Aerospace Innovation Showcase: Cryogenic Hydrogen Fuel Systems

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Liquid Hydrogen at NASA Kennedy Space Center

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CRYOGENICS TEST LABORATORY

- Started in 1994, today it is a **globally networked**, 30+ year institution
- Rooted in practical problem-solving & applied research!

<u>Four Technology Focus Areas</u>

1. Thermal Insulation Systems
2. Integrated Refrigeration Systems
3. Advanced Propellant Transfer Systems
4. Low-Temperature Materials & Applications

Liquid Hydrogen, Rockets, & NASA
Kennedy Space Center

LH_2 and NASA-KSC

- In the 1950's and 1960's DoD and NASA requirements drove the development of large scale LH_2 systems
- LH_2 used for the 2nd and 3rd stages of Apollo Saturn V in the 1960s and 70s; Space Shuttle (1980-2011); and current Space Launch System
- NASA-KSC 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

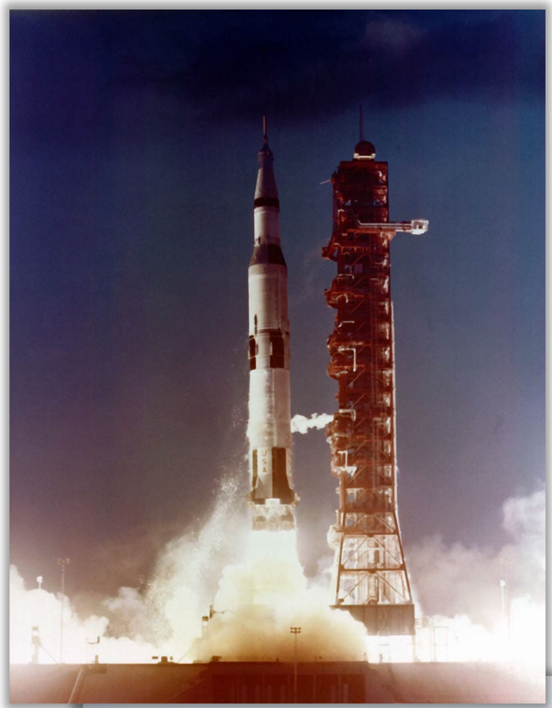


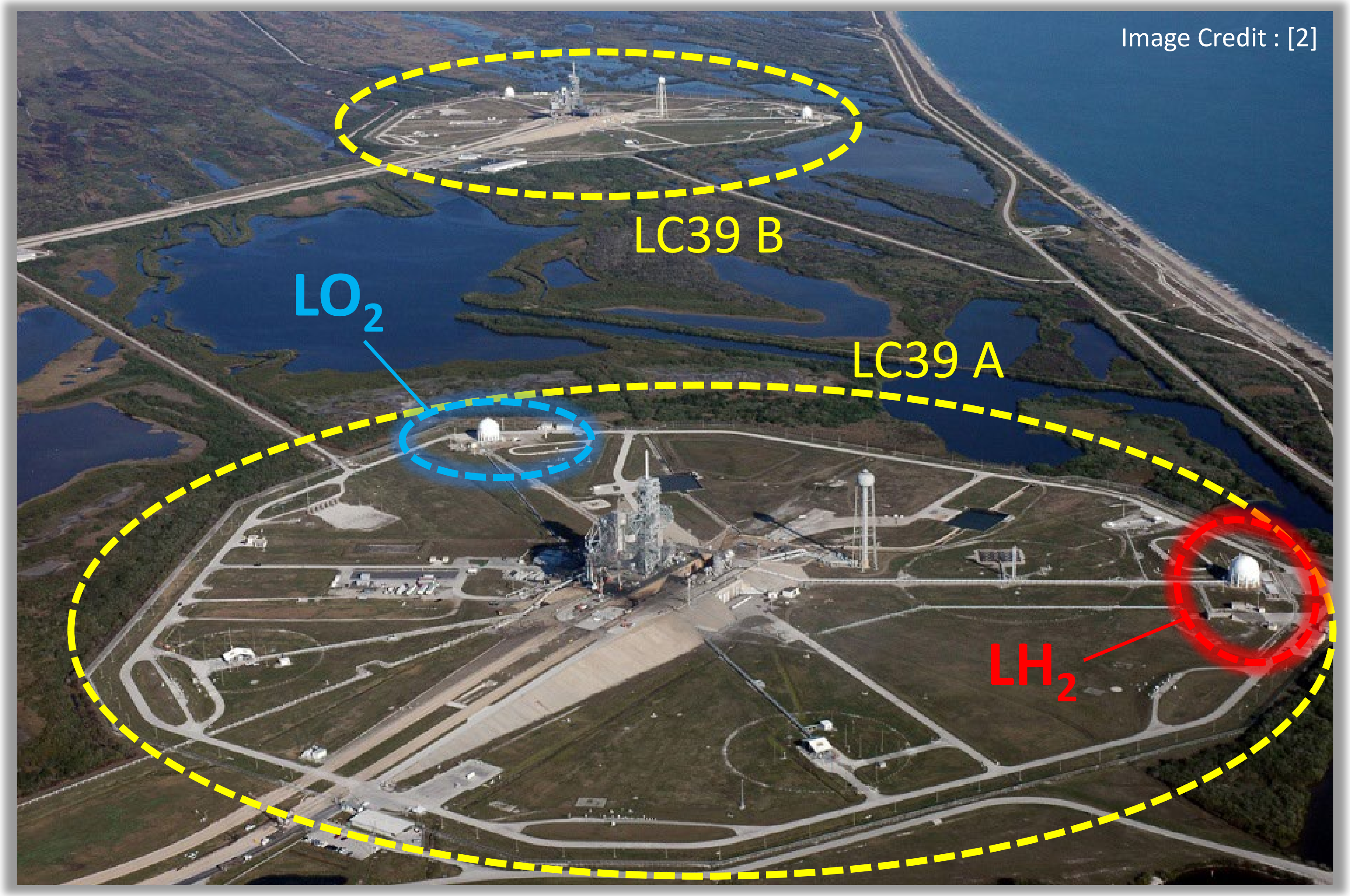
Image Credits : [1]

