HYSKY *presents*

Liquid Hydrogen Lessons From NASA

#57

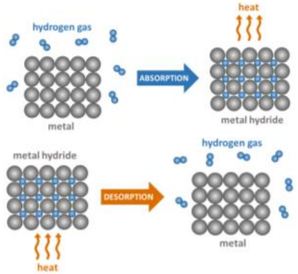
On Zoom
Aug 19, 2024
11:30 AM -
1:00 PM ET

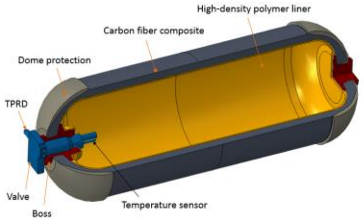
Matt Moran

of

Moran
Innovation

Hydrogen Storage Options



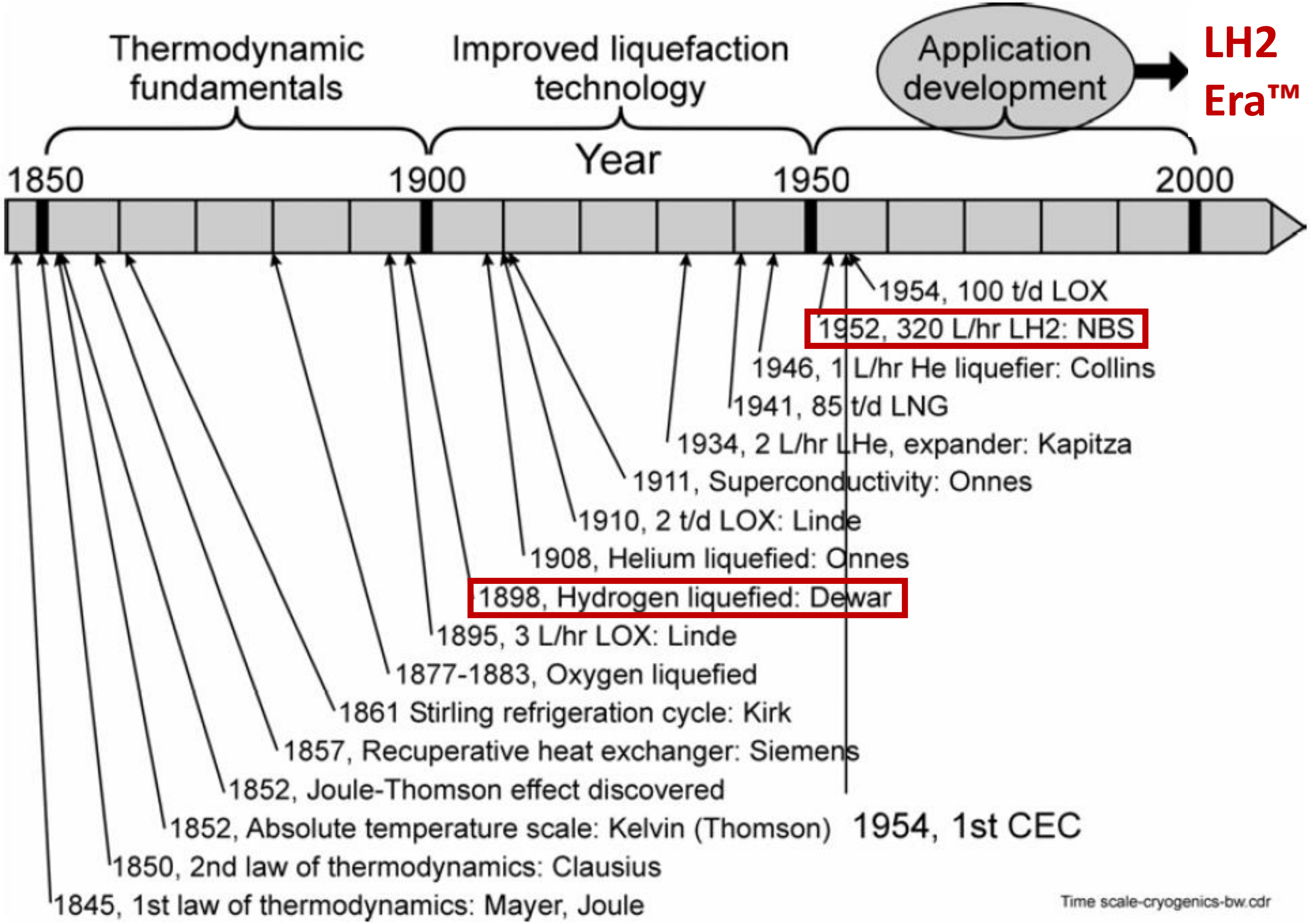


	Underground Storage	Material-Based (Solid State)	Compressed Gas	Cryogenic Liquid	Cryo-compressed
Conditions:	moderate pressures; 15 C	Various	Up to 700 bar; 27 C	Low pressure; -253 C	Up to 450 bar; cryogenic
Energy Input:	Blower or compressor	Various	Compressor; cooler	Liquefaction	Depends on process
Supply Method:	Piping delivery	Onsite	Tubers or onsite	Transport or onsite	Onboard fueling
