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Thermo-physical performance prediction of the KSC GODU for liquid hydrogen

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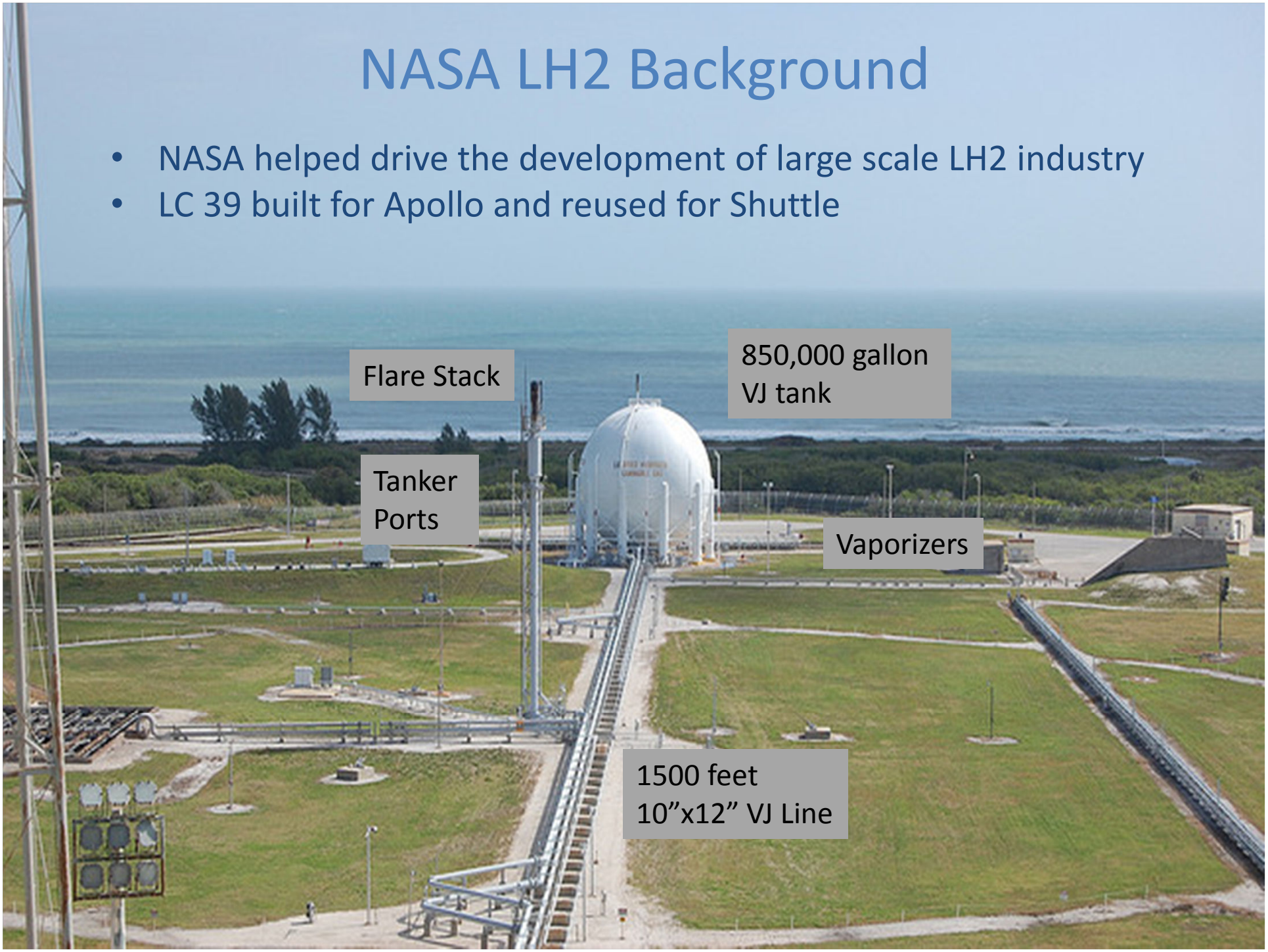
NASA LH2 Background

- NASA helped drive the development of large scale LH2 industry
- LC 39 built for Apollo and reused for Shuttle



LH2 Loss for STS Program

- Replenish
  - heat leak during transit, chill-down of transfer system, and tanker press.
  - Approx. 13% of the KSC hydrogen purchased over the Space Shuttle Program
- Normal Evaporation Loss
  - heat leak from the ambient to the ground storage tank
  - Approx. 12% of the KSC hydrogen purchased over the Space Shuttle Program
- Load Loss
  - chill-down of ground and flight system and ET heat leak during replenish
  - Approx. 21% of the KSC hydrogen purchased over the Space Shuttle Program
- On-board Quantity
  - Volume of the External Tank
  - Approx. 55% of the KSC hydrogen purchased over the Space Shuttle Program.