KSC LAUNCH PAD INFRASTRUCTURE

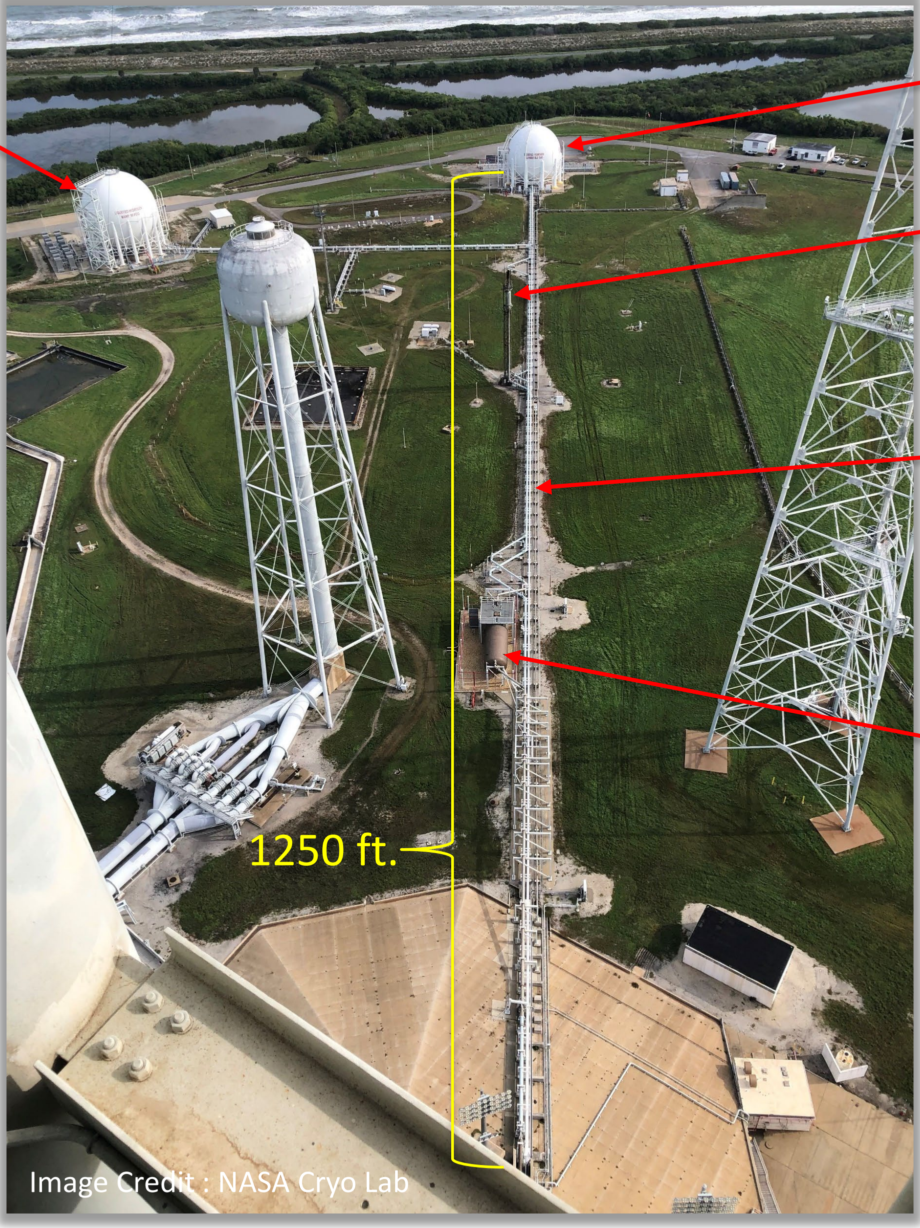
- LC39A & B built in 1960s for Apollo moon program
- Identical layout
- Both used throughout Apollo and Space Shuttle Programs
  - Pad A currently leased to SpaceX
  - Pad B used by NASA for Artemis

