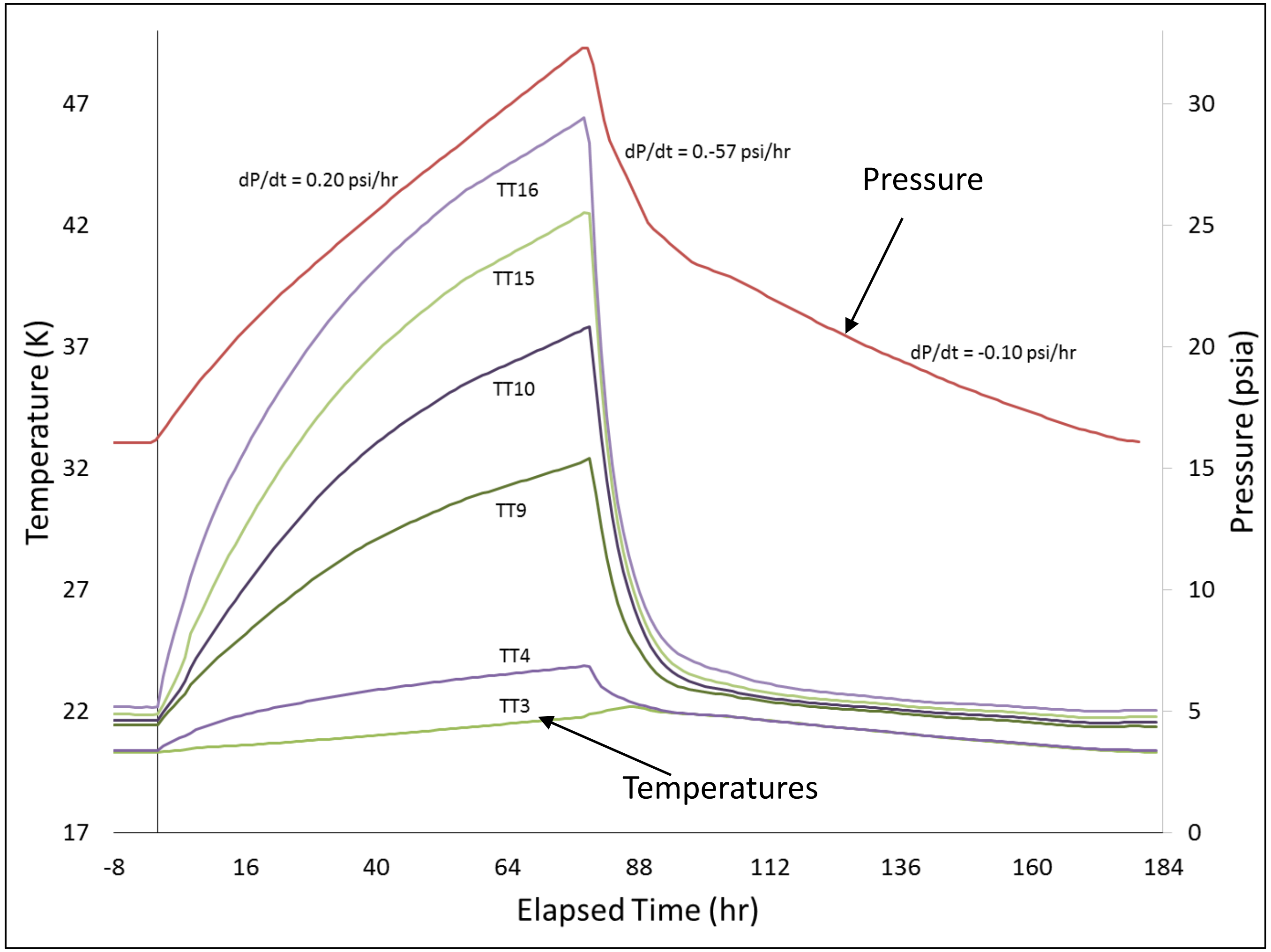
- Linde software controlled refrigerator to achieve and maintain constant helium supply temperature.
- No $LN_2$ pre-cooling used
- Helium supply temperature response fast and accurate
- But $LH_2$ takes long time period to reach equilibrium state




