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LH_2 Storage and Handling Demonstrations Using Active Refrigeration

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Contents

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]

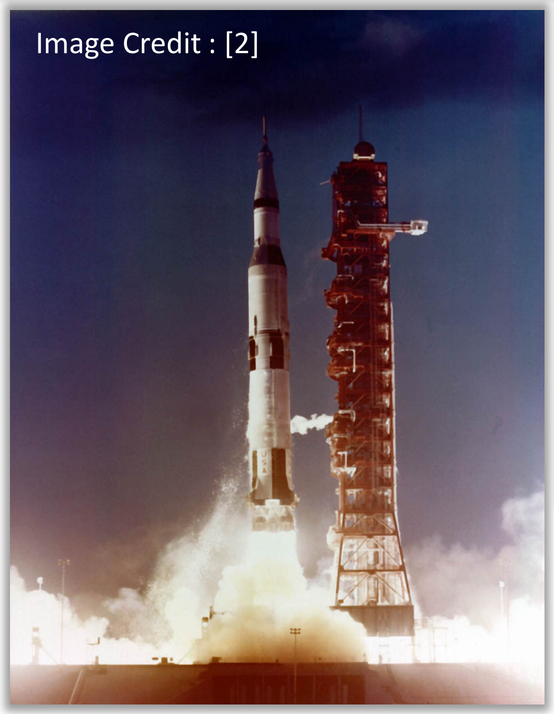
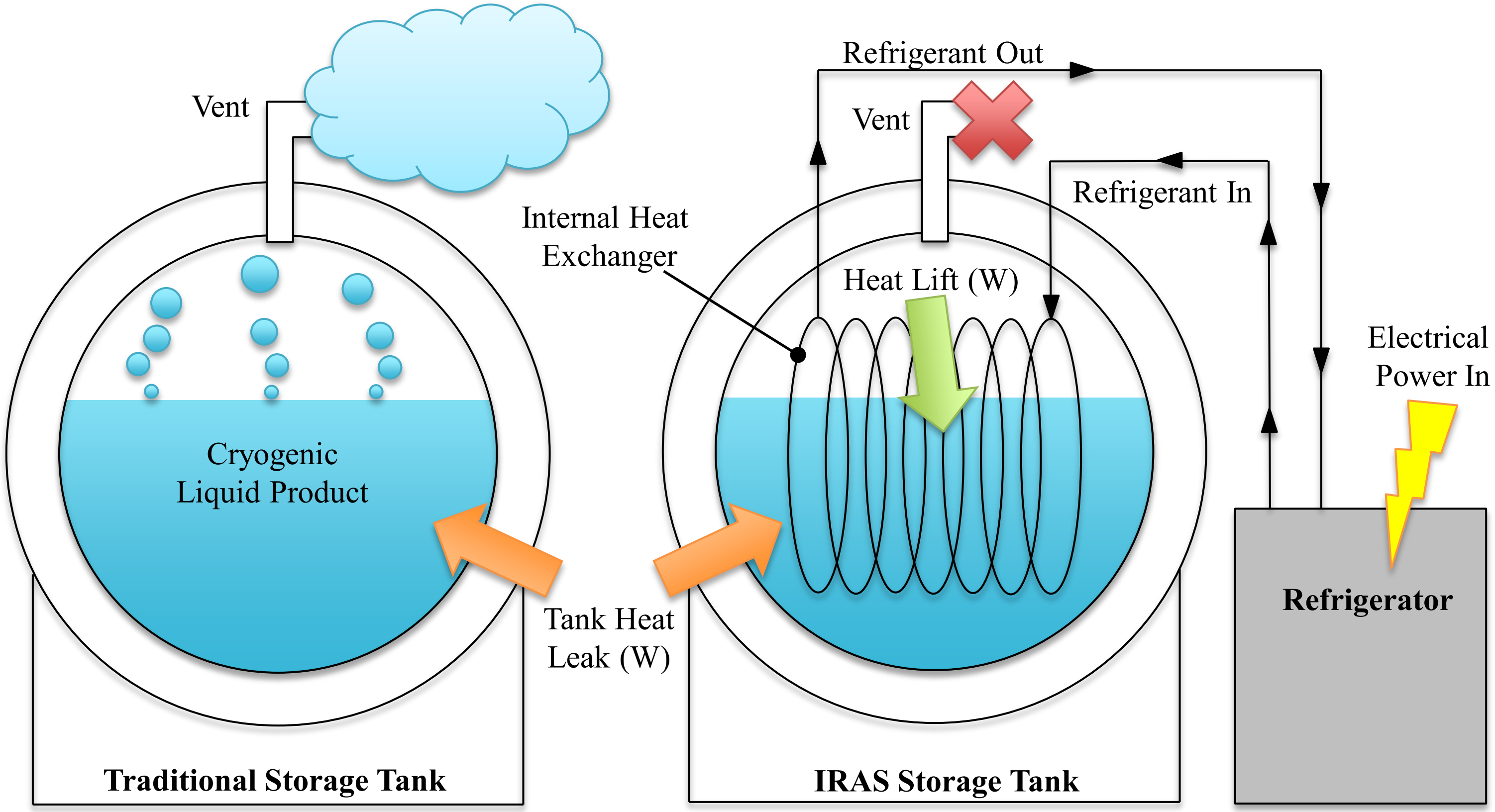


Image Credit : [2]

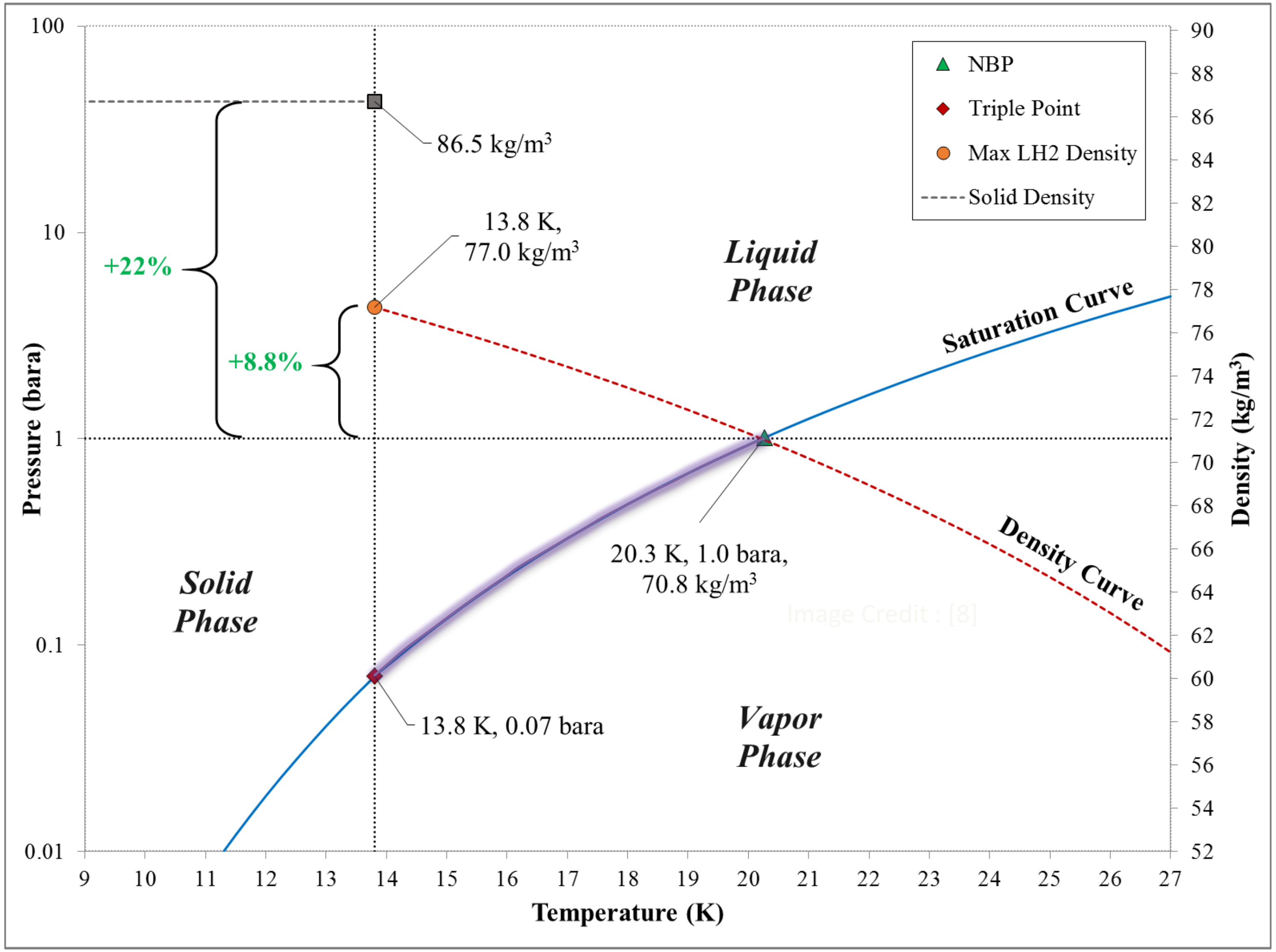
Image Credit : [3]