❖ Important, **unique**, driving requirements

1. Huge flow rates—up to 10,000 GPM for LH_2
2. Vehicle explosion potential—fuel and oxidizer in close proximity
3. Very high chilldown losses



KSC LAUNCH PAD INFRASTRUCTURE—PAD B



New Sphere

Old Sphere

Flare Stack

10” NPS LH_2 VJ Transfer Lines

Phase Separator

12” NPS Vent Line

VESSEL SPECIFICATIONS

Image Credit : [1]

Apollo-Era Sphere

- 850,000 gal (3,200 m^3) useable volume
- ~69 ft. (21 m) outer diameter
- MAWP = 0 to 90 psig (6.2 bar)
- Vacuum-jacketed w/perlite bulk-fill insulation (~4 ft. thick)
- Normal Evaporation Rate = 0.04% per day

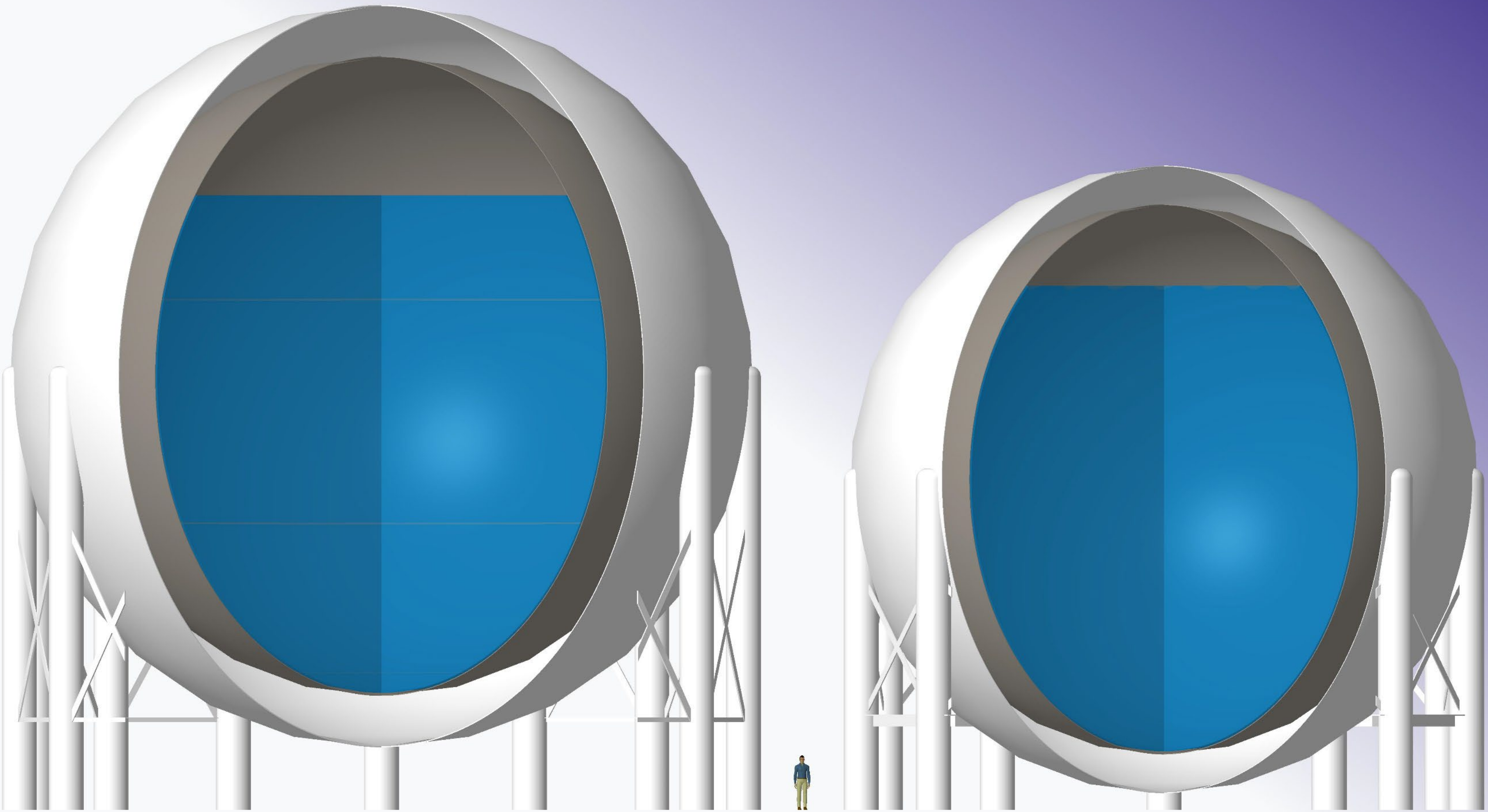
Image Credit : [1]

