

Mission Innovation Offroad Hydrogen Working Group Meeting

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NASA LH₂ Storage and Operations

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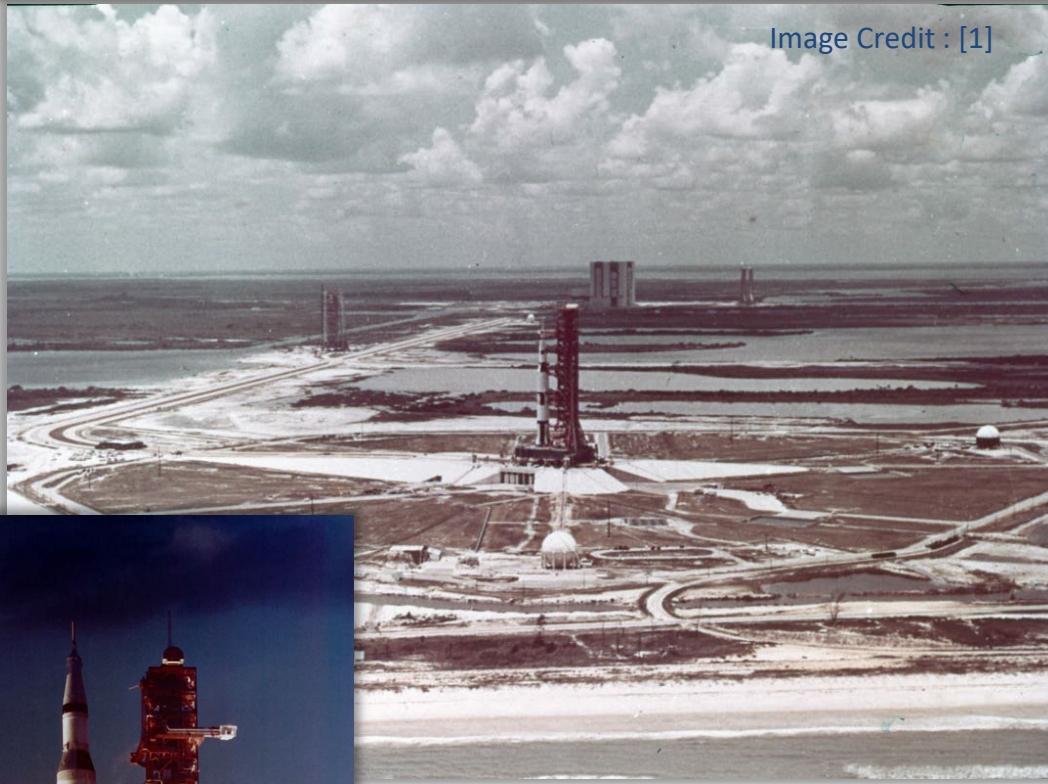
1. LH₂ launch pad infrastructure at NASA Kennedy Space Center
 - Legacy hardware
 - Recent improvements & technology development
2. High level LH₂ operations at the launch pads
3. Topics related to cryogenic tank design

KSC LAUNCH PAD INFRASTRUCTURE

- LC39A & B built in 1960's for Apollo moon program
- Identical layout
- Both used throughout Apollo and Space Shuttle Programs
- Cryogenic storage systems sized for Apollo missions (Saturn V vehicle)
- **Thousands of feet of large diameter piping!**
- ★ Inefficient LH₂ operations
 - Lost around half of the LH₂ purchased during Shuttle Program