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

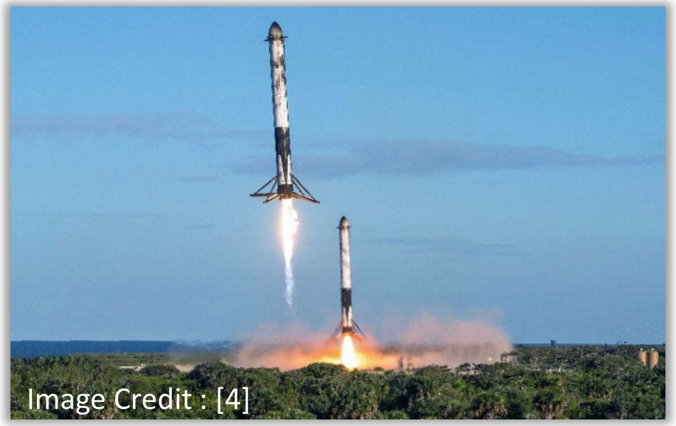


Densification Benefits



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

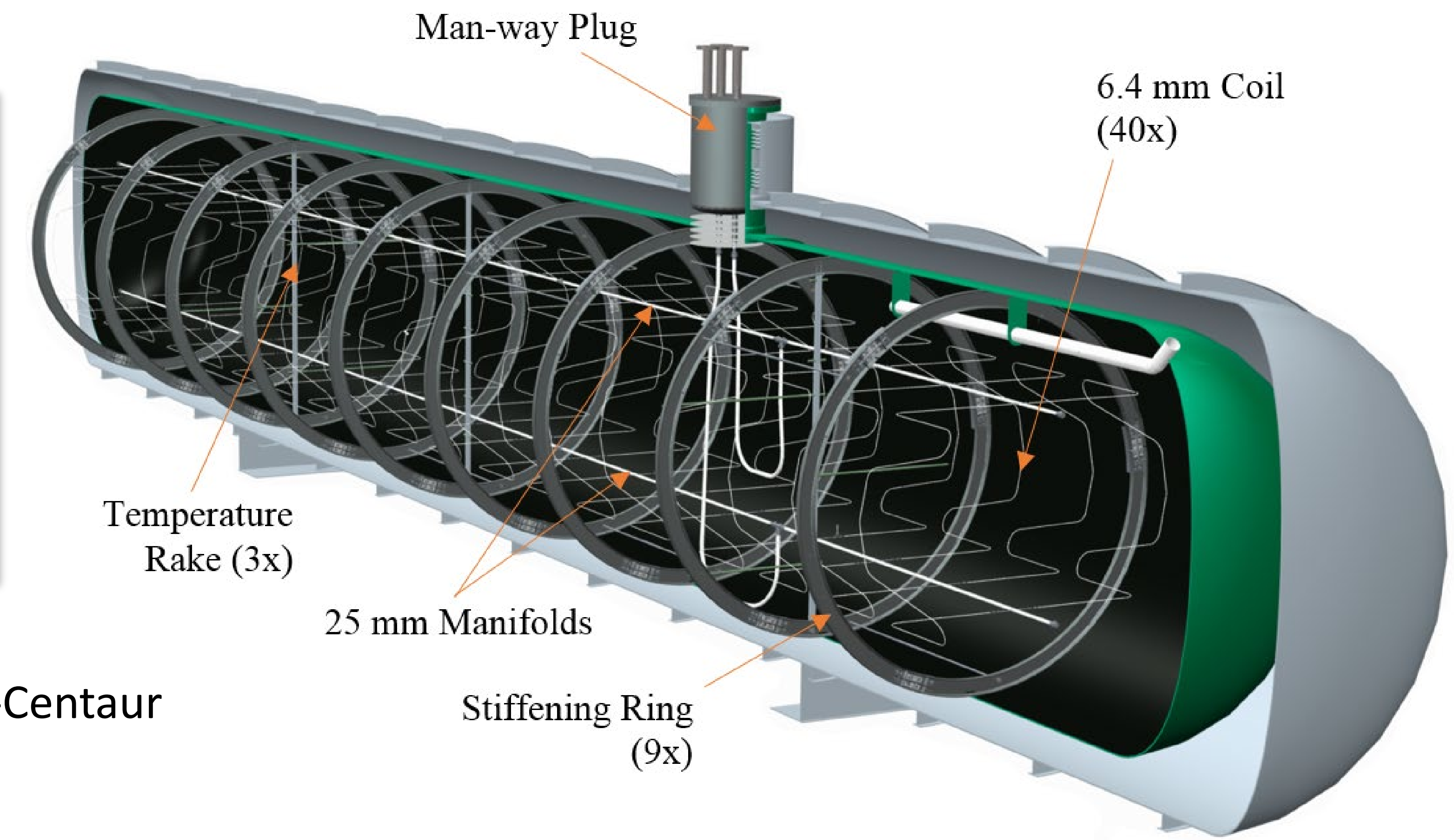
Project Goal

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

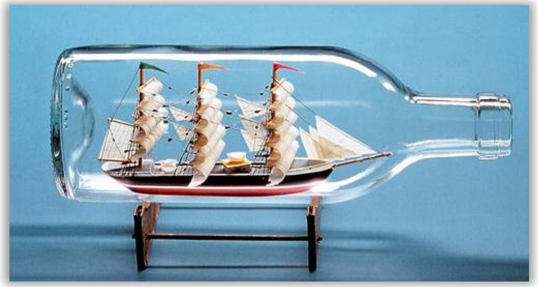
Primary Technical Objectives