New Sphere—Currently the Worlds Largest LH_2 Tank

- 1.25 Mgal (4,700 m^3) useable volume
- ~83 ft. (25.3 m) outer diameter
- MAWP = Full vacuum to 90 psig (6.2 bar)
- Min. Design Metal Temperature (MMDT) = 4 K (-452 °F)
- Vacuum-jacketed w/glass bubble bulk-fill insulation (~6 ft. thick)
- Max Normal Evaporation Rate = 0.048% per day (per spec)

★ 2 New Technologies: Glass bubble insulation, and an internal IRAS heat exchanger

Image Credit : Author



Scale comparison of new 4,700-m³ storage tank (left) and Apollo-era 3,200-m³ tank (right)

X.X+-0.1
X.XX+-0.03
X.XXX+-0.010
ANG.+-0.1

HARDWARE CHALLENGES

- **Maintenance, especially of vacuum jackets**
  - Corrosion control—especially bad due to proximity to the ocean
  - Constant checking/servicing of vacuum lines
- **Sourcing of new or replacement valves and other components for large diameter LH_2 lines**
  - Few manufacturers of 10” and 12” NPS components for LH_2 service due to lack of market historically
  - New, non-heritage components put through a NASA-defined qualification program
  - Also, difficult due to requirements for federal Agencies to procure domestically
- **Hydrogen leaks**
  - For NASA, it’s mostly been an issue at mate/de-mate interfaces with “non-standard” designs, such as vehicle quick-disconnects

10” Check Valve Acceptance Test at the Cryogenics Test Laboratory

KSC LH_2 OPERATIONS

- Fill storage tanks from waves of 10 tankers trucks per day
  - 5 tankers unloading in parallel
  - Tankers travel from Alabama, non-stop to KSC
  - Conducted with personnel on-site
- For launch, no pumps are used; tanks pressurized via vaporizers to around 60 psig and **LH_2 is pressure-fed to the vehicle**
- Slow-fill for piping and vehicle tank chill down, then fast-fill to 100%, then slower replenishment until launch
- Vehicle loading begins roughly 10 hours before launch