LC39 CRYOGENIC STORAGE – APOLLO ERA



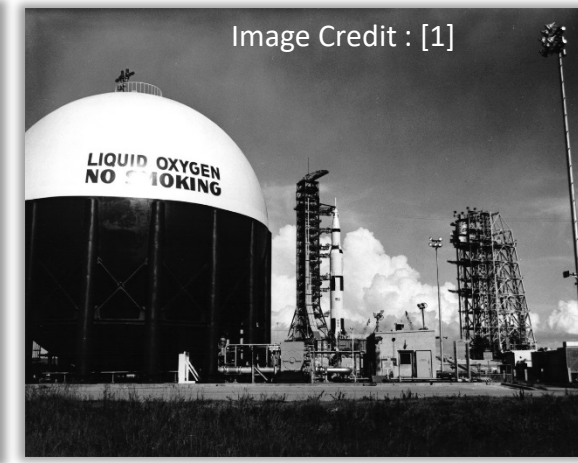
Saturn V

Weight = 6.2 Mlbs

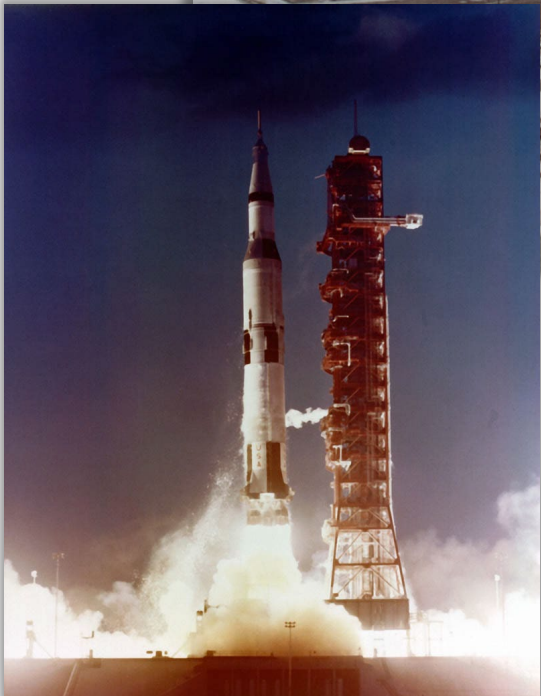
Thrust = 7.5 Mlbs

Total On-Board Cryo Prop.

LO₂ = 454Kgal, LH₂ = 335kgal



- 4 permanent, site-built vessels
- Constructed 1963-1965 by Chicago Bridge & Iron Co.
- **Designed for Normal Boiling Point (NBP) storage**

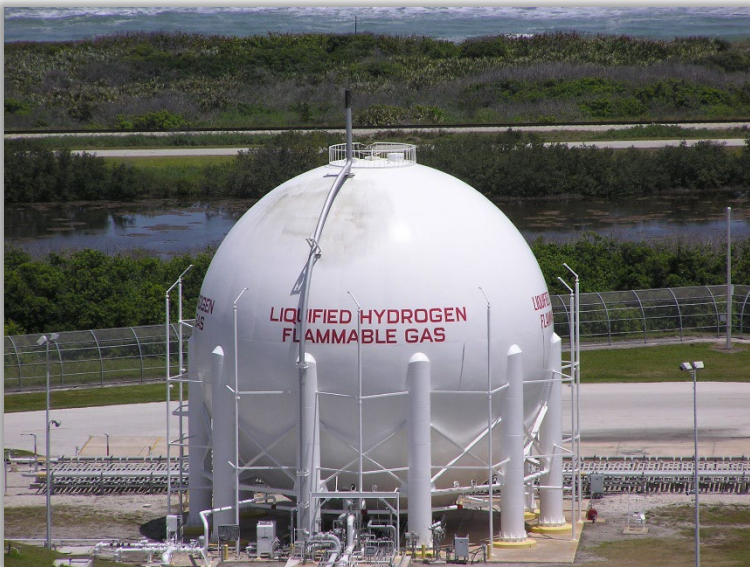


VESSEL SPECIFICATIONS



Liquid Oxygen

- 900,000 gal (3,407 m³) useable volume
- ~69 ft. (21 m) outer diameter; MAWP = 12 psig (0.83 bar)
- Double-walled w/perlite bulk-fill insulation (~4 ft. thick), purged with nitrogen gas
- Normal Evaporation Rate = 0.1% (900 gal/day)



Liquid Hydrogen

- 850,000 gal (3,407 m³) useable volume
- ~69 ft. (21 m) outer diameter; MAWP = 90 psig (6.2 bar)
- Vacuum-jacketed w/perlite bulk-fill insulation (~4 ft. thick)
- Normal Evaporation Rate = 0.04% per day