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



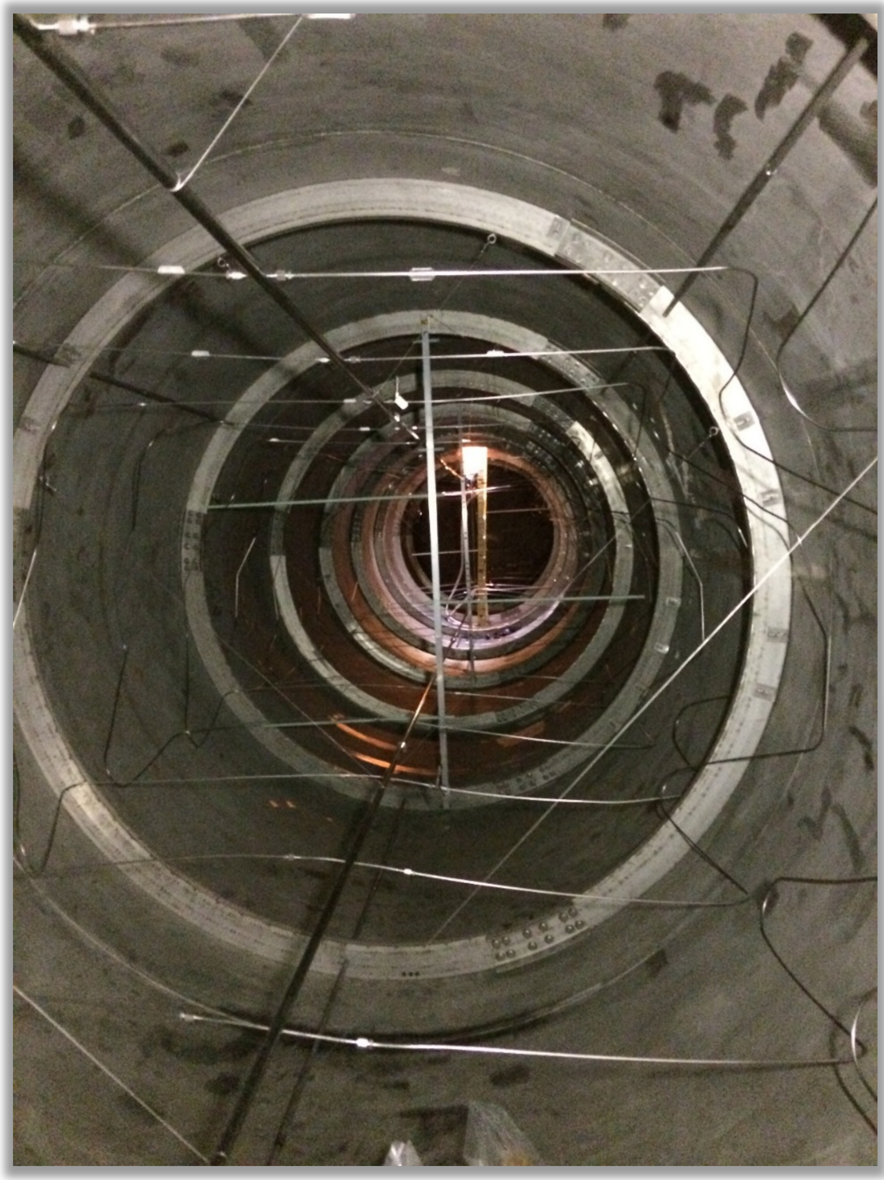
Site Build-Up

September 14th, 2012

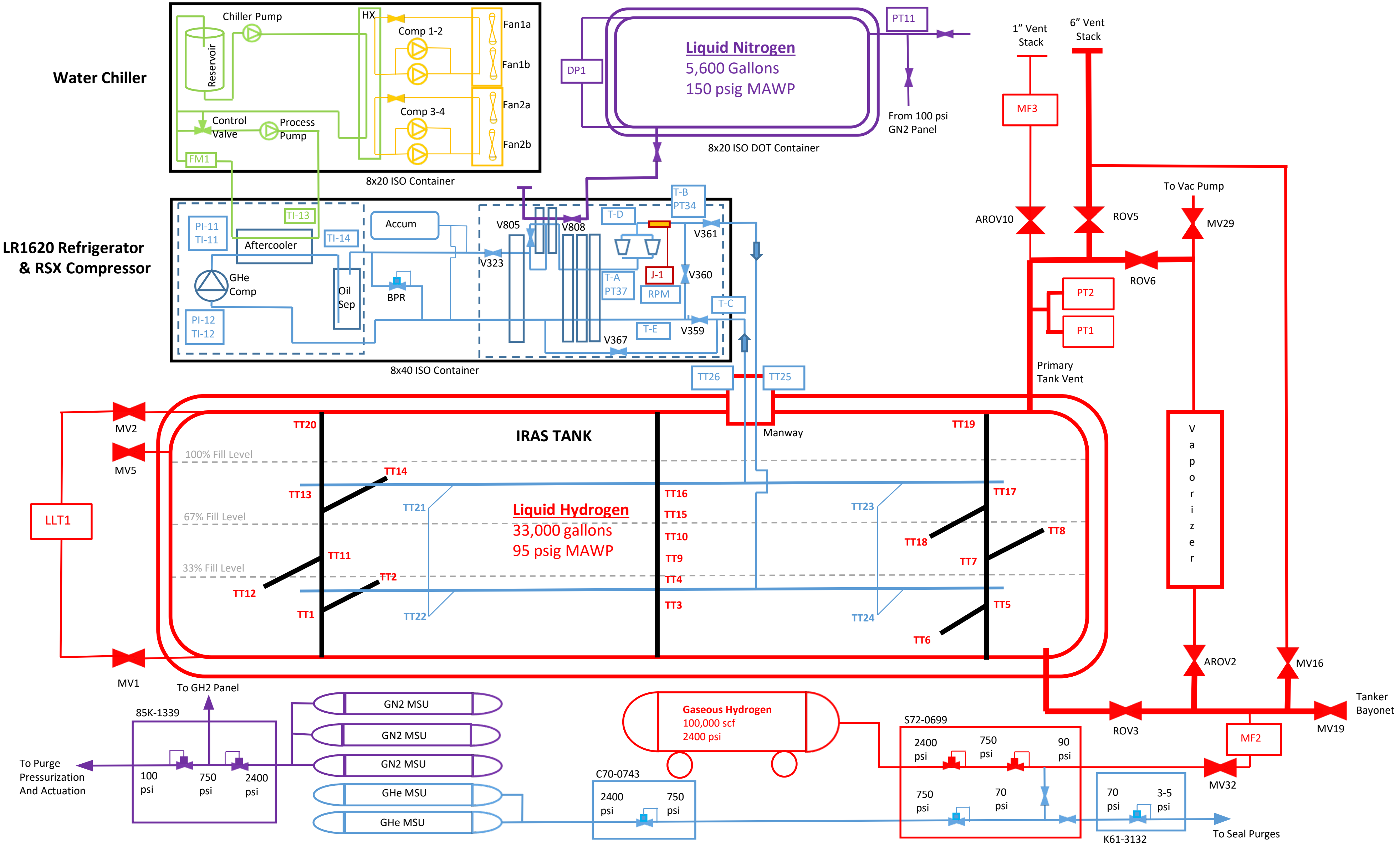
Site Build-Up

October 30th, 2014

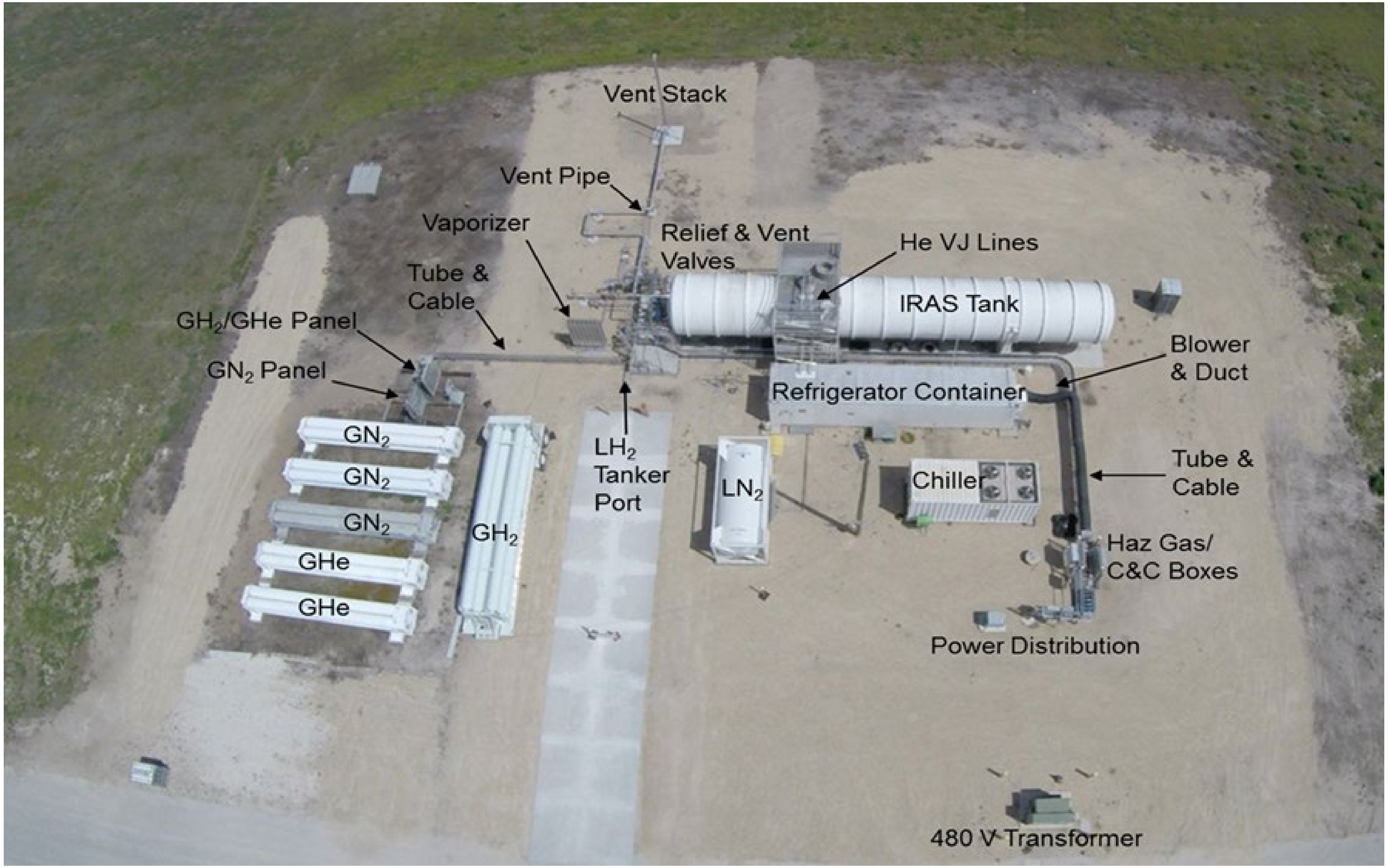
Site Build-Up



GODU-LH2 Functional Diagram



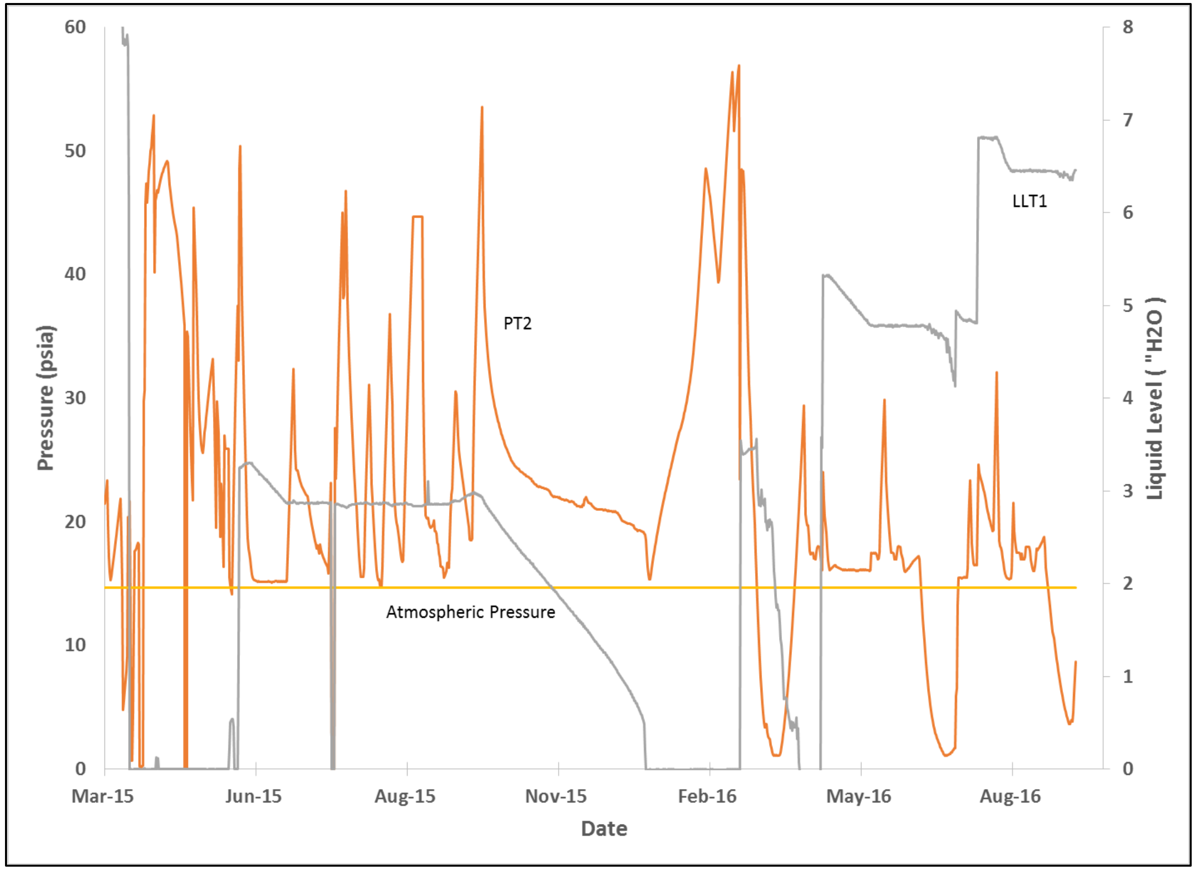
“Bird’s-eye View” of GODU-LH2 Site