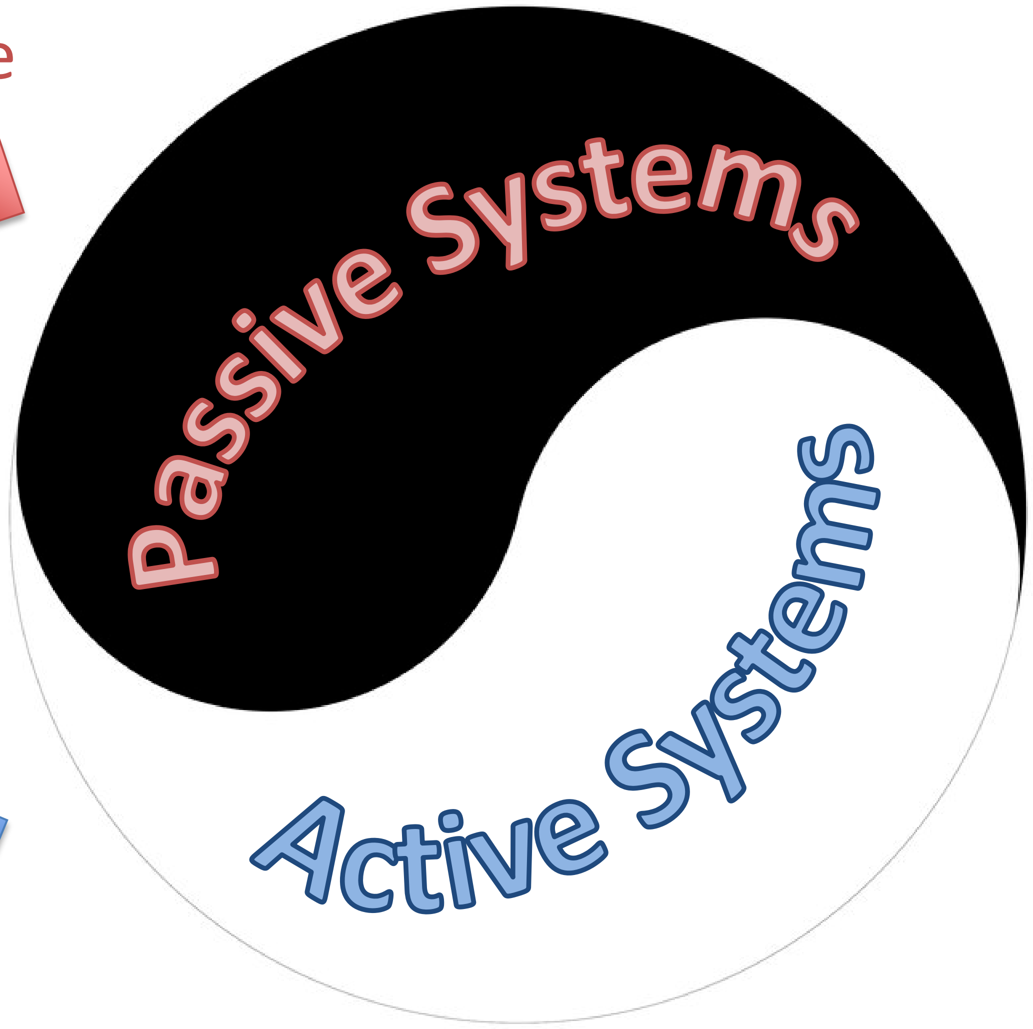
Image Credit: [1]

- Vehicle loading operations are all done remotely
  - Due primarily to vehicle explosion hazard

Liquid Hydrogen Storage R&T

HOLISTIC APPROACH

Thermal insulation system, and storage vessel design



Integrated refrigeration systems

Advanced LH_2 concepts & architectures

INTEGRATED REFRIGERATION AND STORAGE (IRAS)

Integrated Refrigeration and Storage (IRAS) → storage tank + internal heat exchanger + cryogenic refrigeration system

IRAS = Fluid control via direct addition and removal of thermal energy (heat) as opposed to addition and removal of mass