LC39 CRYOGENIC STORAGE – SHUTTLE ERA

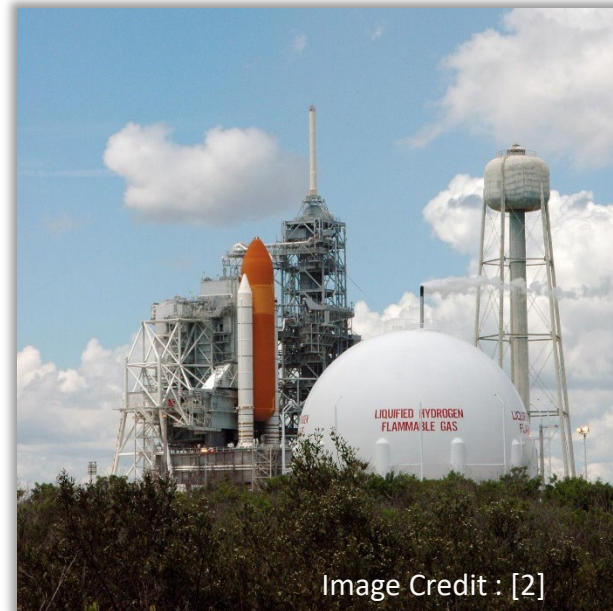
Space Shuttle

Weight = 4.5 Mlbs

Thrust = 7.1 Mlbs

Total On-Board Cryo Prop.

LO₂ = 180Kgal, LH₂ = 385kgal



- Technology remained relatively unchanged since 1960's

LC39B CRYOGENIC STORAGE – ARTEMIS ERA

Space Launch System

Weight = 5.75 Mlbs (EM-1)

Thrust = 8.8-11.9 Mlbs

Total On-Board Cryo Prop.

$\text{LO}_2 = 263\text{Kgal}$, $\text{LH}_2 = 467\text{kgal}$



- NASA studies showed LH_2 capacity at Pad B was insufficient for SLS Block 2 and beyond
- Numerous solutions were explored; ultimately, it was decided to **construct a new, larger, supplemental vessel**

NEW LC39B LH2 VESSEL SPECIFICATIONS

- Detailed design and construction by CB&I Storage Tank Solutions as part of the PMI contract for the launch facility improvements
- ASME BPV Code Section XIII, Div 2 and ASME B31.3 for piping
- Usable capacity = **4,732 m³** (1,250,000 gal) w/ min. ullage volume 10%
- Max. boiloff or NER of 0.048% (600 gal/day, 2,271 L/day)
- Min. Design Metal Temperature (MMDT) = 4 K (-452 °F)
- Pressure rating or Max. Allowable Working Pressure (MAWP) = full vacuum to 6.2 barg (90 psig)

Image Credit: [1]



NEW STORAGE TECHNOLOGIES

- **Passive Thermal Control**: the **glass bubbles insulation** system (evacuated) is implemented in lieu of the perlite powder system
 - Proven to reduce boiloff by **46%** in field tests
- **Active Thermal Control**: internal heat exchanger is implemented for the future addition of **Integrated Refrigeration and Storage** (IRAS) system for complete controlled storage capability