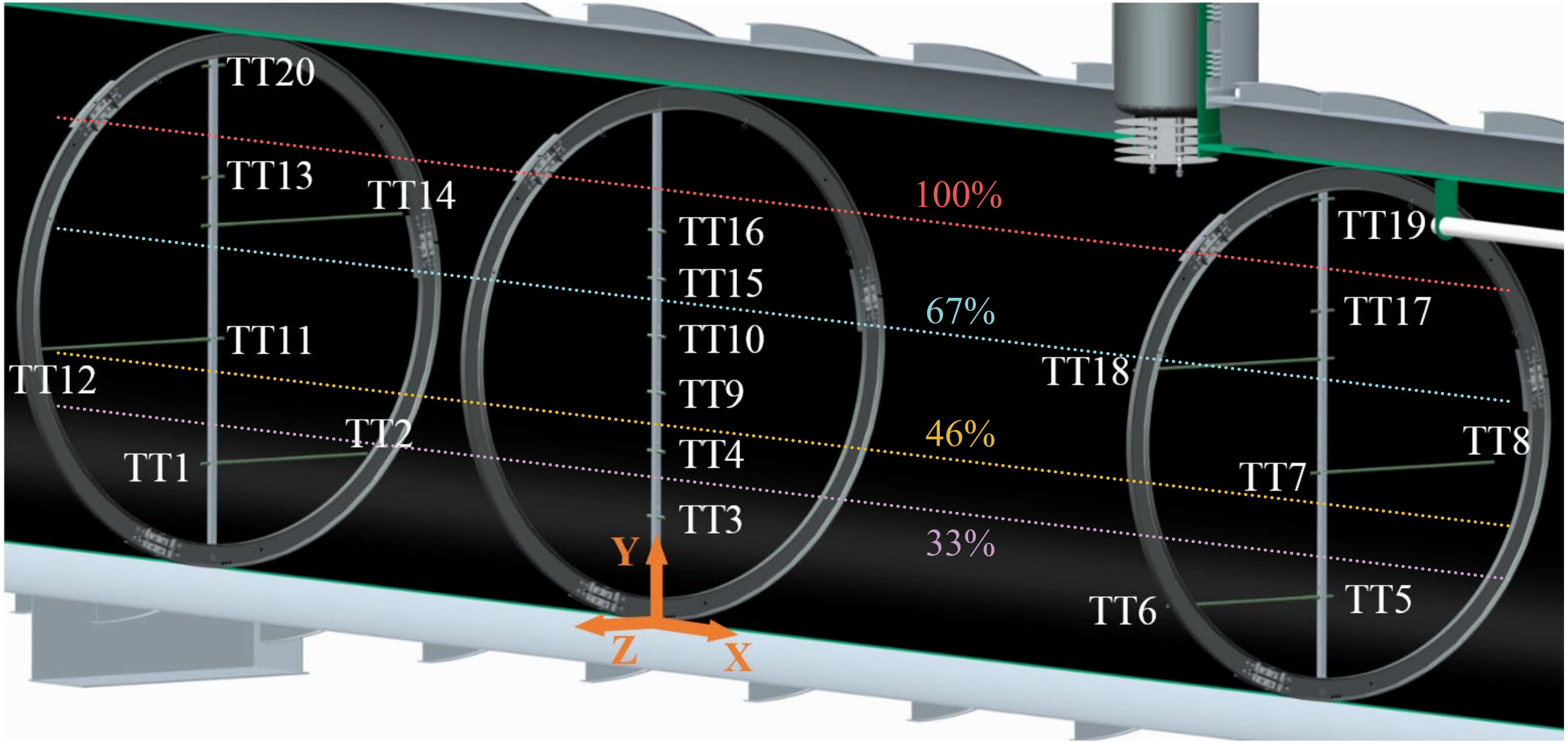
Test Matrix and Timeline

- 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



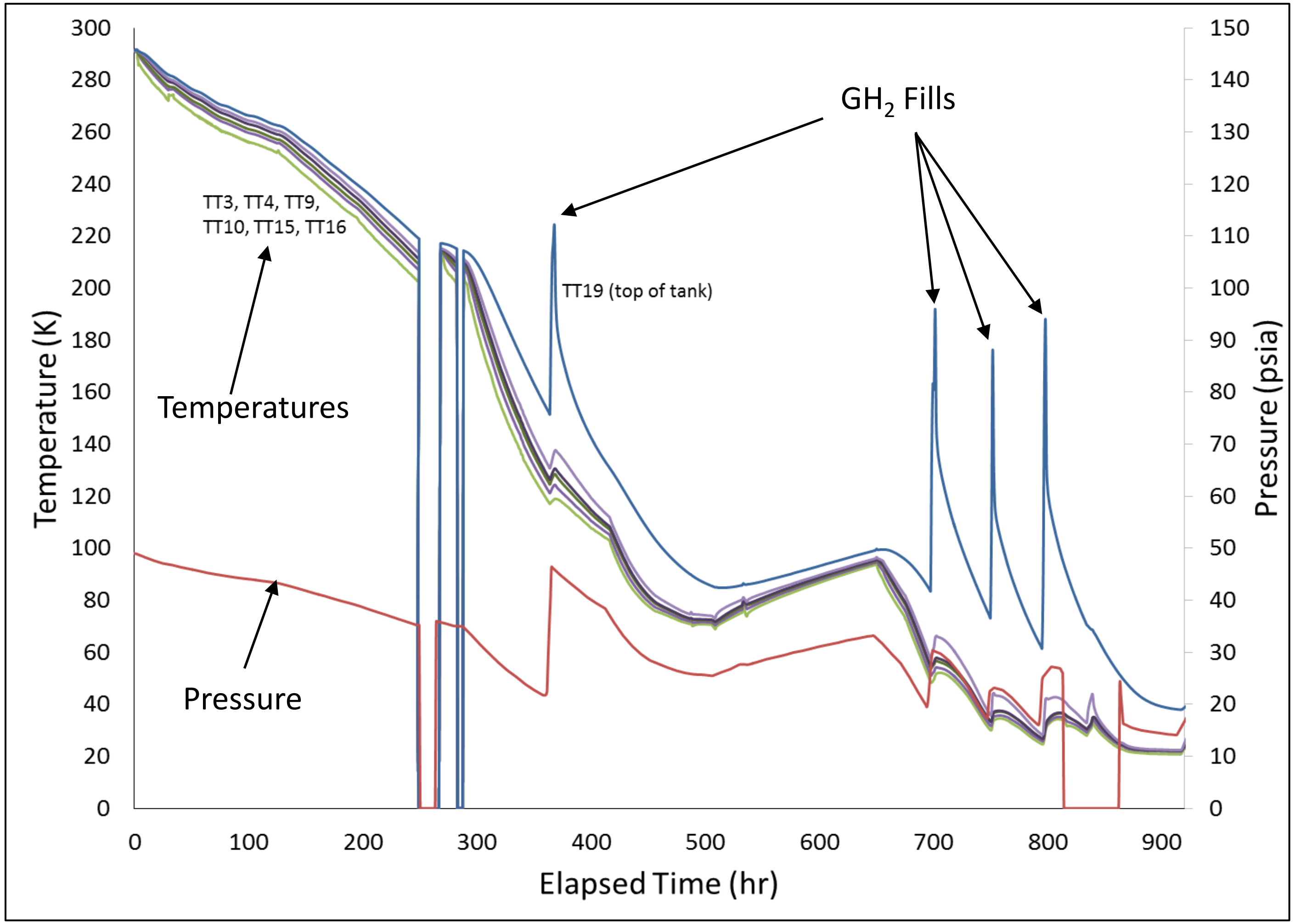
<u>Accuracies</u>

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

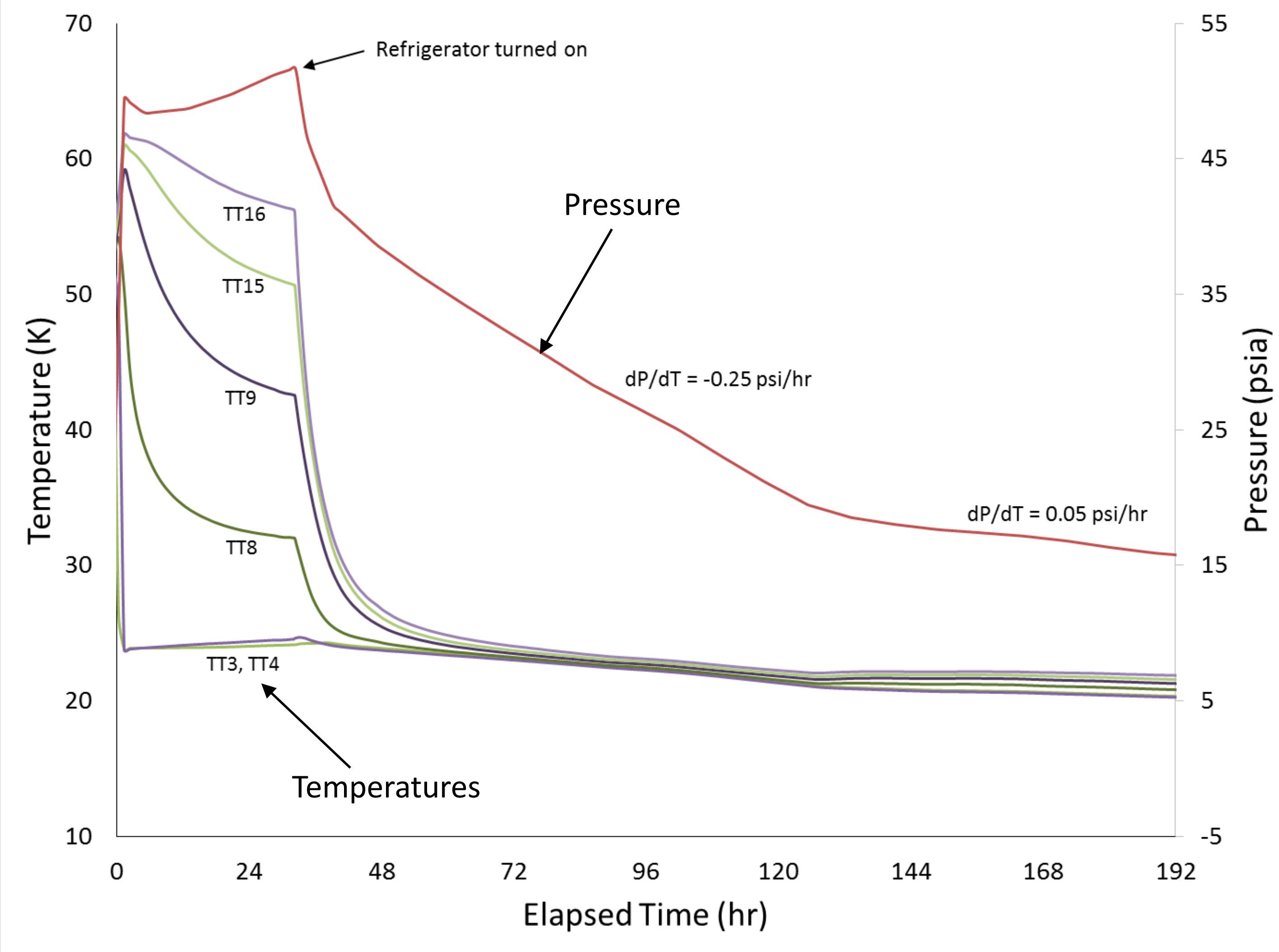
- Initial Conditions
  - 99.95% GH_2 at 300 K and 40 psia.
- Lock up tank and turn on refrigerator at T-0.