H2 Density:	15 kg/m^3 at 200 bar[b]	n/a	39 kg/m^3 at 700 bar	71 kg/m^3 at 1 bar	> 80 kg/m^3 possible
Mass Fraction[a]:	n/a	< 2% (metal hydride)	< 10%	Up to 80%	10% or more

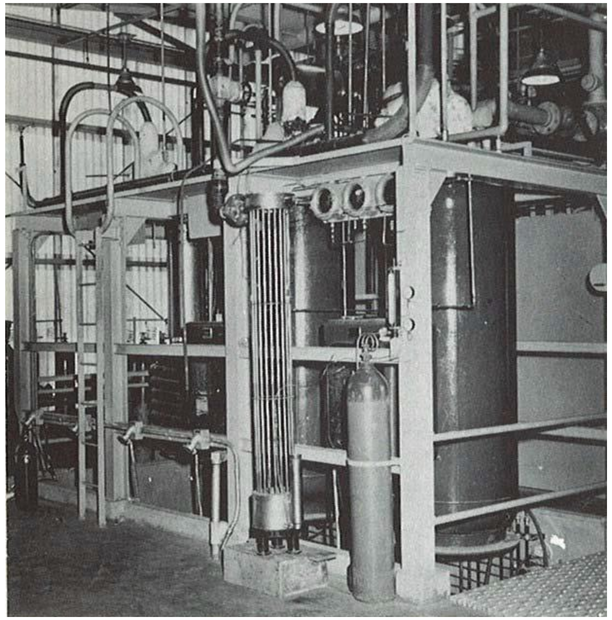
(a) Hydrogen mass divided by hydrogen plus storage vessel mass. (b) Not accounting for roughly one-third buffer gas requirement.

Image credits: FuelCellWorks, Hystorsys, DOE, ANL, NASA, Cryomotive

Liquid Hydrogen (LH2) History (1898 – 1952)



LH2 Era™



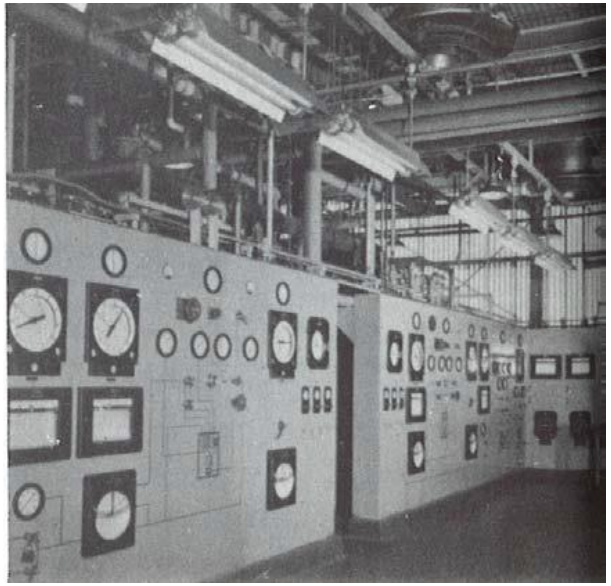
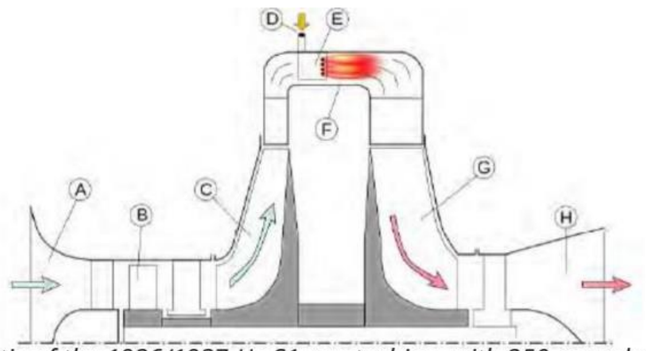


Image source: Radebaugh, Ray, "Historical Summary of Cryogenic Activity Prior to 1950", 2007.