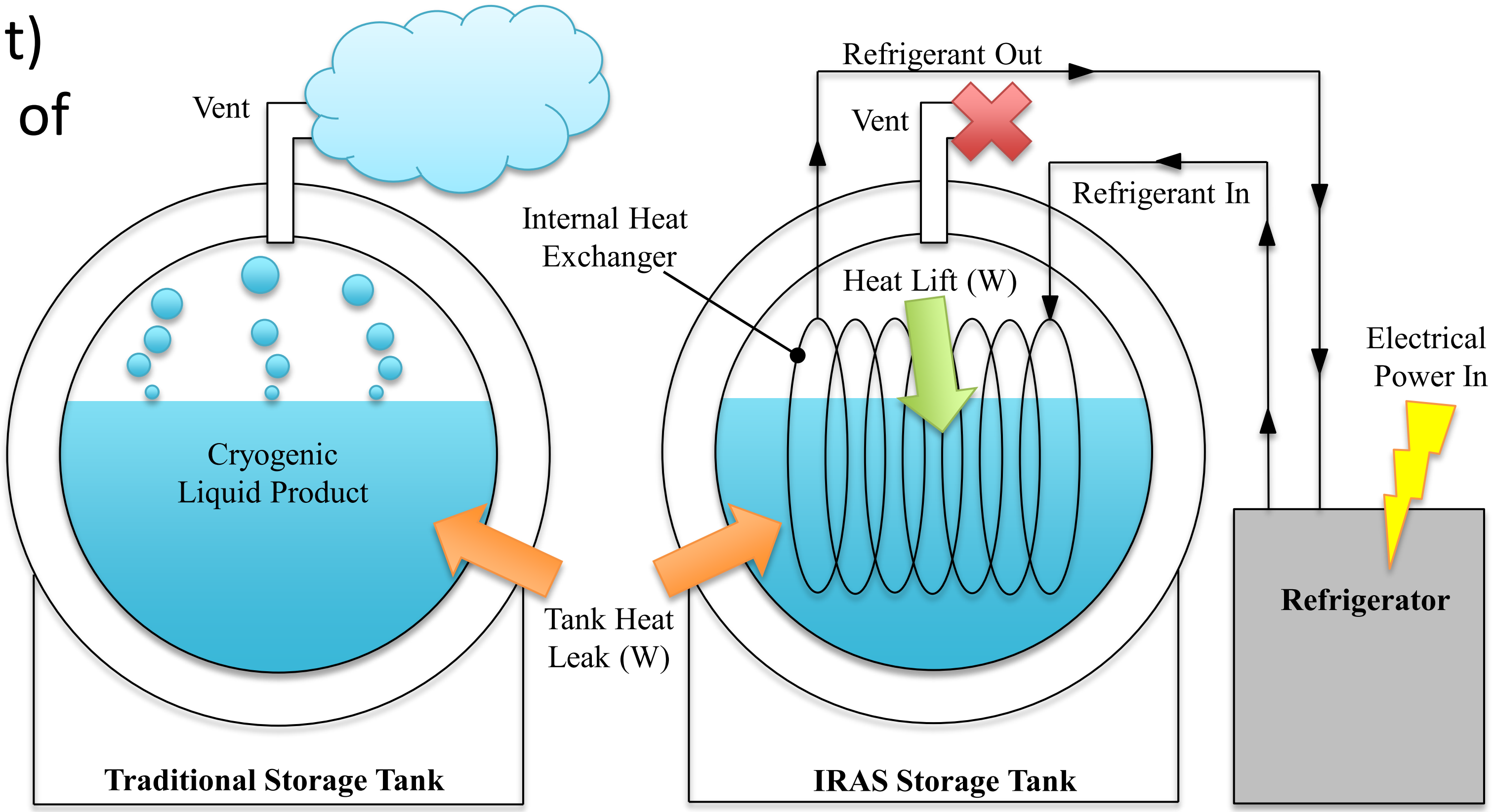


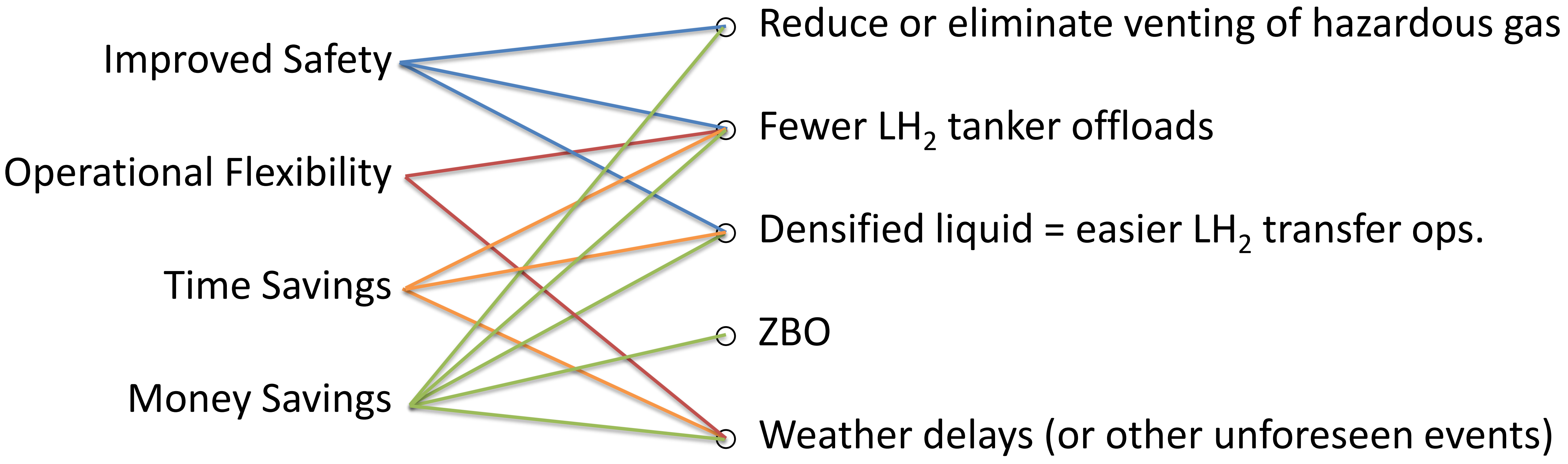
Image Credit: Author

Five IRAS capabilities

1. Zero-loss cooldown of a large cryogenic tank from ambient temperature
2. Zero-loss tanker off-loading of liquid product
3. Zero Boil-off (ZBO)
4. In-Situ Liquefaction
5. Densification