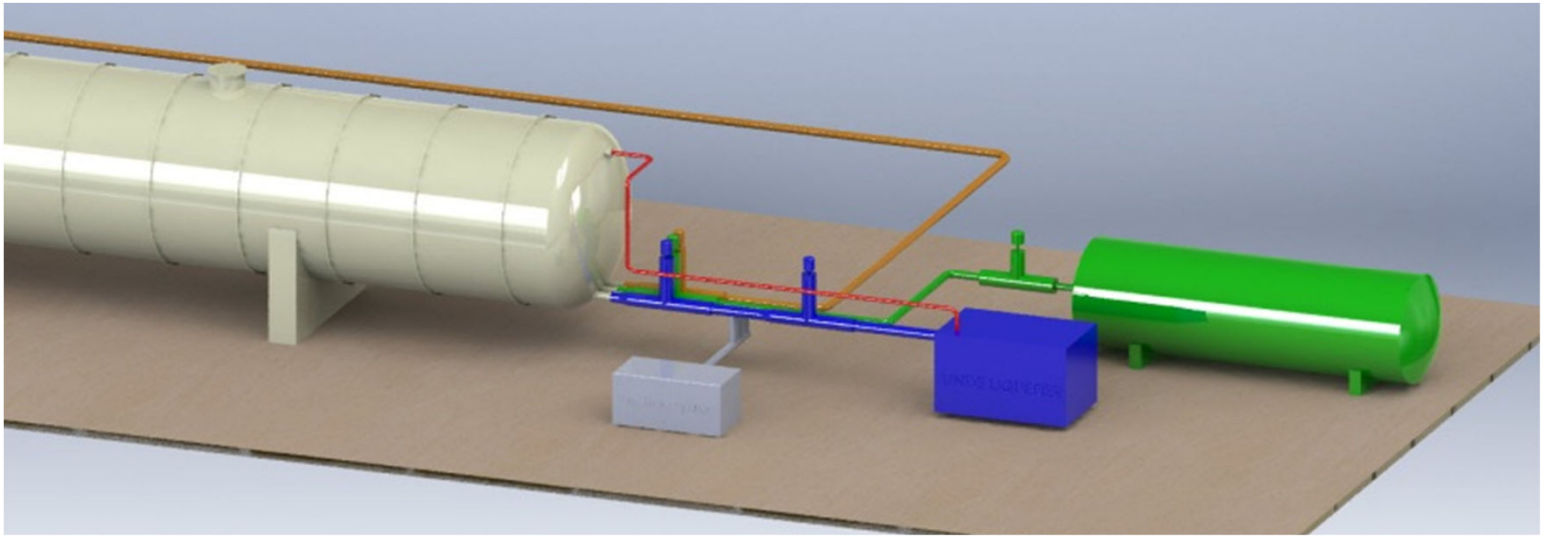
Future Spaceport LH2 Goals

- Goal is to increase the efficiency of hydrogen operations to >80%
  - Current KSC practice is approximately 55%
  - Defined by mass launched/mass purchased
- Targeted hydrogen losses
  - Storage tank boil off
  - Chill down losses
  - Tanker venting recovery
  - Line drain and purge
  - Tank venting
- Local hydrogen production and liquefaction capability
  - Sized for KSC needs but allowed to sell offsite
- Propellant conditioning and densification
  - Bulk temperature to 16 K
  - Thermal energy storage for load balancing
- Reduction in helium use
- Reducing in spaceport carbon footprint