**Conclusion: IRAS using supply temperature control achieves ZBO but takes a long time to reach $LH_2$ equilibrium state**

# ZBO Duty Cycle Test Results

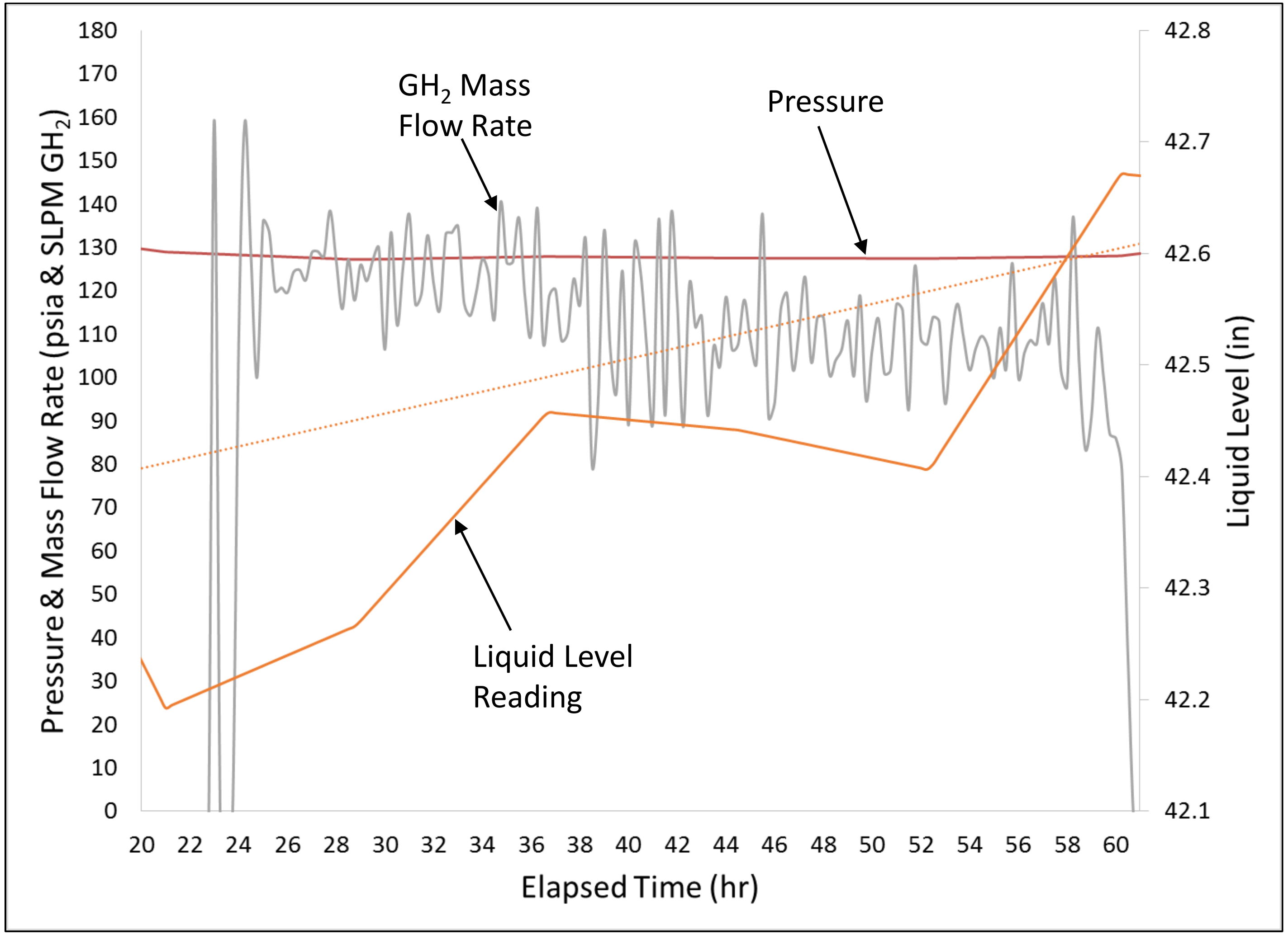
- ZBO achieved in batch processes by turning on and off the refrigerator as required
- Testing was both accidental and purposeful
- Minimum electrical cost but depends on multiple start/stop cycles of cryogenic equipment
- Duty cycle varied from 1.13 (33%) to 1.16 (67%) to 3.6 (100%) on/off with no $LN_2$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