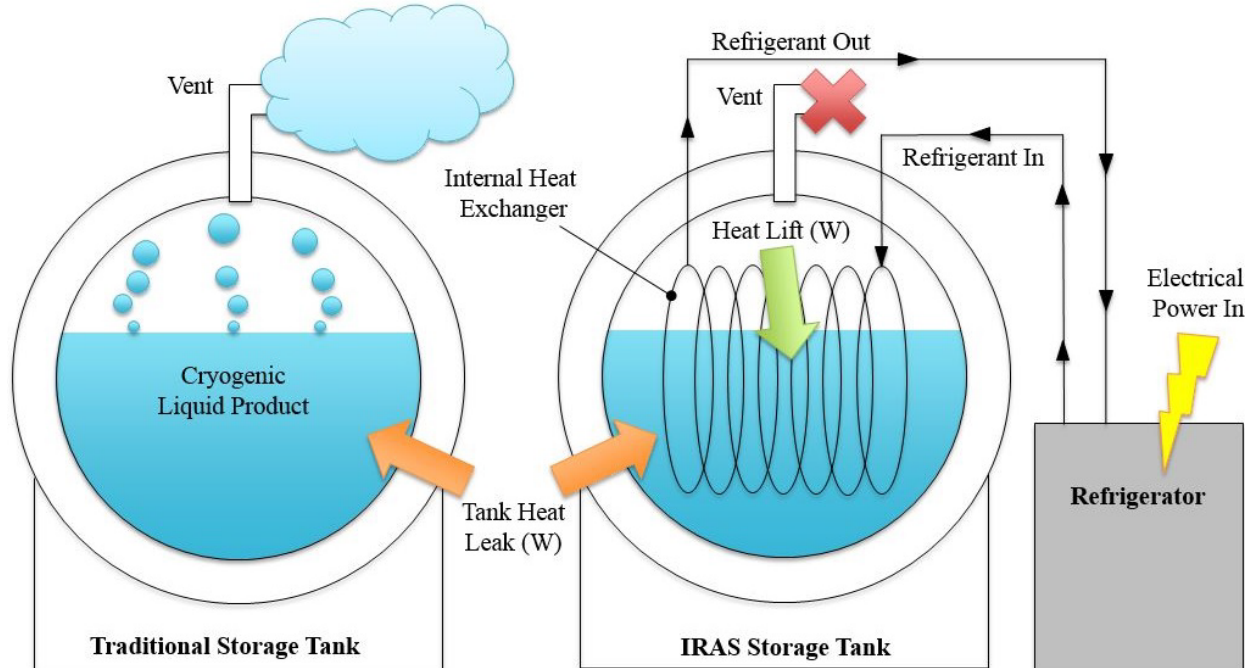


Image Credit: Author



Image Credit: [2]

- From 2012 -2016, the GODU-LH2 project at NASA-KSC proved IRAS for **LH₂** on a large scale
 - 33,000 gal (125 m³) IRAS tank
 - Linde LR1620 helium refrigerator, 850 W @ 20 K max cooling

Testing Milestones

- ✓ Dry chardown of tank to LH₂ 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 14 cents spent on electricity, one dollar in liquid hydrogen was saved