GODU LH2 Objectives

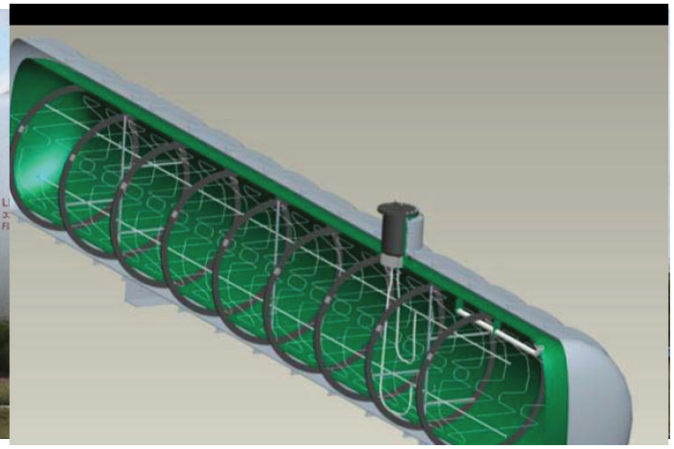
- Demonstrate zero loss storage and transfer of LH2 at a large scale
- Demonstrate hydrogen liquefaction using close cycle helium refrigeration
- Demonstrate hydrogen densification in storage tank and loading of flight tank
- Also, includes a number of secondary objectives including creating a densified hydrogen servicing capability, maintaining critical cryogenic design and operations skills, demonstrating low-helium usage operations, and validating modern component technologies

GODU LH_2 at the Hydrogen Technology Demonstration Site at NASA KSC.



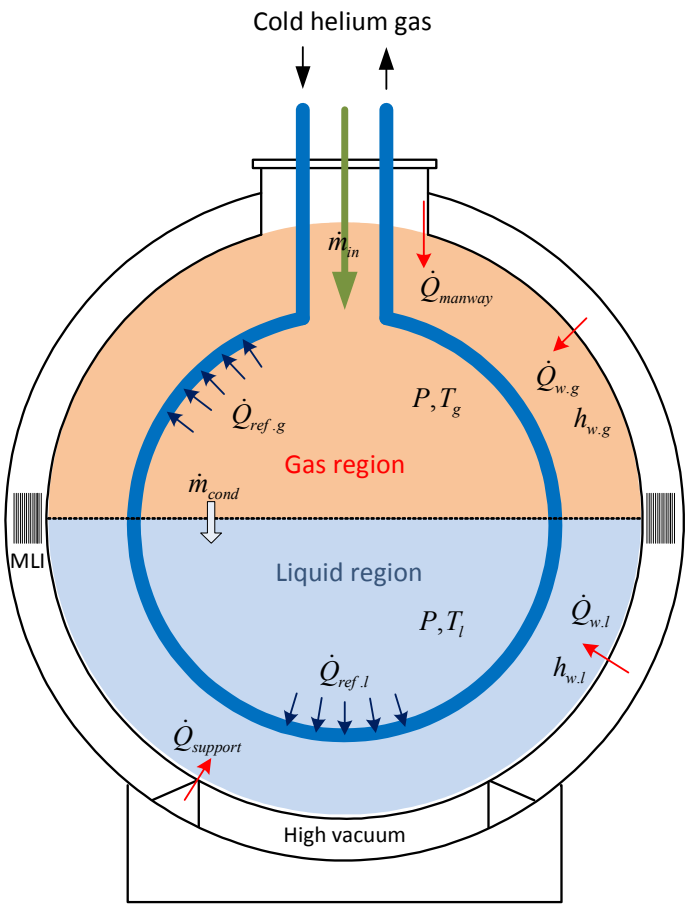
Refrigerator, storage tank, HX

- Linde R1620 reverse-Brayton helium refrigerator
  - 800W at 20K, 400W at 17K
- 33K gal storage tank : LxD= 21.3mx2.9m
  - MLI , manway, 3 line penetrations, vent
- Cold hx – 40 lobes, 8m^2 hx surface, SUS 1/4”OD, 244m long



Ref : Fesmire et al., “Integrated hx design for a cryogenic storage tank, ACE Proc 1573, p.1365-1372 (2014)”