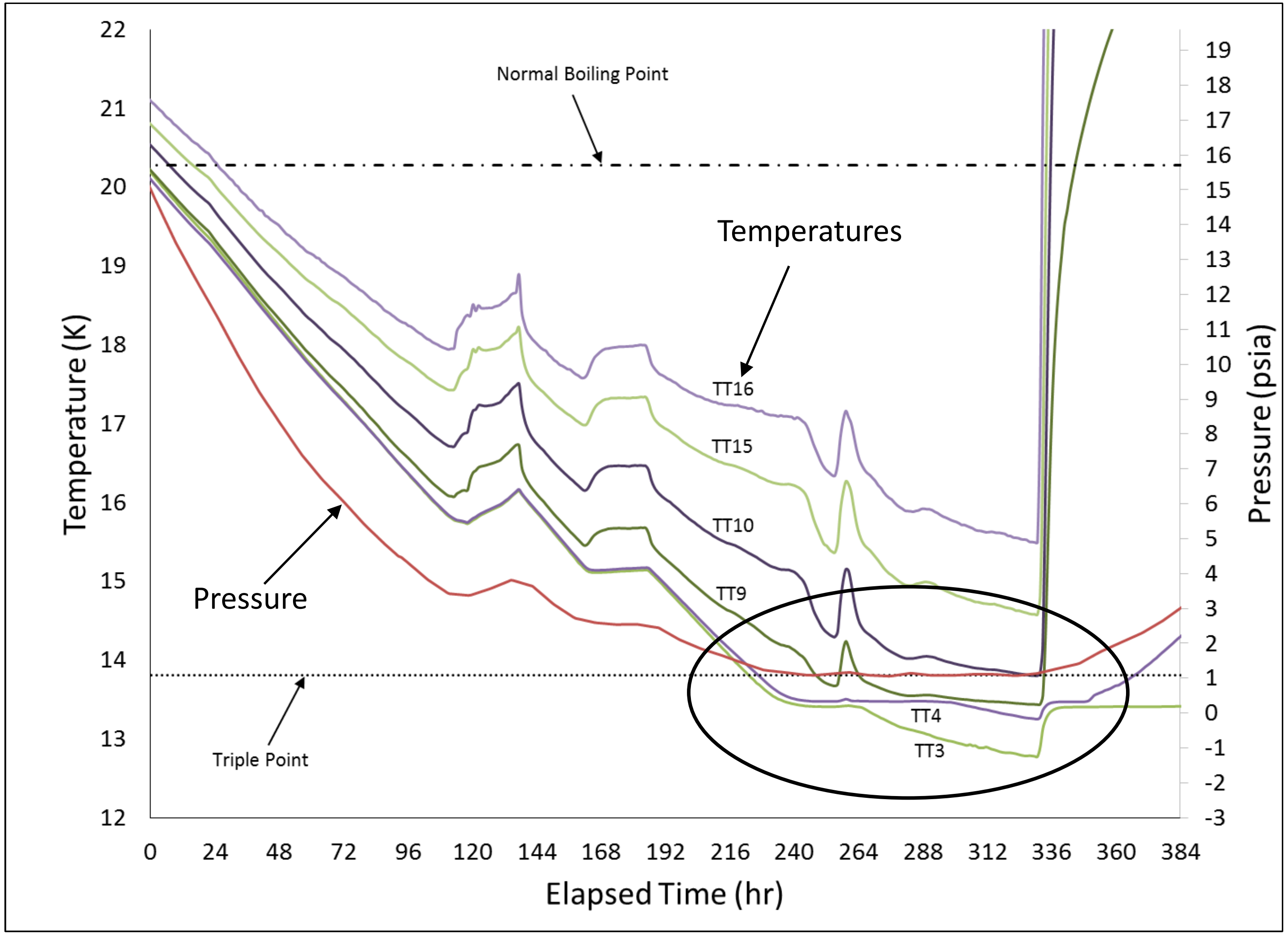
- $GH_2$ was controlled using a mass flow controller until the tank pressure remained constant.
- <u>NOT</u> optimized for liquefaction. $GH_2$ was fed in at ambient temperature.
- Using $LN_2$ pre-cooling, roughly 78 gal of $LH_2$ was produced during the test.