KSC LH₂ OPERATIONS

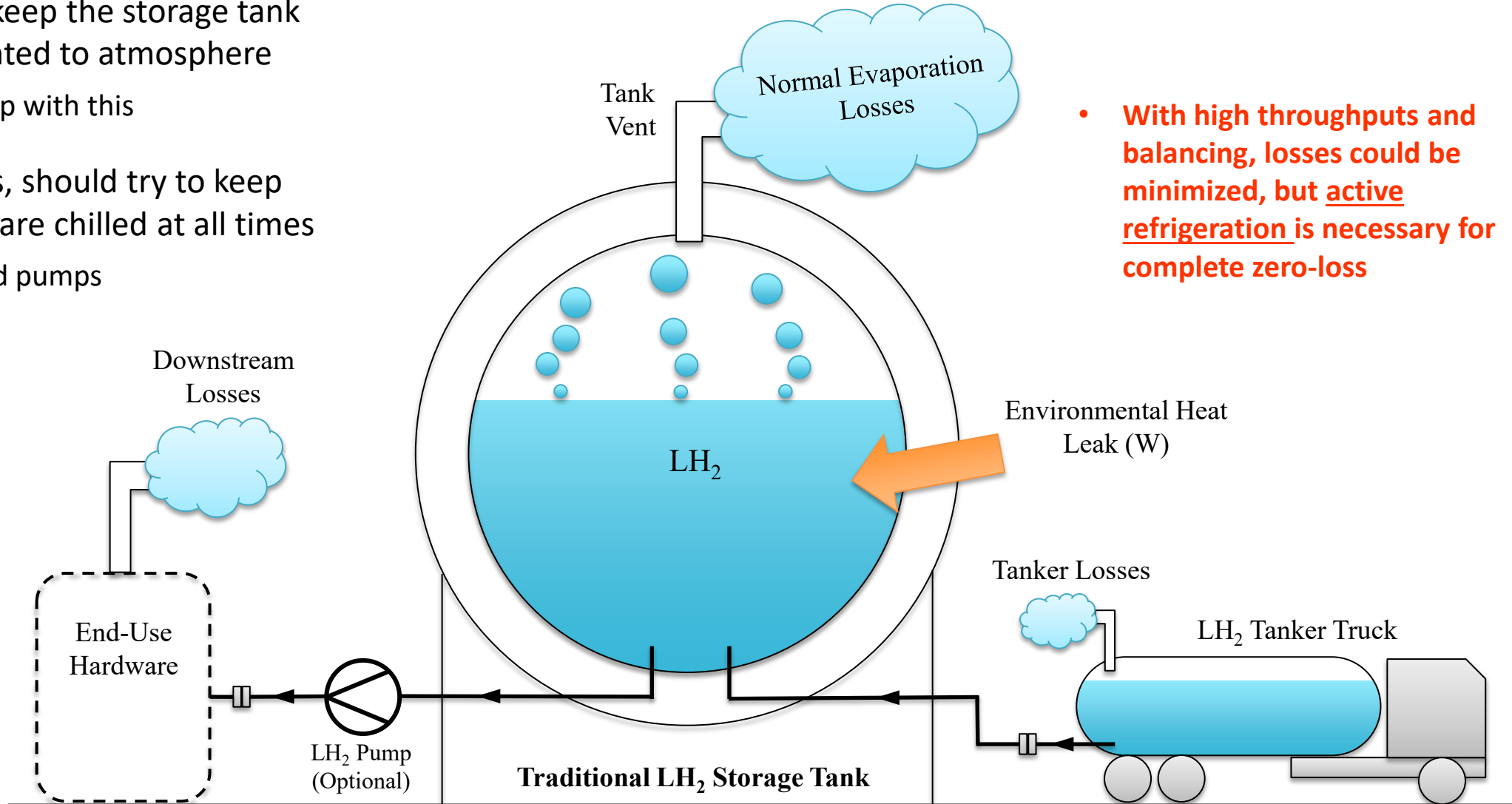
- Fill storage tanks from waves of 10 tankers trucks per day
 - 5 tankers unloading in parallel
 - Tankers travel from Alabama, non-stop to KSC
- Tanks kept vented near atmospheric pressure during normal storage
 - Normal boiloff vented locally, not flared-off
- For launch, tanks pressurized via vaporizers to around 60 psig and **LH₂ is pressure-fed to vehicle**
- Slow-fill for piping and vehicle tank chill down, then fast-fill (up to 10,000 GPM) to 100%, then slower replenishment until launch



- During vehicle loading, boiloff gas flow is very high, hence is safely flared-off
 - ★ Per AIAA G-95 standard, up to 0.5 lb/sec (0.226 kg/s) can be vented without flaring
 - Equivalent to 50.8 GPM of LH₂, or a heat load of 101.4 kW at NBP