- Add GH_2 as tank pressure decreases
- Final Conditions
  - Tank near isothermal at 20.8K - 22.4 K and 14.7 psia
  - Saturated vapor with condensation on HX tubing
- Multiple lessons learned would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



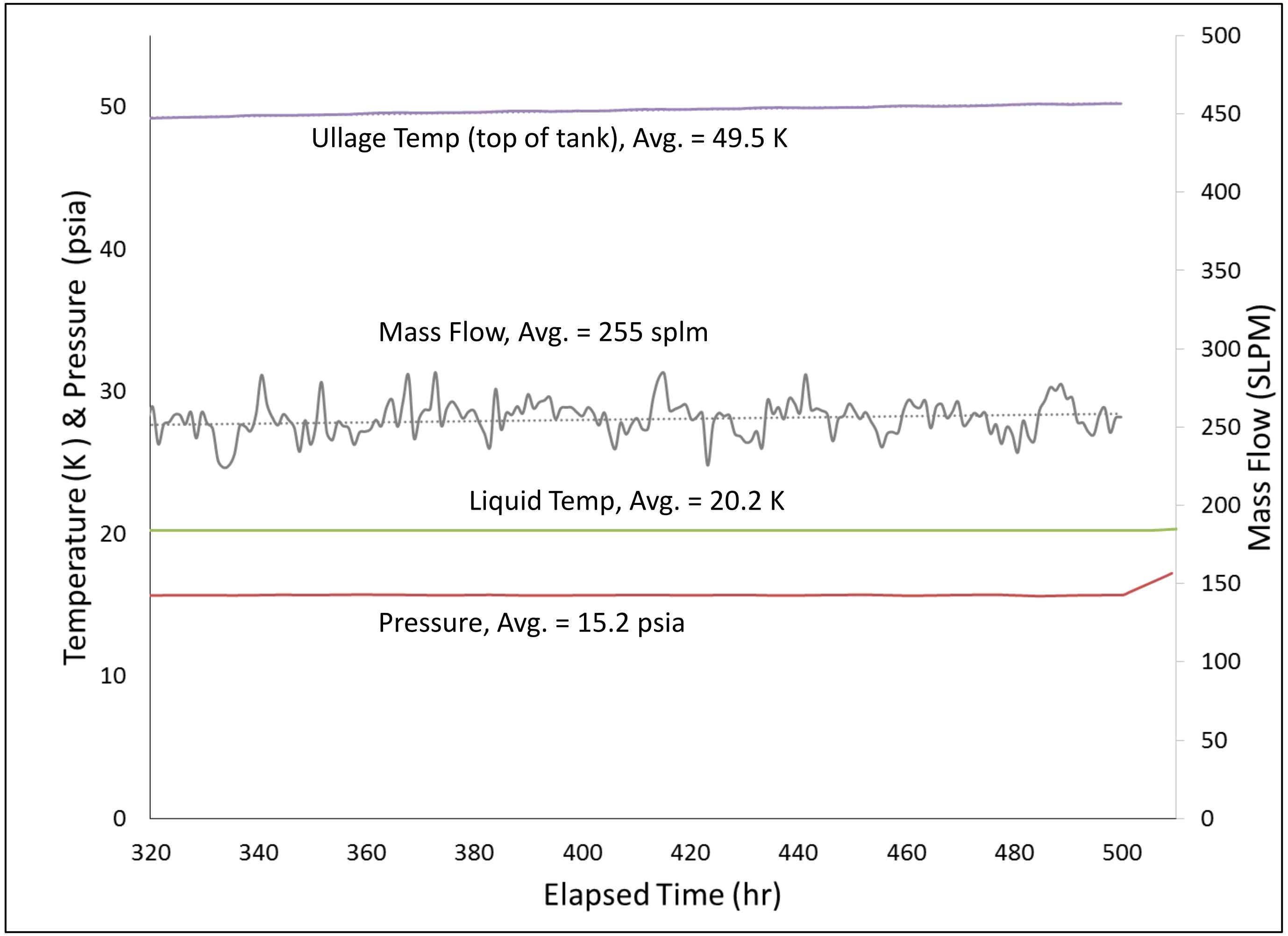
Conclusion: IRAS enables zero-loss tanker offloads at all fill levels