SIGNIFICANCE OF IRAS

- IRAS is more than just zero boiloff (ZBO)—It is a about gaining control!
- Benefits of Full Control Storage via IRAS:



GODU-LH2 PROJECT

- From 2012 -2016, the GODU-LH2 project at NASA-KSC proved IRAS for LH_2 on a large scale
  - ➢ 33,000 gal (125 m^3) IRAS tank
  - ➢ Linde LR1620 helium refrigerator, 880 W @ 20 K max cooling

<u>Testing Milestones</u>

✓ Dry chilldown of tank to LH_2 temperature

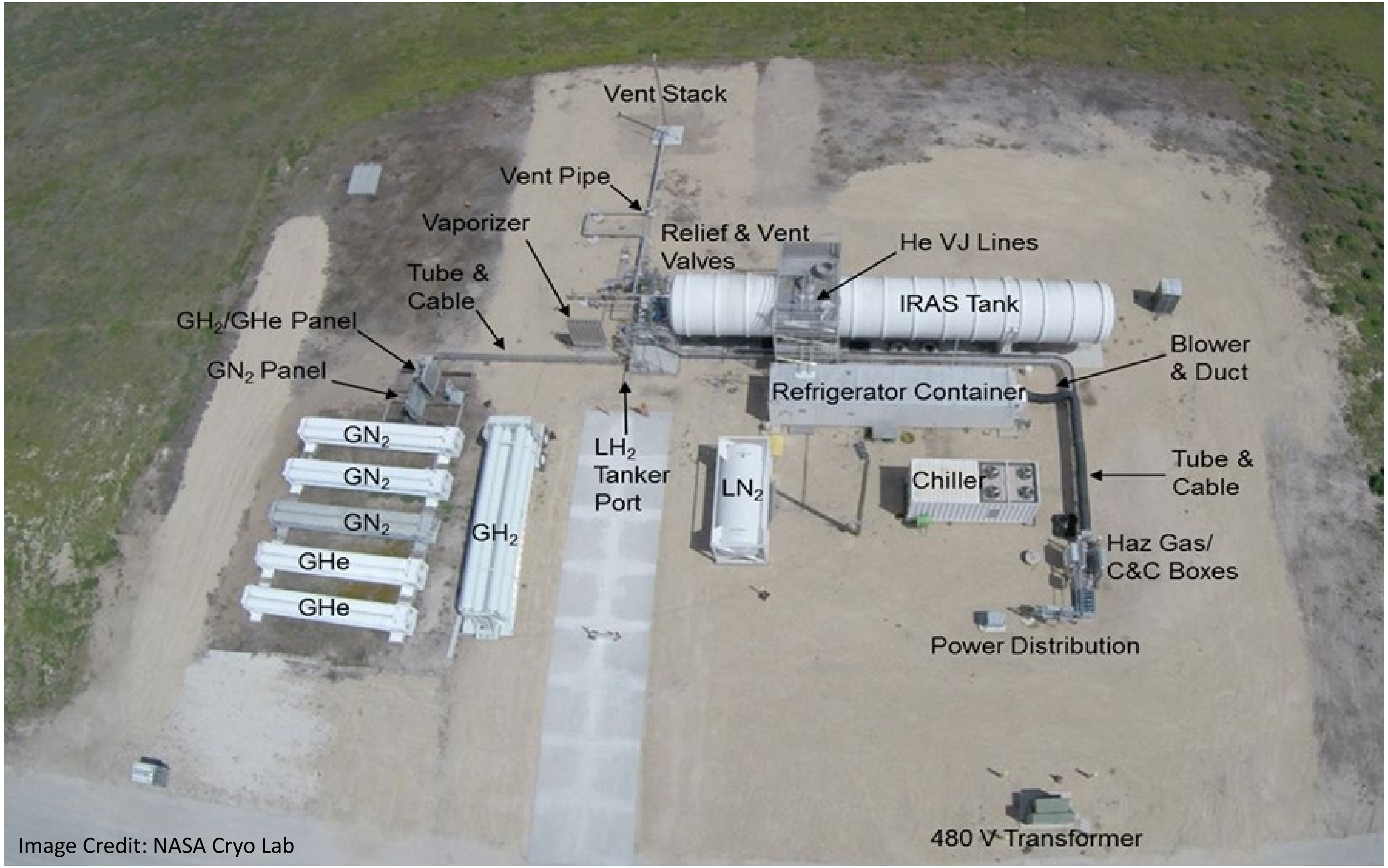
✓ Performed 3 zero-loss tanker off-loads