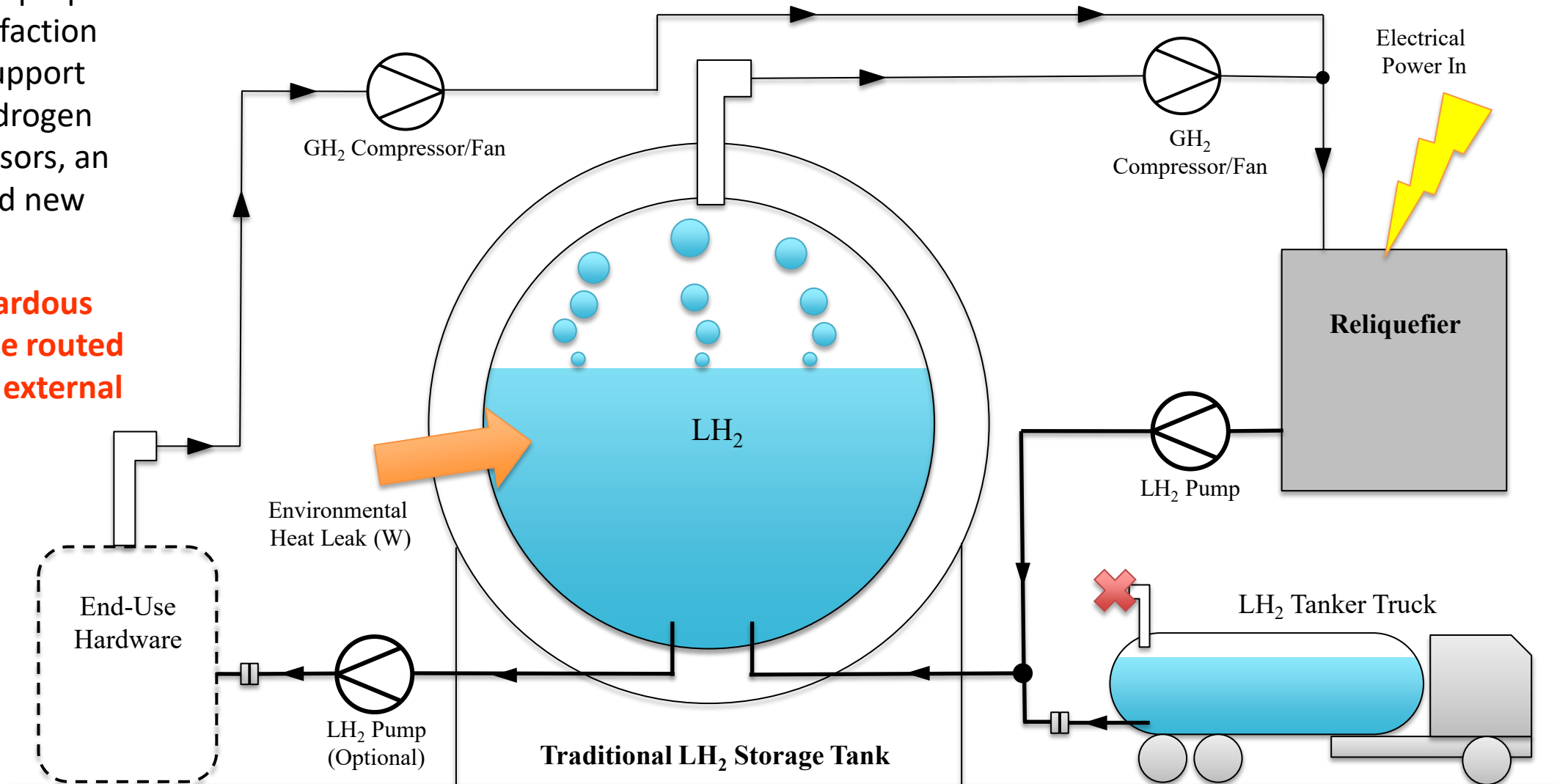
TRADITIONAL "GENERIC" LH₂ OPERATIONS

- Generally, want to keep the storage tank close to NBP, so vented to atmosphere
 - Pumps could help with this
- If application allows, should try to keep downstream hardware chilled at all times
 - Bypass loops and pumps