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

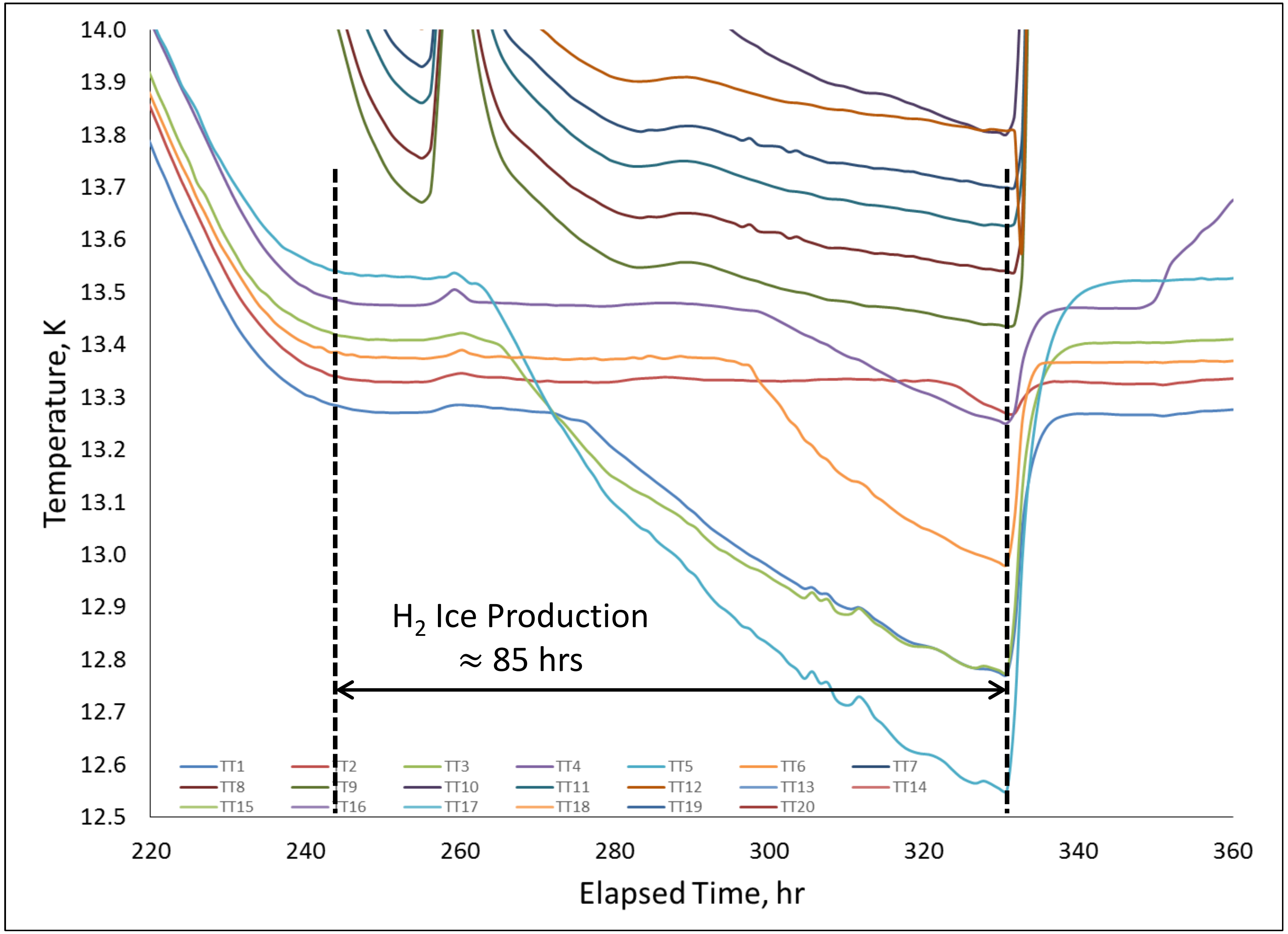
# Densification Test Results

- 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**



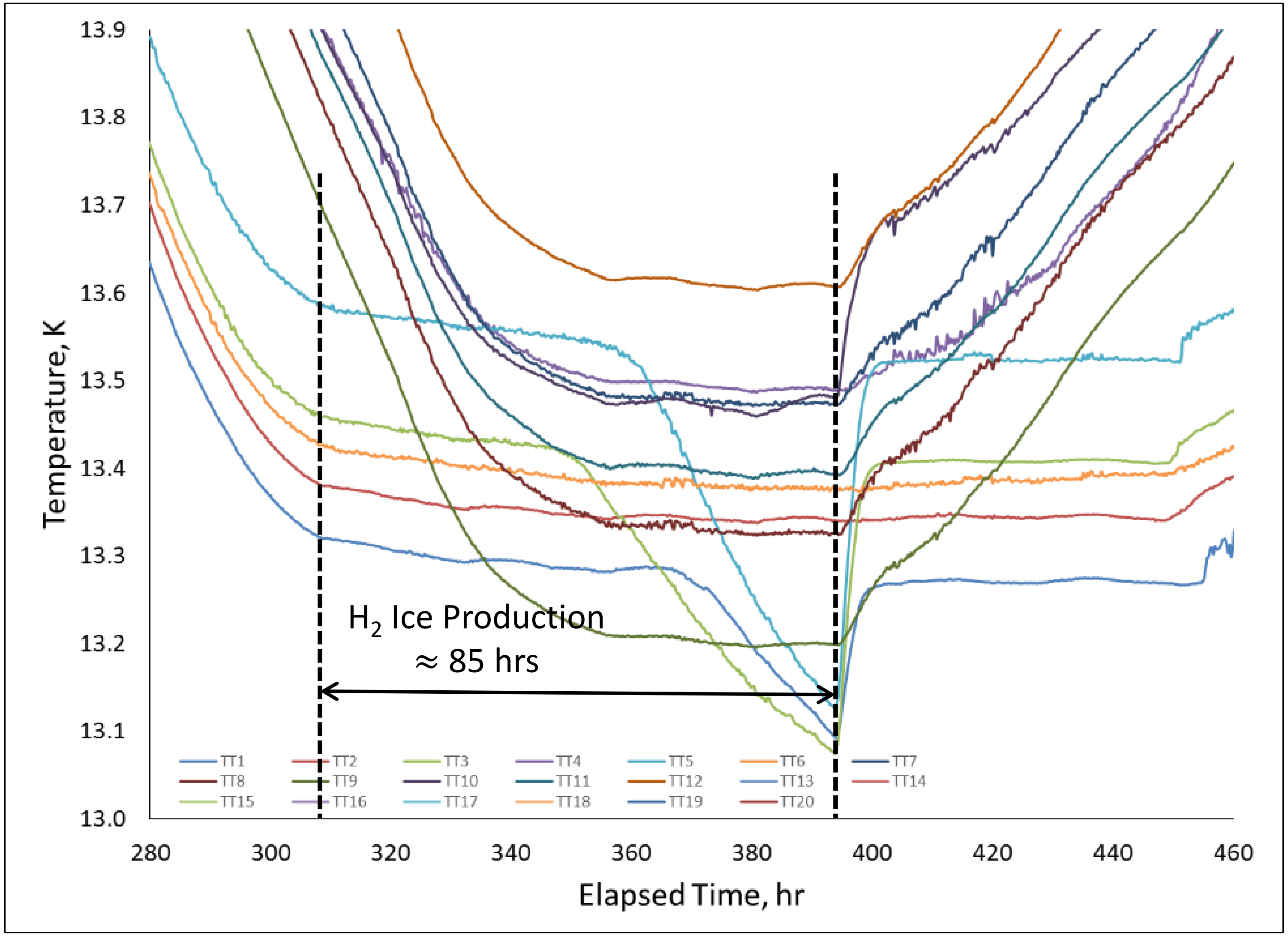

**Conclusion: IRAS enables propellant densification down to the freezing point**

# Solid Hydrogen Production




46% $LH_2$ Fill Level Test

# Solid Hydrogen Production




67% $LH_2$ Fill Level Test

# Conclusions

- The GODU-LH2 system successfully met all test objectives at the 33%, 46%, 67%, and 100% tank fill levels
- Complete control over the state of the fluid has been demonstrated using Integrated Refrigeration and Storage (IRAS)
  - First large-scale demonstration of **Full Control Storage** of $LH_2$
  - Almost any desired point within the liquid phase envelop can essentially be “dialed in” and maintained indefinitely
- System can also be used to **produce densified/slush hydrogen in large quantities**