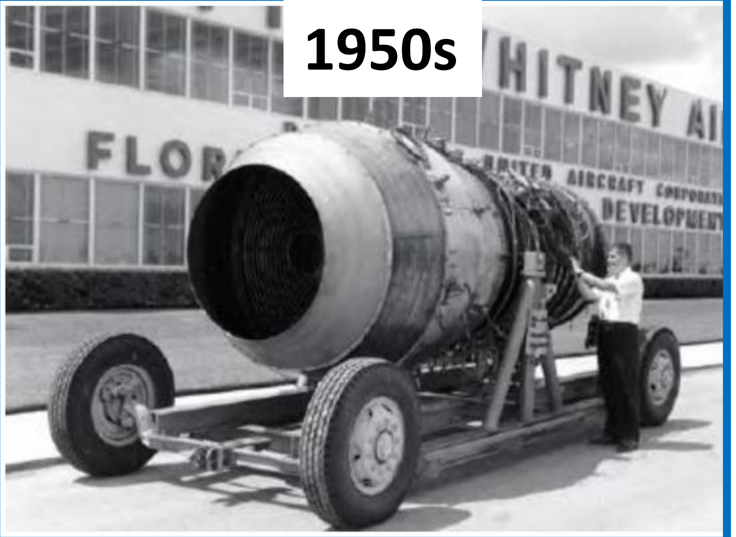
Evolution of Aerospace LH2 Systems (1930s – 1960s)

1930s



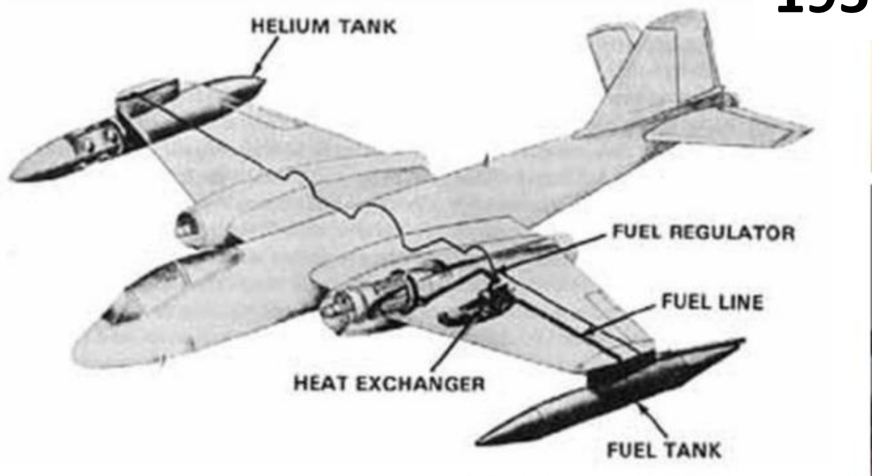
Schematic of the 1936/1937 He S1 gas turbine, with 250 pounds thrust,

1950s



1966

1955



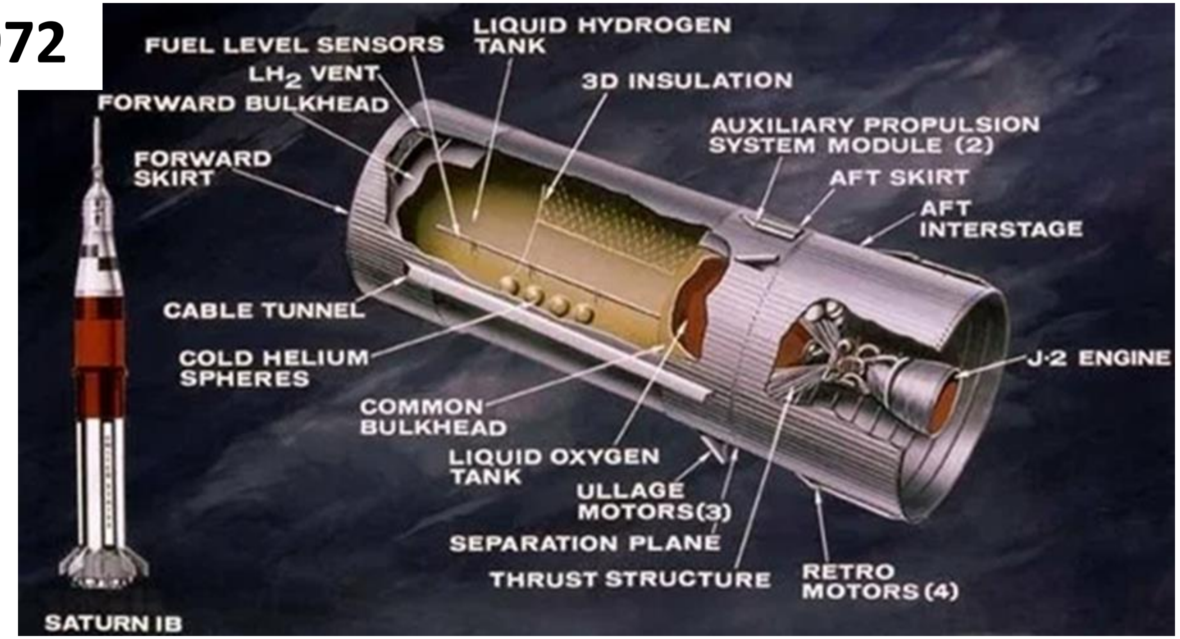
Liquid-hydrogen fuel system for one engine of a B-57 airplane installed by the NACA Lewis