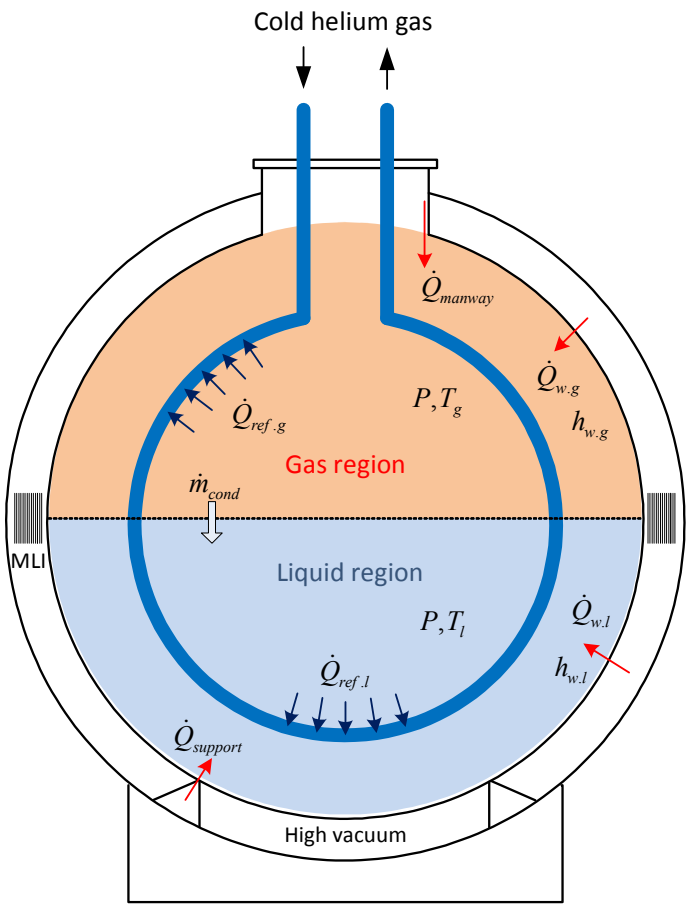
Thermal model of the storage tank



$P = \text{constant},\ T_g = 78K, T_l = T_{sat}(P)$

(a)

liquefaction



$P \neq \text{constant},\ T_g = 50K,\ T_l = T_{sat}(P)$

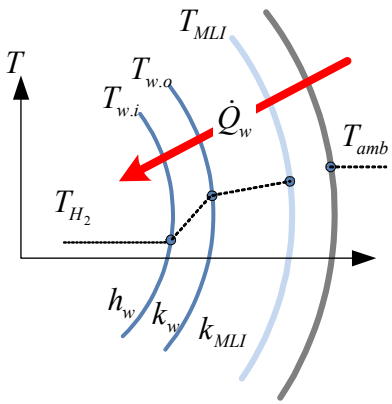
(b)

densification

Mass, energy balance for gas and liquid hydrogen regions

Liquefaction model	Densification model
$\frac{dm_g}{dt} = \dot{m}_{in} - \dot{m}_{cond}$ $\frac{d(m_g u_g)}{dt} = \dot{m}_{in} h_{in} - \dot{m}_{cond} h_l + \dot{Q}_{w.g} + \dot{Q}_{manway} - \dot{Q}_{ref.g}$	$\frac{dm_g}{dt} = -\dot{m}_{cond}$ $\frac{d(m_g u_g)}{dt} = -\dot{m}_{cond} h_l + \dot{Q}_{w.g} + \dot{Q}_{manway} - \dot{Q}_{ref.g}$
$\frac{dm_l}{dt} = \dot{m}_{cond}$ $\frac{d(m_l u_l)}{dt} = \dot{m}_{cond} h_l + \dot{Q}_{w.l} + \dot{Q}_{support} - \dot{Q}_{ref.l}$	$\frac{dm_l}{dt} = \dot{m}_{cond}$ $\frac{d(m_l u_l)}{dt} = \dot{m}_{cond} h_l + \dot{Q}_{w.l} + \dot{Q}_{support} - \dot{Q}_{ref.l}$

Natural convection heat transfer correlation



$$Nu = \frac{h_w \cdot k_{H_2}}{D_{tank}} = 0.555\, Ra^{1/4} \quad \text{for laminar}$$