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

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

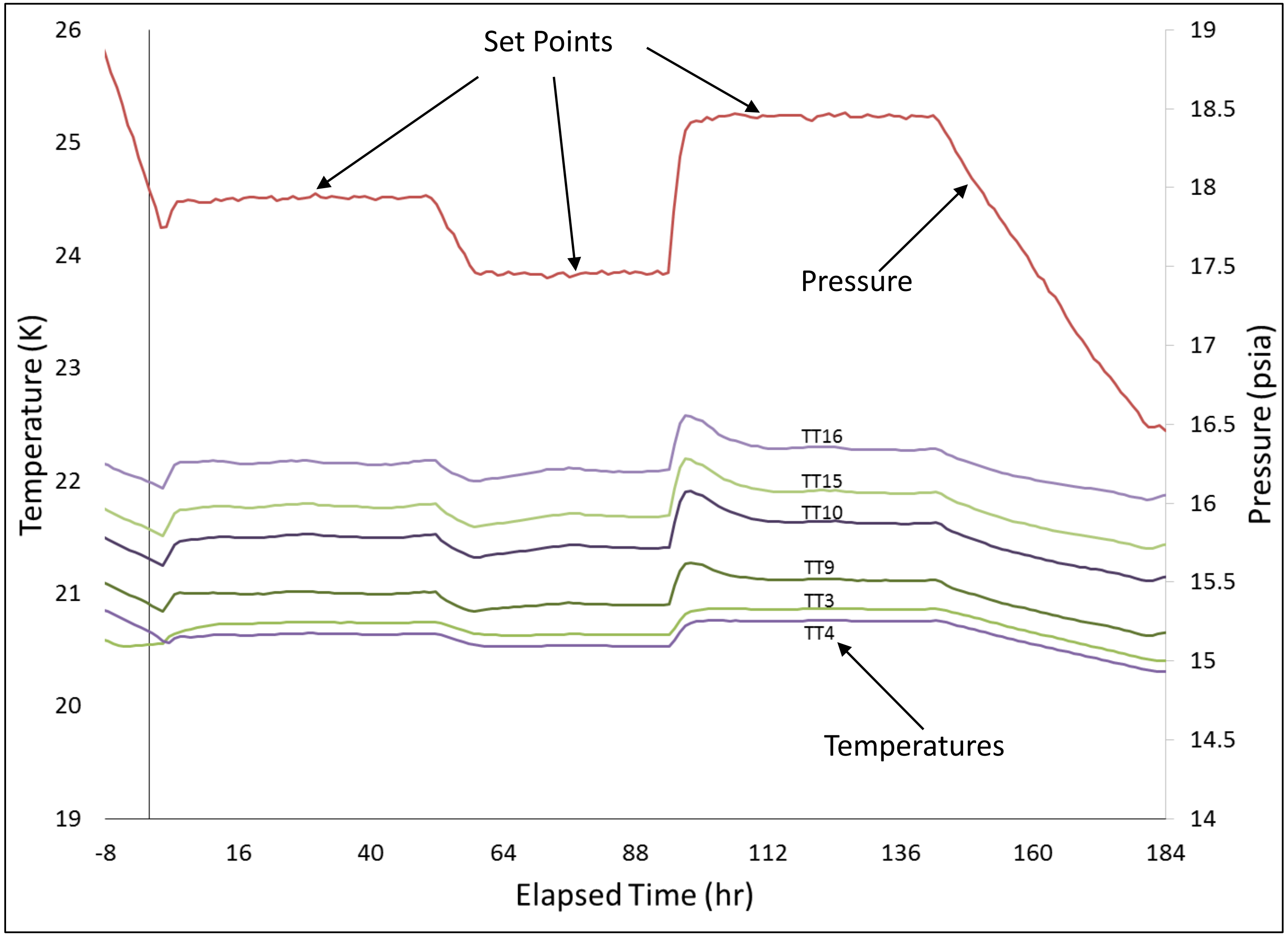
Level	MF3	PT2	TT19	Q_L	Q_V	Q
%	(slm)	(psia)	(K)	(W)	(W)	(W)
33	255	15.2	49.5	170	120	290
67	295	16.6	41.3	196	100	296
100	351	15.9	34.5	234	81	315



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

ZBO Pressure Control Test Results

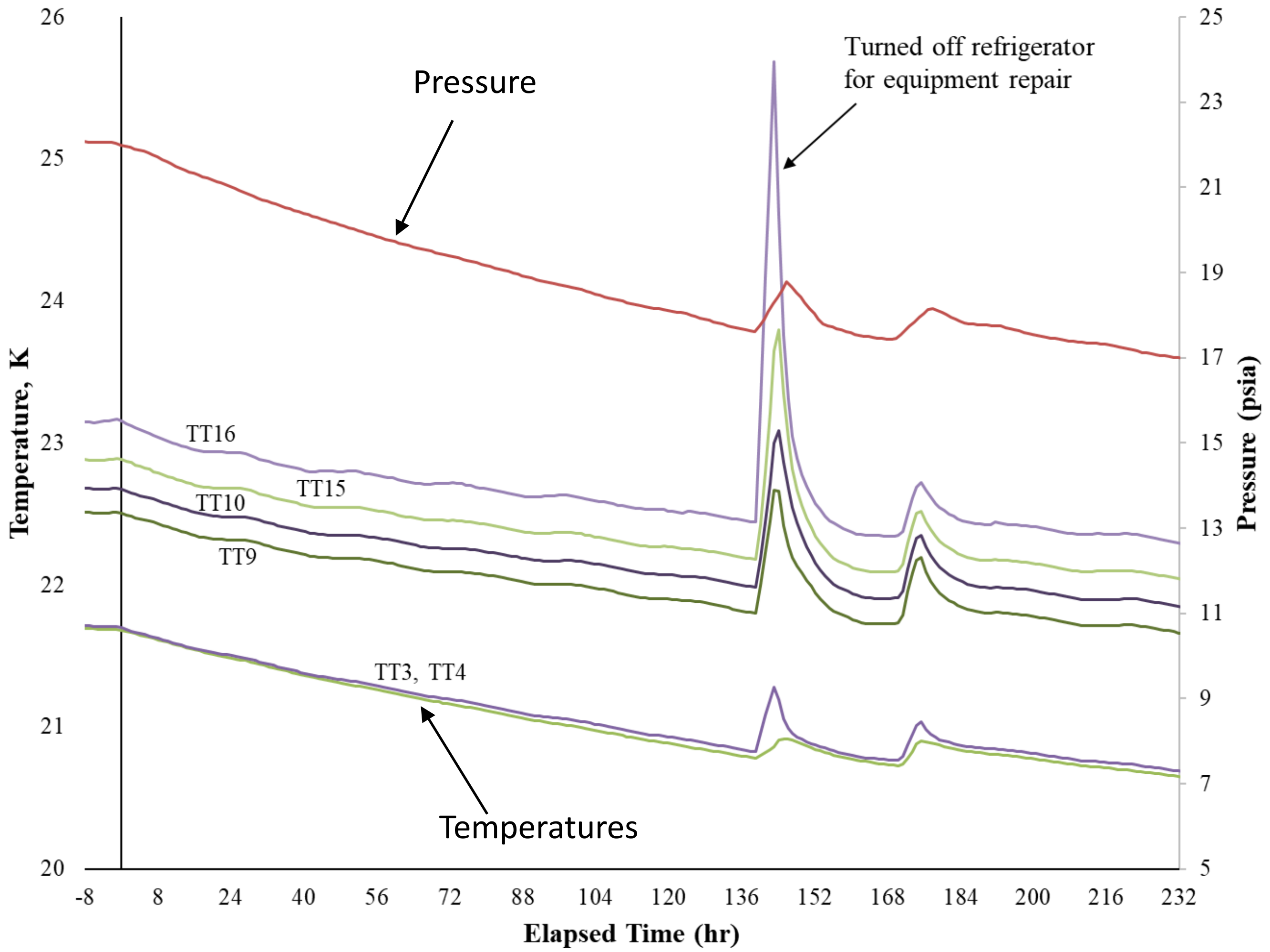
- GODU-LH2 software controlled refrigerator to achieve and maintain IRAS tank pressure set-point.
- No LN_2 pre-cooling used
- Approach set points from above and below
- Pressure stability +/- 0.5% for all three fill levels
- Near isothermal temperature profile following saturation line