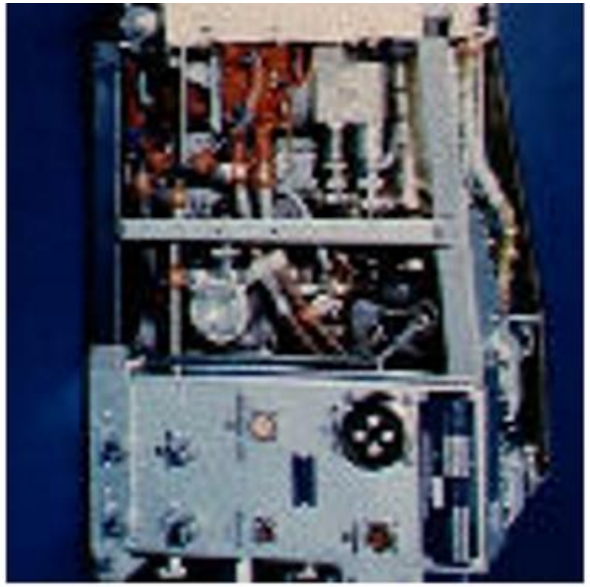
First flight in 1955: https://youtu.be/Z6rsMyyQnBA

Image credits: Mechanical Engineering, NASA

Evolution of Aerospace LH2 Systems (1961 – 2011)

1961-1972





1981-2011

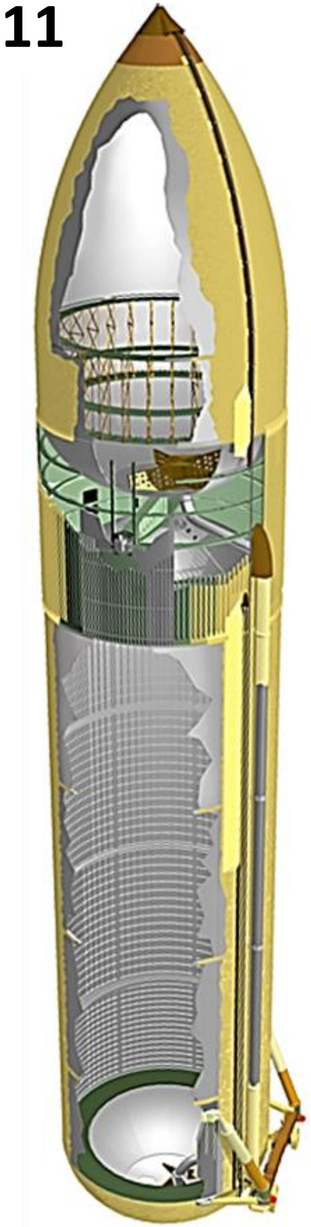


Image credits: NASA

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Space Applications Examples Now*