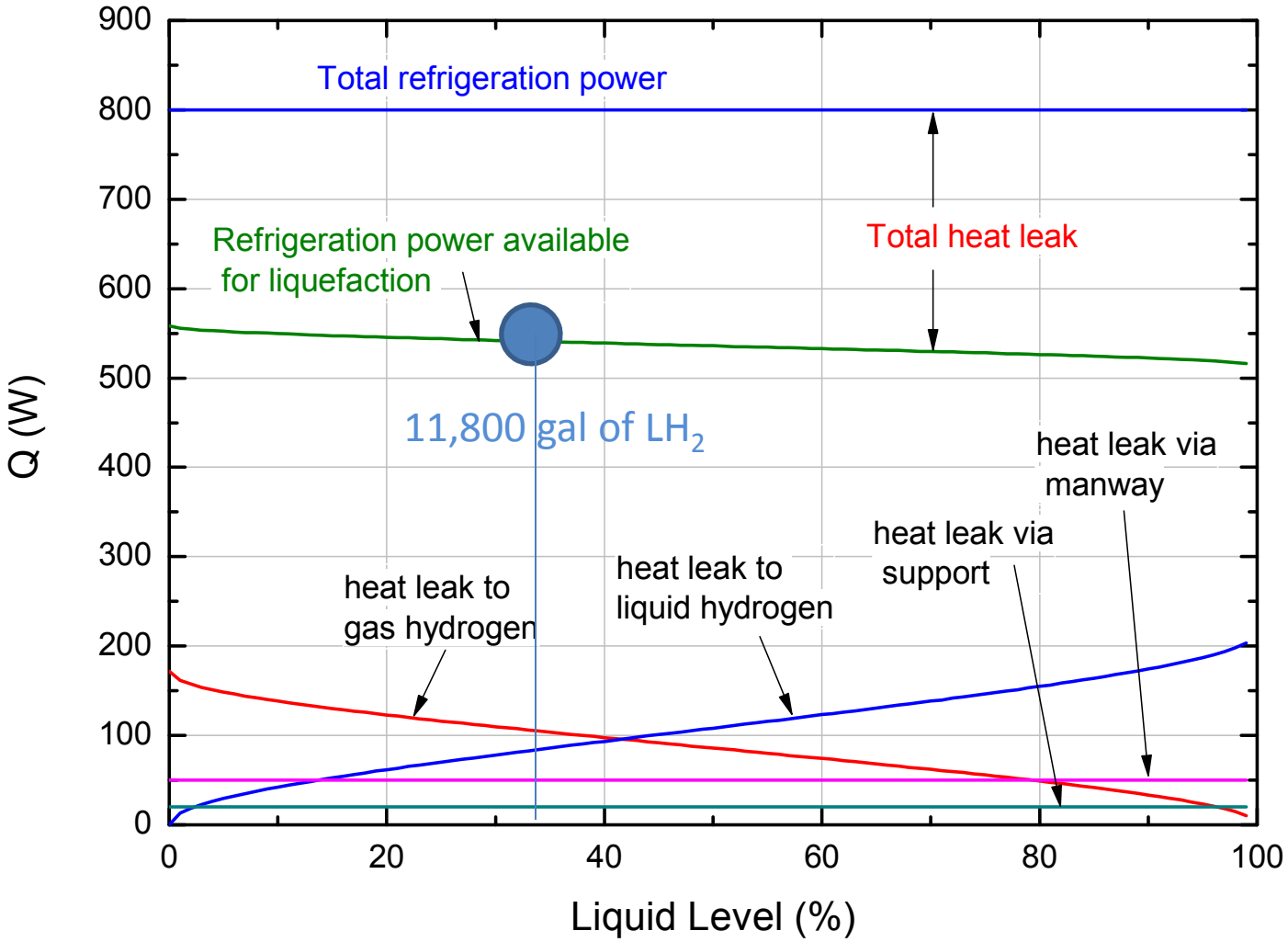
$$Nu = \frac{h_w \cdot k_{H_2}}{D_{tank}} = 0.0210\, Ra^{2/5} \quad \text{for turbulent}$$

$$\text{where, } Ra = Gr \cdot Pr, \quad Gr = \frac{g\beta\left(T_w - T_{H_2}\right) D_{tank}^{\ 3}}{\nu^2}$$