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

ZBO Temperature Control Test Results

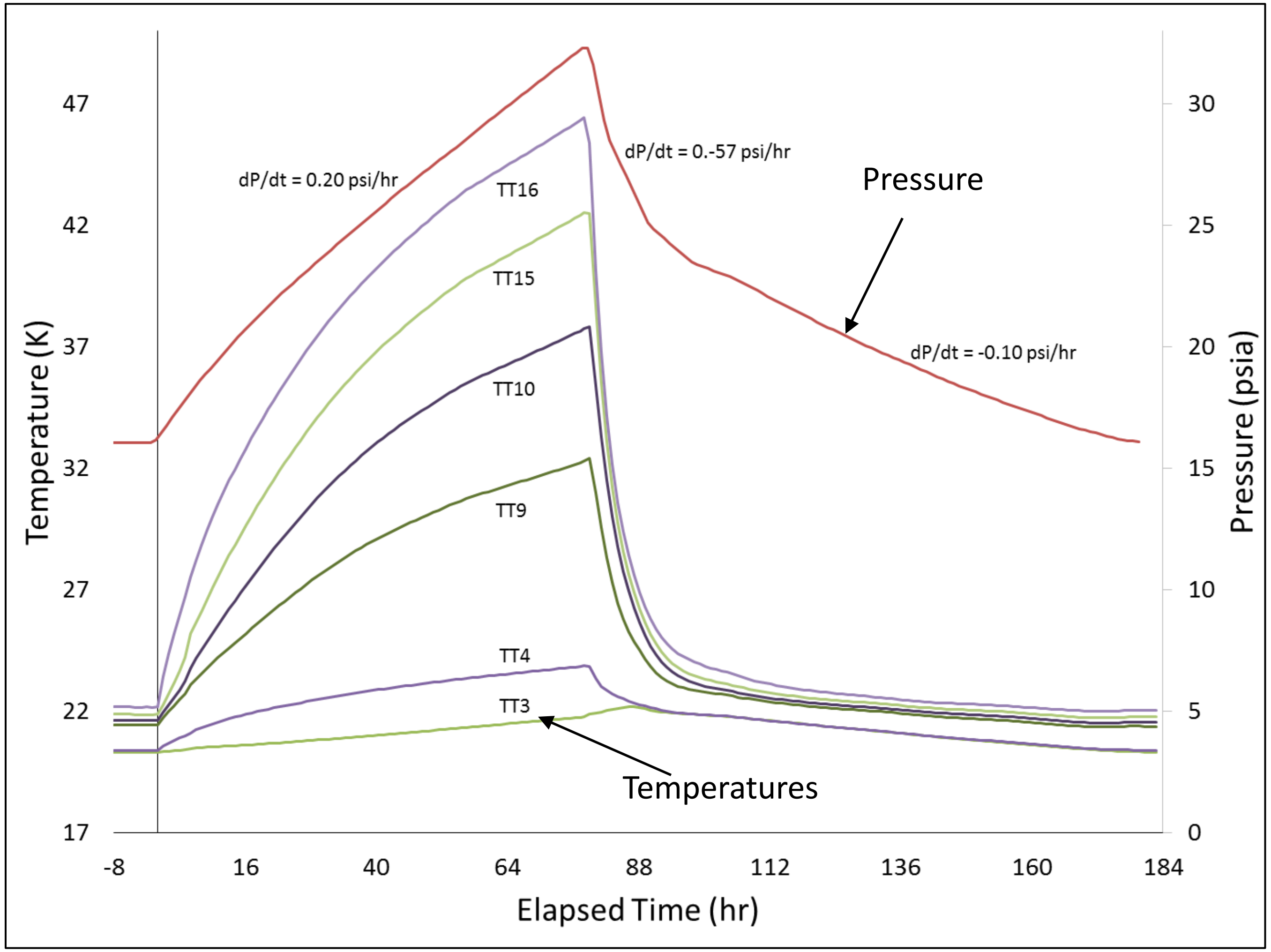
- Linde software controlled refrigerator to achieve and maintain constant helium supply temperature.
- No LN_2 pre-cooling used
- Helium supply temperature response fast and accurate
- But LH_2 takes long time period to reach equilibrium state



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

ZBO Duty Cycle Test Results

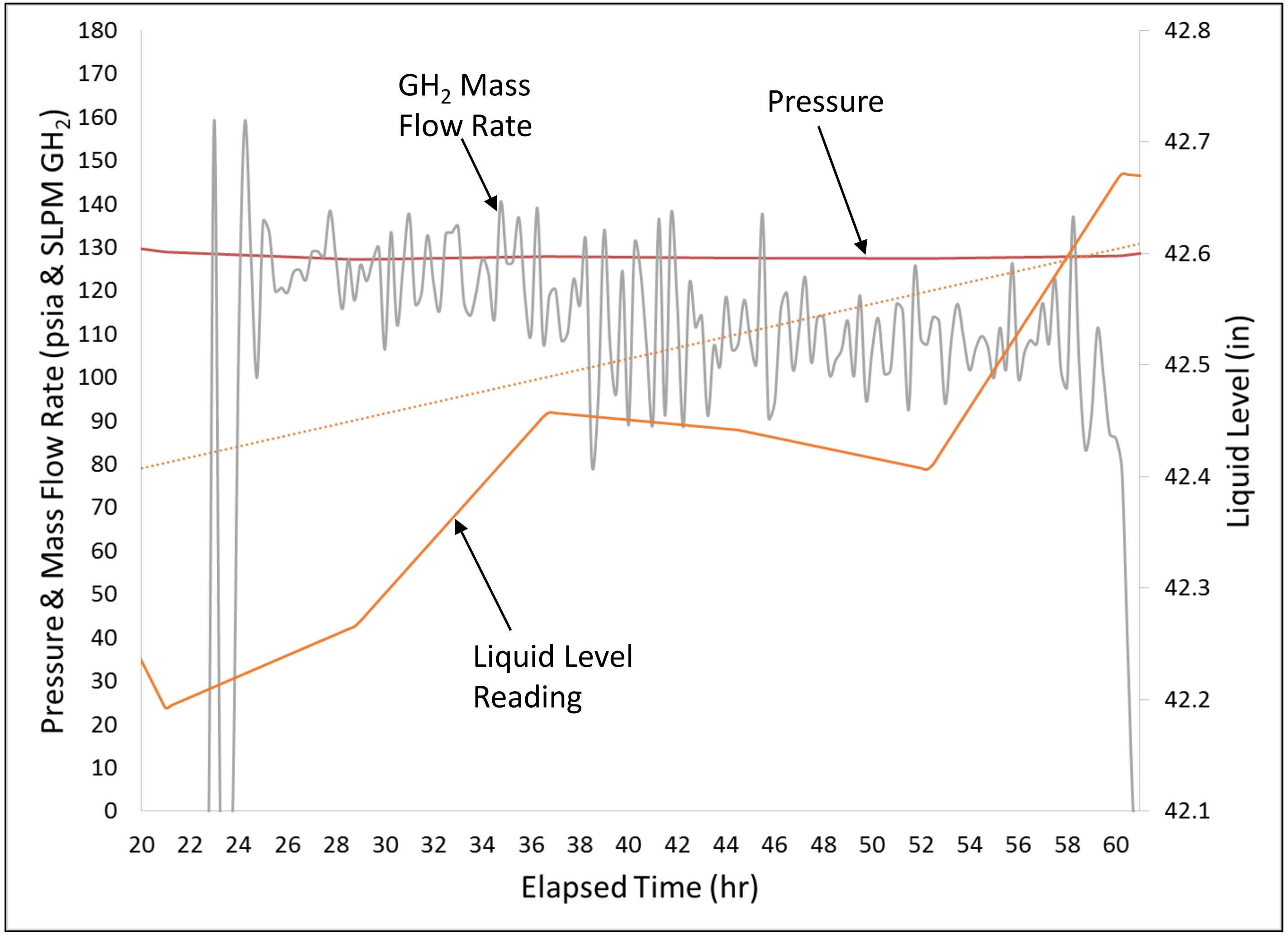
- ZBO achieved in batch processes by turning on and off the refrigerator as required
- Testing was both accidental and purposeful
- Minimum electrical cost but depends on multiple start/stop cycles of cryogenic equipment
- Duty cycle varied from 1.13 (33%) to 1.16 (67%) to 3.6 (100%) on/off with no LN_2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

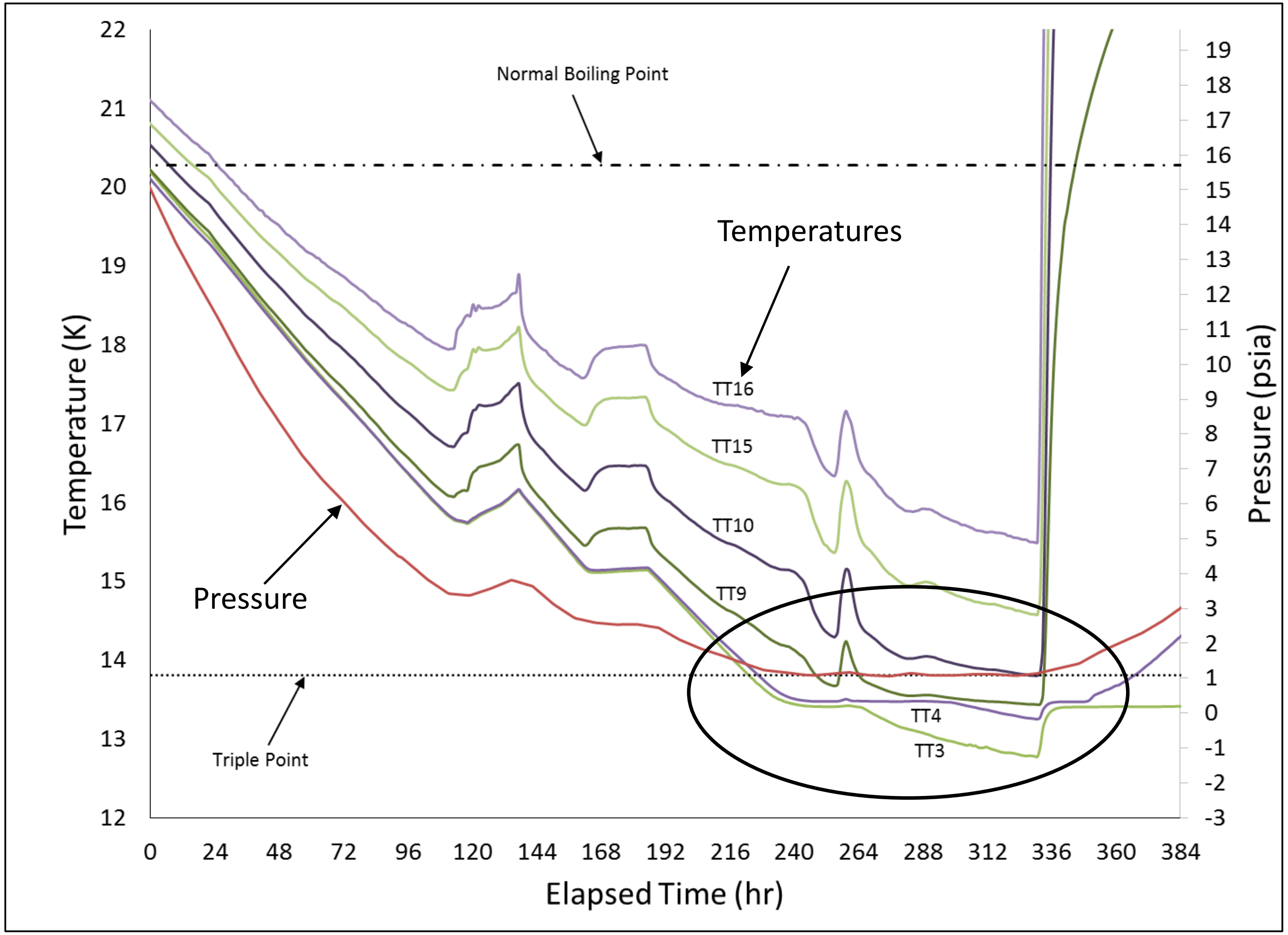
- GH_2 was controlled using a mass flow controller until the tank pressure remained constant.
- NOT optimized for liquefaction. GH_2 was fed in at ambient temperature.
- Using LN_2 pre-cooling, roughly 78 gal of LH_2 was produced during the test.