Image credit: NASA


Image source: ISRO


Credit: Chris Gunn - Ariane 5 with James Webb Space Telescope Prelaunch

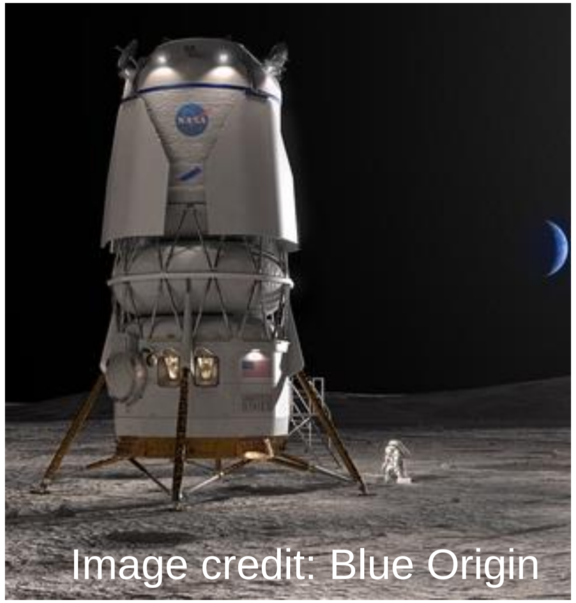


Image credit: Blue Origin


Image credit: ULA

*Countries and regions with active LH2-fueled rockets: US, EU, Japan, China, and India

Stationary (Ground): Vacuum-Jacketed LH2 Dewars

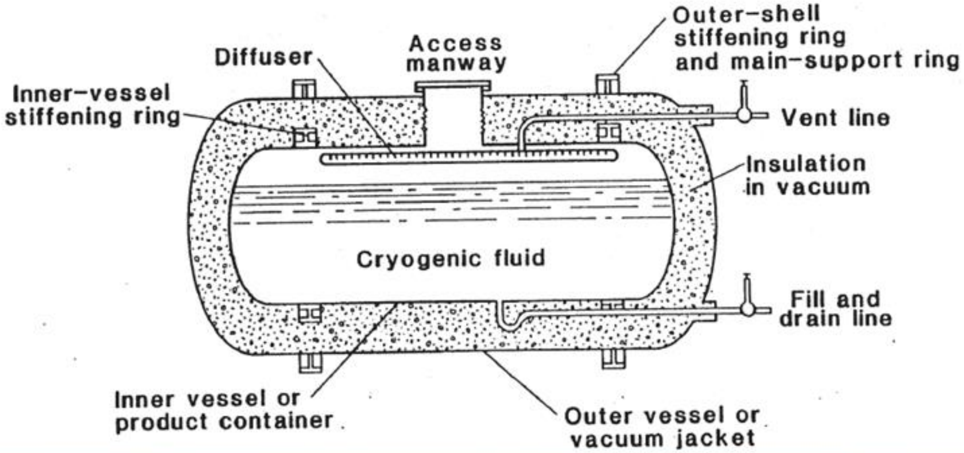


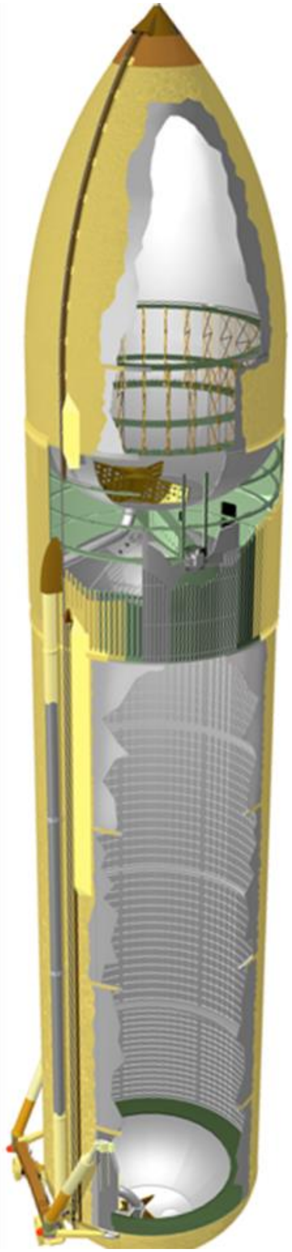
Image credits: NASA

- Liquid hydrogen ground systems from laboratory scale through large scale storage use vacuum jacketed double-wall dewars
- The vacuum annulus is filled with insulating material (e.g. pearlite, multilayer insulation, glass microspheres, aerogel, etc.)
- Resulting high thermal performance enables storage with low boil-off (e.g., 0.5% per day)
- Further reduction or elimination of boil-off can be achieved by a variety of methods
- Operating pressures generally less than 5 bar at 20.3 K (−252.87 °C) and above
- Usually ASME code designed, tested, and stamped

For more information: see Section 3.4, ***Cryogenic Fluid Management…***, Moran Innovation LLC, 2023