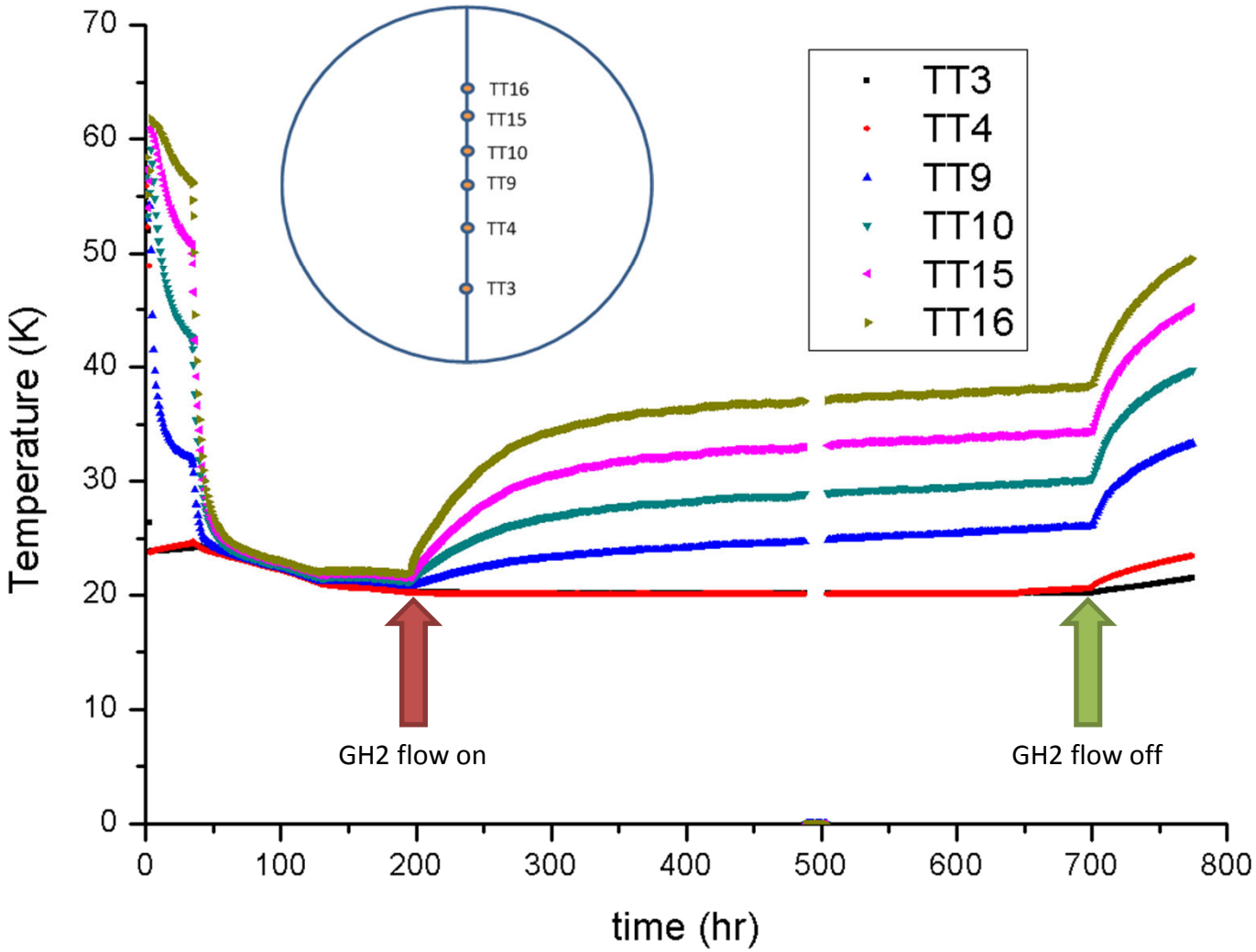
Reduced equations

Liquefaction model	Densification model
$$\dot{m}_{cond} = \frac{\dot{Q}_{ref.g} - \dot{Q}_{w.g} - \dot{Q}_{manway}}{\left(h_{in} - h_l\right) + \frac{\rho_g}{\rho_l} u_g}$$	$$\dot{m}_{cond} = \frac{\dot{Q}_{ref.g} - \dot{Q}_{w.g} - \dot{Q}_{manway}}{u_g - h_l}$$
$$\dot{m}_{in} = \dot{m}_{cond}\left(1 - \frac{\rho_g}{\rho_l}\right)$$	$$\frac{dT_l}{dt} = \frac{1}{m_l C_l}\left[\dot{Q}_{support} + \dot{Q}_{w.l} - \dot{Q}_{ref.l} + \dot{m}_{cond}\left(h_l + u_l\right)\right]$$
$$\dot{Q}_{ref} = \dot{Q}_{ref.g} + \dot{Q}_{ref.l}$$	$$\frac{dP}{dt} = \frac{\dot{m}_{cond} R T_g}{V_g}\left(\frac{P}{\rho_l R T_g} - 1\right)$$
$$P = constant$$	$$\dot{Q}_{ref} = \dot{Q}_{ref.g} + \dot{Q}_{ref.l}$$
	$$P = P_{sat}\left(T_l\right)$$