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

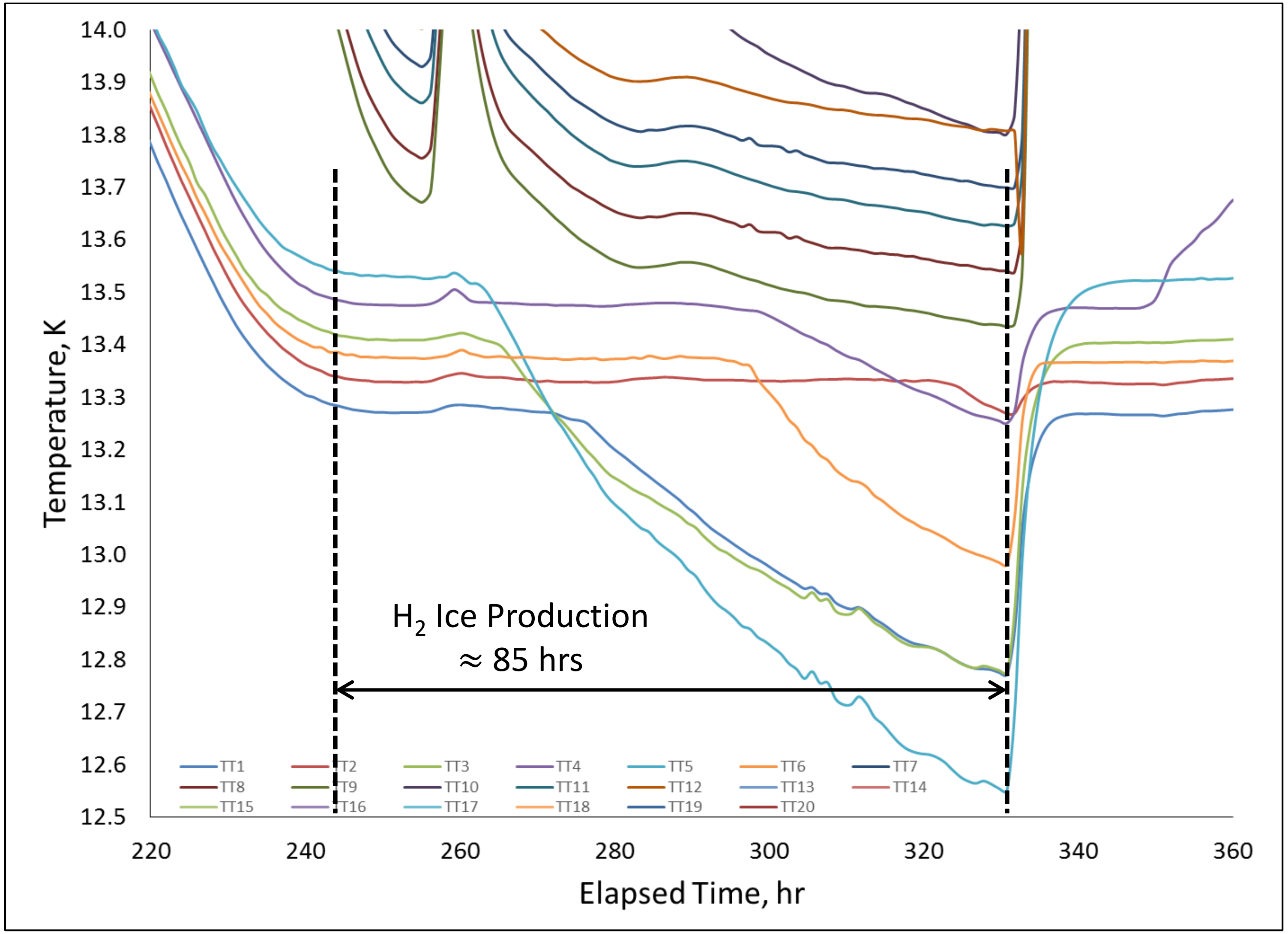
Densification Test Results

- 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**



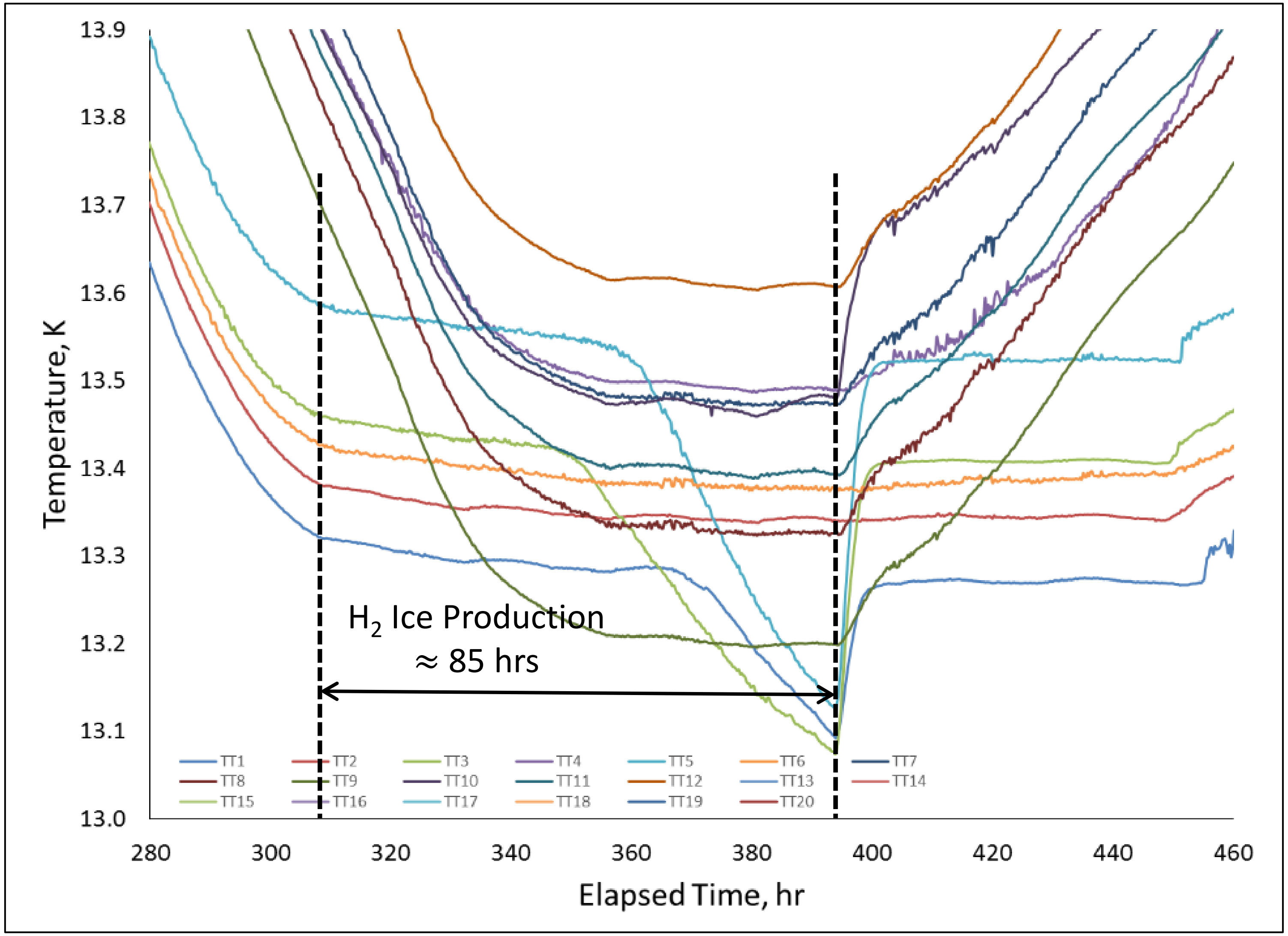
Conclusion: IRAS enables propellant densification down to the freezing point

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

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