Launch Vehicles: Single Wall LH2 Tanks

Image credits: NASA



- Single wall metal liquid hydrogen tanks with foam insulation have been used on launch vehicle upper/main stages and the space shuttle external tank
- The foam insulation provides enough thermal resistance to prevent condensing of air constituents and mitigates frost buildup on the external surface
- Much lower weight compared to dewar designs, but poor thermal performance and much higher boil-off
- Good design choice for launch vehicles due to short storage times and high consumption rate
- Operating pressures kept low (under 2 bar to ~ 4 bar)
- Lightweight design requires significant analysis and proof testing

For more information: see Section 3.4, ***Cryogenic Fluid Management…***, Moran Innovation LLC, 2023

NASA Artemis SLS LH2 and LOx Tanks (Al 2219)

Image credits: NASA

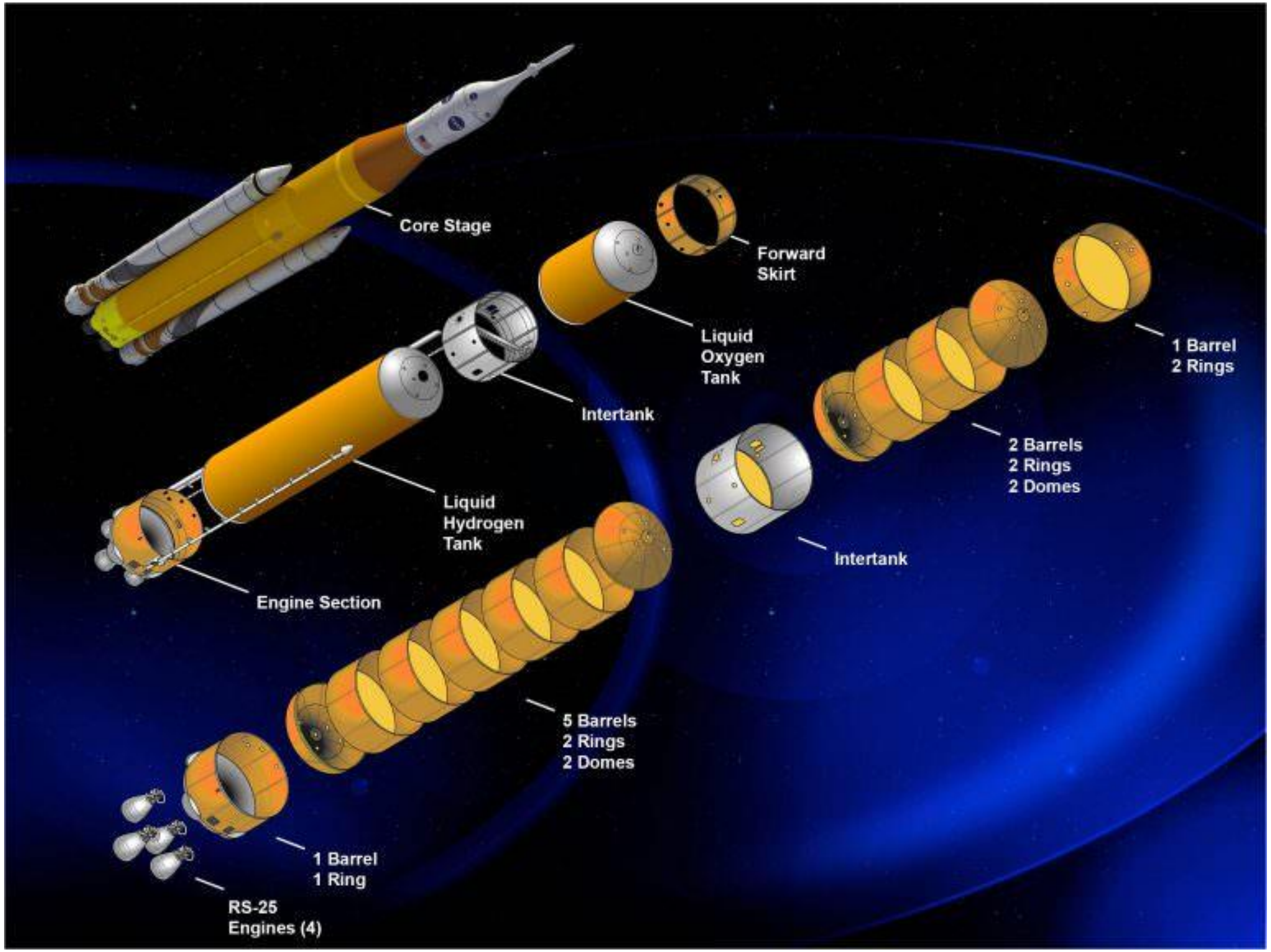
For more information: see Section 3.4, ***Cryogenic Fluid Management…***, Moran Innovation LLC, 2023