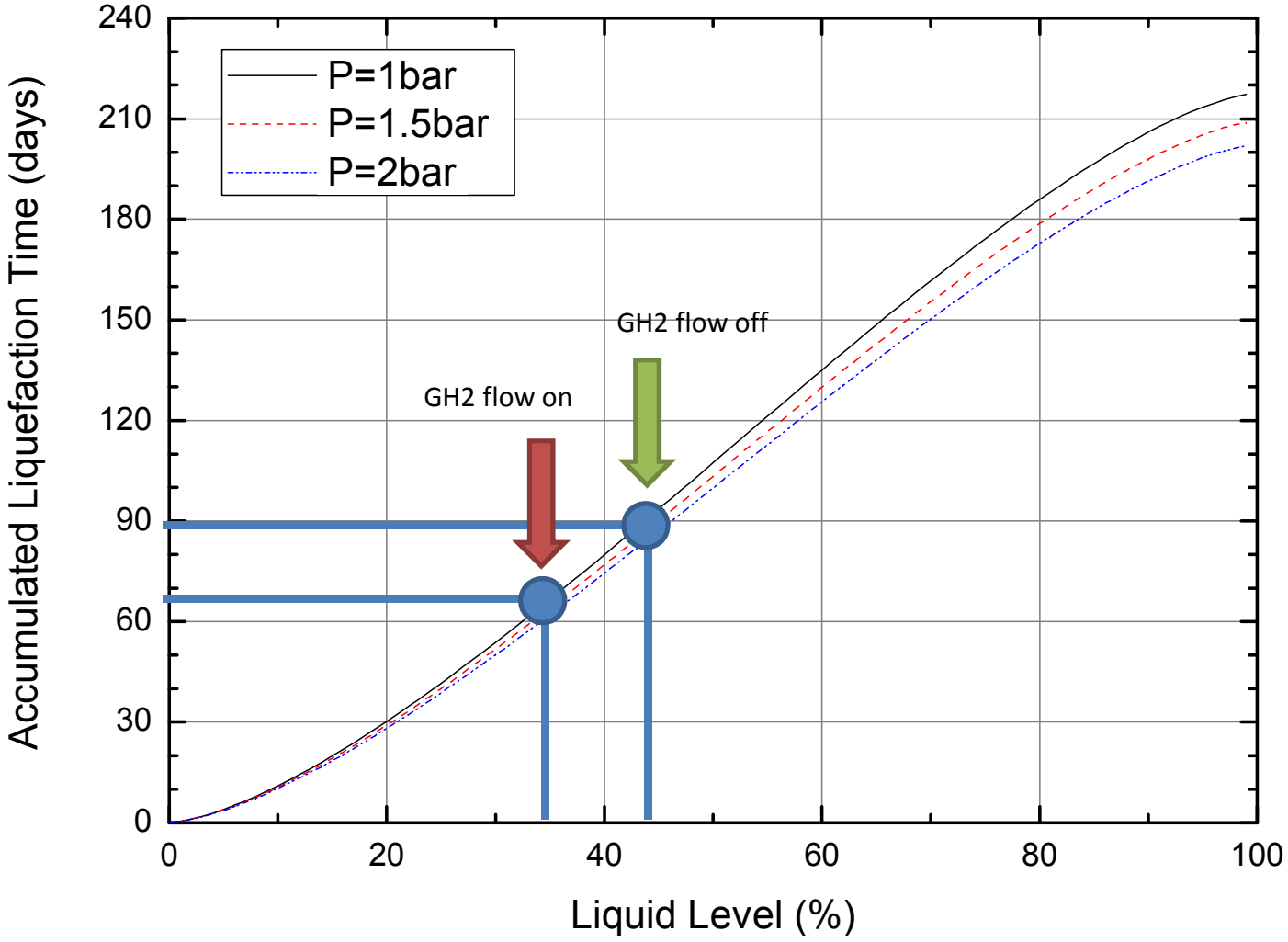
Heat leaks vs. Liquid level



Liquefaction & ZBO



Liquefaction time



Conclusion

- A simple lumped thermal model the NASA KSC GODU LH_2 has been developed to predict,
  - Thermal losses to the storage tank
  - In-situ Liquefaction time required for various fill levels
  - Transient LH_2 temperature and pressure during densification behavior
- The modeling results show very good agreements with recent KSC experiment data
  - Total heat leak measurement at 33% LH_2 level matches its modeling prediction.
  - The liquefaction modeling demonstrates its useful capability of liquid level estimation or time estimation required for specific liquid level in the storage tank.

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