CLOSED-LOOP, ZERO-LOSS LH₂ OPERATIONS with RELIQUIFICATION

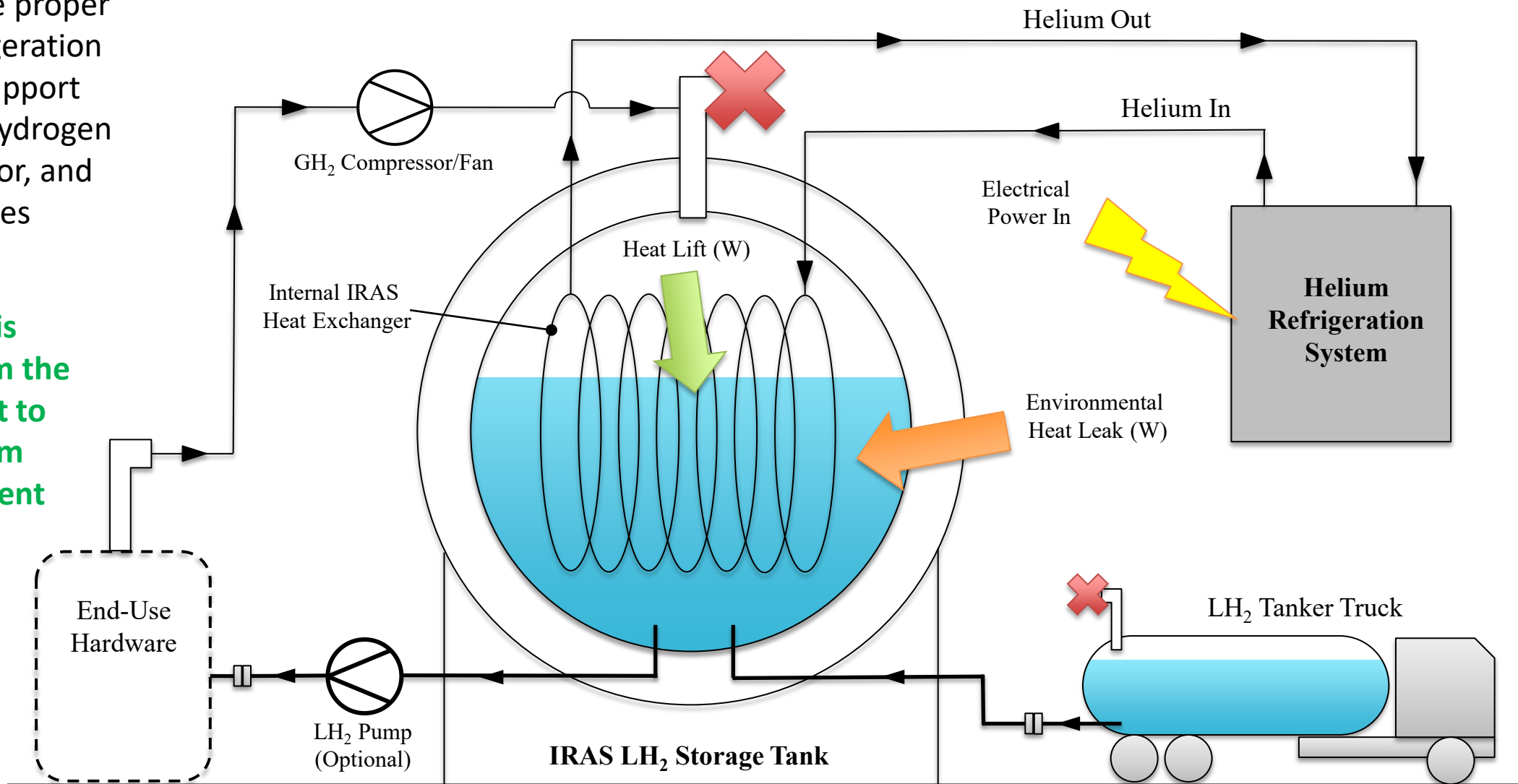
- Would require proper sizing of liquefaction system and support hardware, hydrogen fans/compressors, an LH₂ pump, and new procedures
- **Requires hazardous commodity be routed to additional external equipment**



CLOSED-LOOP, ZERO-LOSS LH₂ OPERATIONS with IRAS

- Would require proper sizing of refrigeration system and support hardware, a hydrogen fan/compressor, and new procedures

★ **Hazardous commodity is isolated from the environment to the maximum practical extent**