NASA SLS Integrated Core Stage

Image credit: NASA

For more information: see Section 3.4, *Cryogenic Fluid Management…*, Moran Innovation LLC, 2023

NASA SLS Launch Vehicle Tank Integration



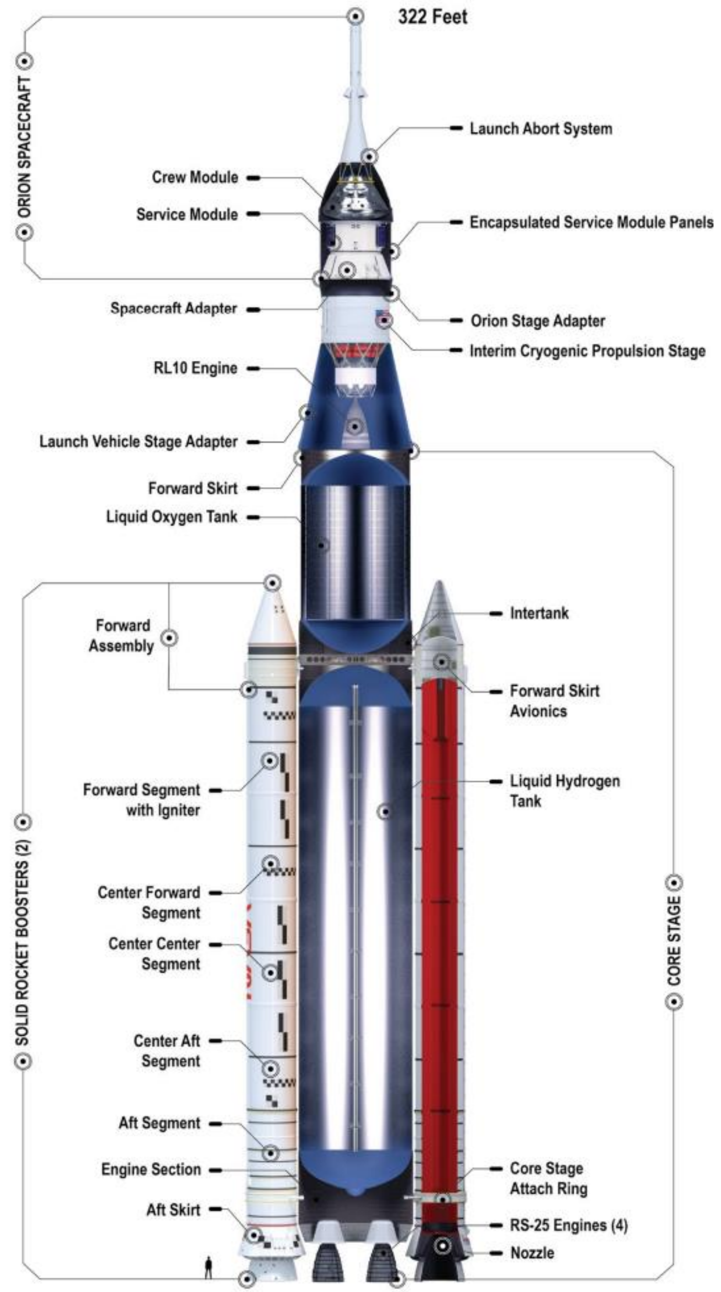


Image credits: NASA; SLS Reference Guide 2022

Composite Liquid Hydrogen Tanks

Image credit: NASA

- Many types and designs attempted over the years with mixed success
- Challenges include stochastic structural failures; permeability of hydrogen; interface connections (support, piping, etc.), cryogenics
- Metal inner liners improve structural interfaces, containment and load sharing; but also increase mass & CTE mismatch (i.e., Type III pressure vessel)
- Fabrication/layup defects and minor damage during assembly and operations can be difficult to detect
- Technology development activity increasing for both single and double wall composite (and thermoplastic) tanks

For more information: see Section 3.4, ***Cryogenic Fluid Management…***, Moran Innovation LLC, 2023