✓ Performed long duration ZBO via 3 different methods

✓ Performed densification down to the triple point, with significant slush production

For every <u>14 cents</u> spent on electricity, <u>one dollar</u> in liquid hydrogen was saved

"BIRD'S-EYE VIEW" OF GODU-LH2 SITE



GLASS BUBBLE INSULATION

- Type K1 glass bubbles by 3M - filling the entire annular space
- Nominal 65-micron diameter hollow microspheres of borosilicate glass
- Material tanker offloading/installation for demonstration testing at NASA Stennis Space Center in 2008 (bottom photo)
- Field testing with a 190-m^3 (50,000-gal) VJ LH_2 sphere at Stennis Space Center gave an **average boiloff reduction of 46%** over three thermal cycles in six years

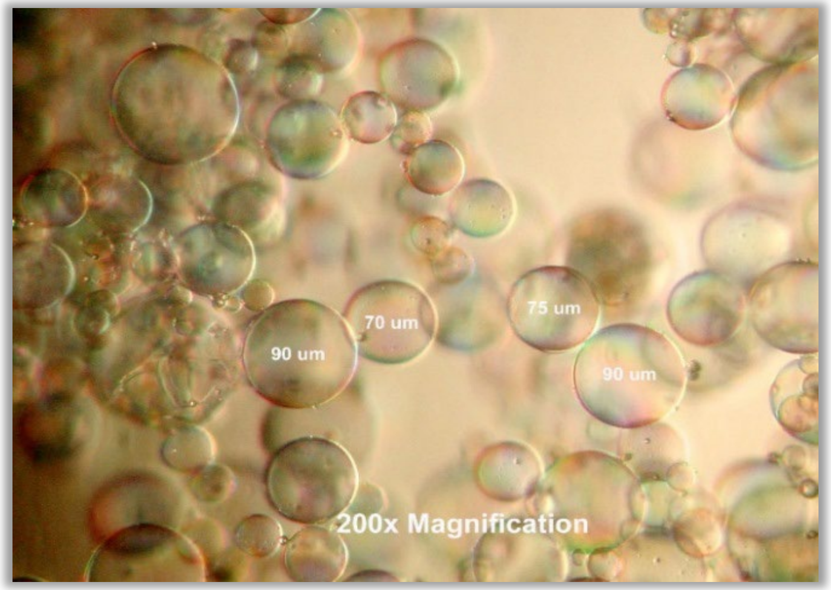


Image Credits: NASA Cryo Lab

FUTURE PERSPECTIVES, CHALLENGES, & OPPORTUNITIES

PERSPECTIVES, CHALLENGES, & OPPORTUNITIES

- **Single largest loss mode in NASA-KSC LH_2 systems/operations is chilldown of hardware during every launch attempt (roughly half of the total losses)**
  - This is also a function of the particular application → long duration between launches
  - If at all practical, future LH_2 systems and operations should aim to maintain low temperature of downstream equipment
    - Need development of high volume, low pressure LH_2 pumps for continuous, closed-loop liquid flow throughout the supply system = liquid on-tap!

- **Strive for zero venting of hydrogen boiloff to atmosphere**
  - Need to think about losing hydrogen like we think about losing helium….only acceptable in the event of an emergency!
    - Not only is hydrogen a secondary greenhouse gas, but the current LH_2 supply chain is very dirty!
      - In the USA currently, roughly 27 kg of CO_2 is generated per kg of LH_2 created; not counting tanker truck emissions
    - Need implementation of active refrigeration in the system, as well as hardware designs and transfer operations that place an emphasis on reducing hydrogen losses

PERSPECTIVES, CHALLENGES, & OPPORTUNITIES

- **Lack of expertise and facilities for LH_2 testing is an issue**
  - Minimal or zero LH_2 supply chain in many places; in the USA, no supply chain for small, "lab" quantities of LH_2……it's either a full tanker truck or nothing
  - Overall risk averse, litigious culture can slow things down…….**need some courage**!
- **To maximize efficiency, and boost economic viability, a holistic approach should be taken for the end-to-end design**
  - Segments such as LH_2 production, storage, transport, transfer, and end-use need to be **analyzed and designed as a whole system architecture**, not as individual parts to be integrated

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Technical References

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Additional available upon request

Thank you for your attention!

Questions?

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