DESIGN OF CRYOGENIC FUEL TANKS

- **General NASA approach to design and manufacture of cryogenic tanks**
 - Characterize loads and environments
 - Maximum Design Pressure (MDP) is a one-fault or two-fault pressure maximum, depending on program requirements.
 - Dynamic loads developed using coupled loads analysis
 - NASA-STD-5001 – “*Structural Design and Test Factors of Safety for Spaceflight Hardware*”
 - Sets minimum design factors for FTU, FTY, and buckling
 - Requires stress and stability analysis
 - AIAA S-080 “*Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components*”
 - Sets minimum factors for proof, burst, and negative pressure
 - Requires damage tolerance (fracture control) for pressure vessels and pressurized structures
 - Establishes qualification and acceptance test requirements
 - Damage tolerance analysis
 - Qualification testing to verify design
 - Acceptance testing of each cryogenic tank
 - Nondestructive evaluation (NDE) – radiography, dye penetrant, ultrasonic, eddy current, etc
 - Proof testing
 - Damage control
- **Spaceflight industry distinguishes between pressure vessels and pressurized structure and levies slightly different requirements**

DYNAMIC LOADS DEVELOPMENT

- **Coupled Loads Analysis**

- MSFC loads team is responsible for developing primary structure limit loads for launch vehicles and spacecraft using coupled loads analysis (CLA).
- SLS CLA uses a suite of integrated vehicle Finite Element Models (FEM) that represents the assembled launch vehicle for discrete loading events including Rollout, Pad-Stay, Liftoff and Ascent. CLA subjects these FEMs to a variety of forcing functions that represent dynamic loading events experienced during the life cycle of the vehicle (e.g. crawler loads from Rollout, ground winds for Pad-stay, engine start and ignition overpressure for Liftoff, buffet and gust during Ascent, etc.).
- An assembled launch vehicle loads model includes an LH2 propellant tank substructure FEM, which is in the primary load path of the vehicle (i.e. primary structure). Section loads are recovered during CLA at various stations along the length of the LH2 tank and are then flowed via a loads requirement document for downstream use in primary structure strength and life assessments.
- All CLA loads FEMs, including the LH2 tank, are modeled using simplifying assumptions geared towards accurately representing the mass and stiffness, load path and low frequency dynamics of the primary structure. Primary structure is modeled using shell and beam elements and smeared properties are used to represent orthogrid or isogrid stiffening geometries if present. Secondary structure and components are often modeled as simple lumped masses, and non-structural mass is used for distributed items such as TPS and wire harnesses.
- Special model considerations for the LH2 tank include the use of cryogenic material properties, modified geometry to account for shrinkage due to cryogenic conditions, pressure stiffening effects from flight ullage pressure and use of a hydroelastic fluid models to capture propellant-structure interaction and free-surface slosh dynamics at discrete fill levels (models are created for every 5% fill increment).

DAMAGE TOLERANCE & DAMAGE CONTROL

- **Damage Tolerance (Fracture Control)**

- Used by NASA and the spaceflight industry to address the risk of:
 - Material defects – cracks, inclusions, discontinuities, porosity, casting defects, weld defects, etc
 - Hardware damage – scratches, tooling gouges, impact damage, corrosion, etc
- The damage tolerance approach assumes there is a sharp, crack-like defect that is:
 - Sized at the threshold of NDE capability (minimum detectable flaw size)
 - In the worst-case location and worst-case orientation for crack growth
- Fracture mechanics analysis is required to show 4X operational lives (or 4X lives between inspections)
 - Typically use NASGRO software
 - Fatigue crack growth rate and fracture toughness data is required
 - May substitute damage tolerance testing in some circumstances

- **Damage Control**

- Formal written work procedures are typical for manufacturing, transportation, test, and integration
- In some cases, a top-level Damage Control Plan is required
 - Lists all the physical locations, environments, and operations the hardware may see, step-by-step, from manufacturing through retirement
 - Attempts to identify all credible damage threats for each step – impacts, tool drops, foreign materials, etc
 - Develops a mitigation for each threat – protective covers, inspection points, stay-out zones, etc
- Goal is to inspect hardware to screen for damage, and then to ensure its protected from damage after the last inspection point

REFERENCES

Image References

1. <https://ntrs.nasa.gov/citations/20210020920>
2. <https://images.nasa.gov/>

Additional References

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