# Current Status of the System

- Refrigeration system consolidated into a single 40’ shipping container
- IRAS tank and fridge currently installed at Test Stand 300 at NASA-MSFC in Alabama for an upcoming densification loading test

# Thank you for your attention!

# Questions?

# Image References


1. Krenn, A., et. al.,  2015, The safe removal of frozen air from the annulus of an LH2 storage tank, *Advances in Cryogenic Engineering, AIP Conference Proceedings,* doi:10.1088/1757-899X/101/1/012031
2. http://www.apolloarchive.com/apollo_gallery.html
3. https://www.nasa.gov/mission_pages/shuttle/flyout/launchpadflyout.html
4. https://www.teslarati.com/spacex-nears-third-falcon-heavy-launch/

# Technical References


1. *Kennedy Engineering Academy #144: Final Results of the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) Project,* Kennedy Space Center, FL, March 28th, 2017 (https://ntrs.nasa.gov/citations/20170002713)
2. *IRAS Maximizes Cryogenic Process Efficiency*—Notardonato, Fesmire, & Swanger, *Cold Facts* magazine, Vol 33, Number 3, June 2017 (https://cryogenicsociety.org/35879/news/iras_maximizes_cryogenic_process_efficiency/)
3. *New Technology at NASA Offers Full Control Of Cryogenic Liquids*—*Cold Facts* magazine, Vol 35, Number 1, February 2019 (https://cryogenicsociety.org/36886/news/new_technology_at_nasa_offers_full_control_of_cryogenic_liquids/)
4. *ASME Section VIII Recertification of a 33,000 Gallon Vacuum-Jacketed LH2 Storage Vessel for Densified Hydrogen Testing at NASA Kennedy Space Center,* Swanger A. M., Notardonato W. U., and Jumper K. M., Proceeding of the ASME Pressure Vessels and Piping Conference, Massachusetts, Boston, PVP2015-45625, (2015)
5. *Modification of a Liquid Hydrogen Tank for Integrated Refrigeration and Storage,* Swanger A. M., Jumper, K. M., Fesmire J. E., and Notardonato W. U., Advances in Cryogenic Engineering, IOP Conf. Series: Materials Science and Engineering 101 (2015) 012080 doi:10.1088/1757-899X/101/1/012080
6. *Integrated Refrigeration and Storage for Advanced Liquid Hydrogen Operations,* Swanger A. M., Notardonato W. U., Johnson W. L., and Tomsik T. M., Cryocooler 19: Proceedings of the 2016 International Cryocooler Conference, San Diego, California, 513-522 (2016)
7. *Large scale production of densified hydrogen to the triple point and below,* Swanger A. M., Notardonato W. U., Fesmire J. E., Jumper K. M., Johnson W. L., and Tomsik T. M., Advances in Cryogenic Engineering, IOP Conf. Series: Materials Science and Engineering 101 (2017)
8. *Zero boil-off for large scale liquid hydrogen tank using integrated refrigeration and storage,* Notardonato W. U., Swanger A. M., Fesmire J. E., Jumper K. M., Johnson W. L., and Tomsik T. M., Advances in Cryogenic Engineering, IOP Conf. Series: Materials Science and Engineering 101, (2017)
9. *Final test results for the ground operations demonstration unit for liquid hydrogen,* Notardonato W. U., Swanger A. M., Fesmire J. E., Jumper K. M., Johnson W. L., and Tomsik T.M., *Cryogenics*, Volume 88, (2017), Pages 147-155, ISSN 0011-2275, https://doi.org/10.1016/j.cryogenics.2017.10.008.