Ground vs Flight vs 'New' Tank Design Approaches

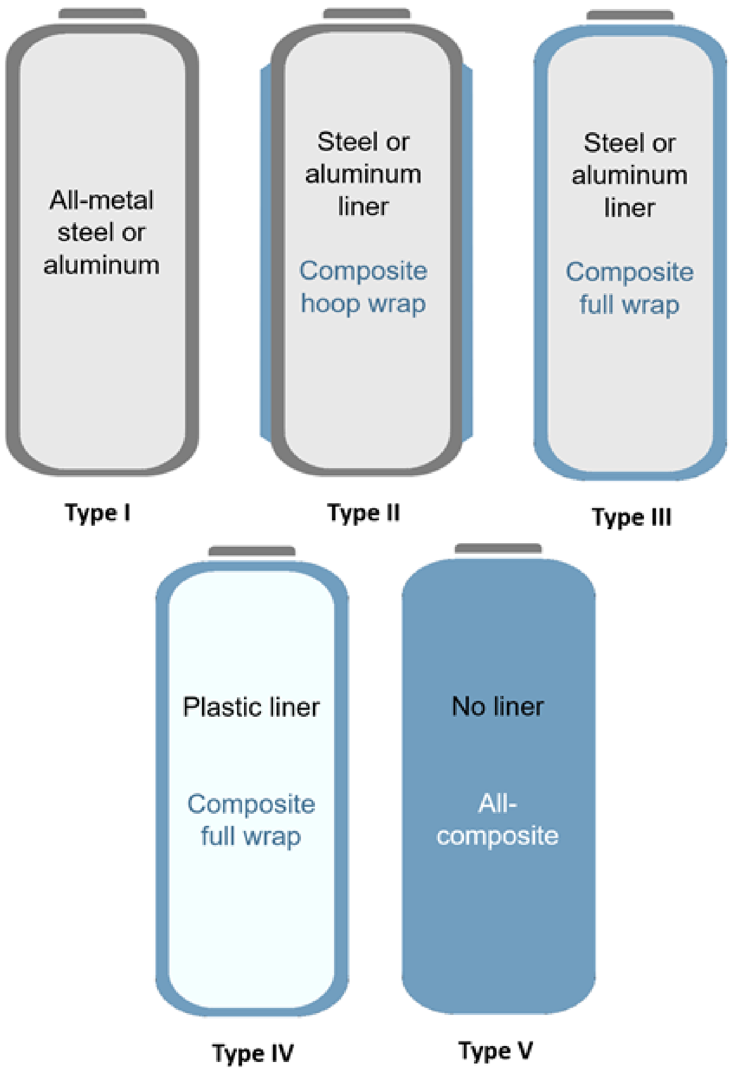


Image source: Engineering Technology Corp.

- LH2 stationary (ground) tanks are generally:
  - Vacuum-jacketed metal construction (e.g., 300 series stainless steel or aluminum alloy)
  - Have insulation in the vacuum annulus (e.g., MLI, perlite, aerogel, glass beads)
  - Designed to ASME Boiler and PV code for LH2 service (stamped with temp & pressure limits); Safety factor 3.5+; Max fill < 90%
- LH2 tanks for launch vehicles & spacecraft are:
  - Usually single-wall metal construction (lightweight alloys)
  - Insulated with foam and/or MLI or similar (aerogel blankets are also an option)
  - Generally custom designed with extensive analysis, modeling, and testing to certify; Safety factor ~1.5± ; Max fill ~95%±
- LH2 tank designs for aircraft and other 'new' uses:
  - Vacuum-jacketed metal construction is typical, with ongoing development of composite and thermoplastic designs
  - Insulation consistent with tank configuration and application
  - Custom designed? Certification? Safety factor? Max fill?

Hydrogen Safety

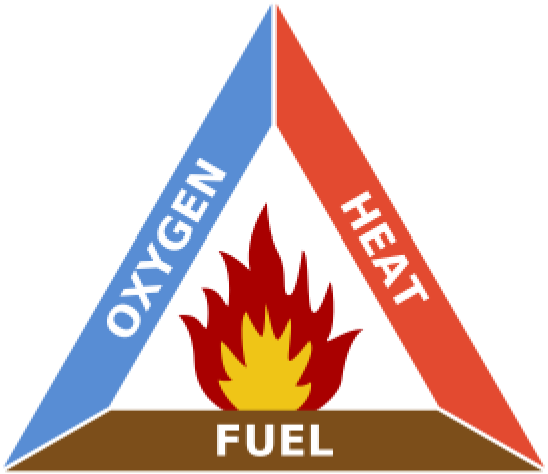


Image source

1. **Prevent leaks**
2. **Provide ventilation**
3. **Eliminate ignition sources**

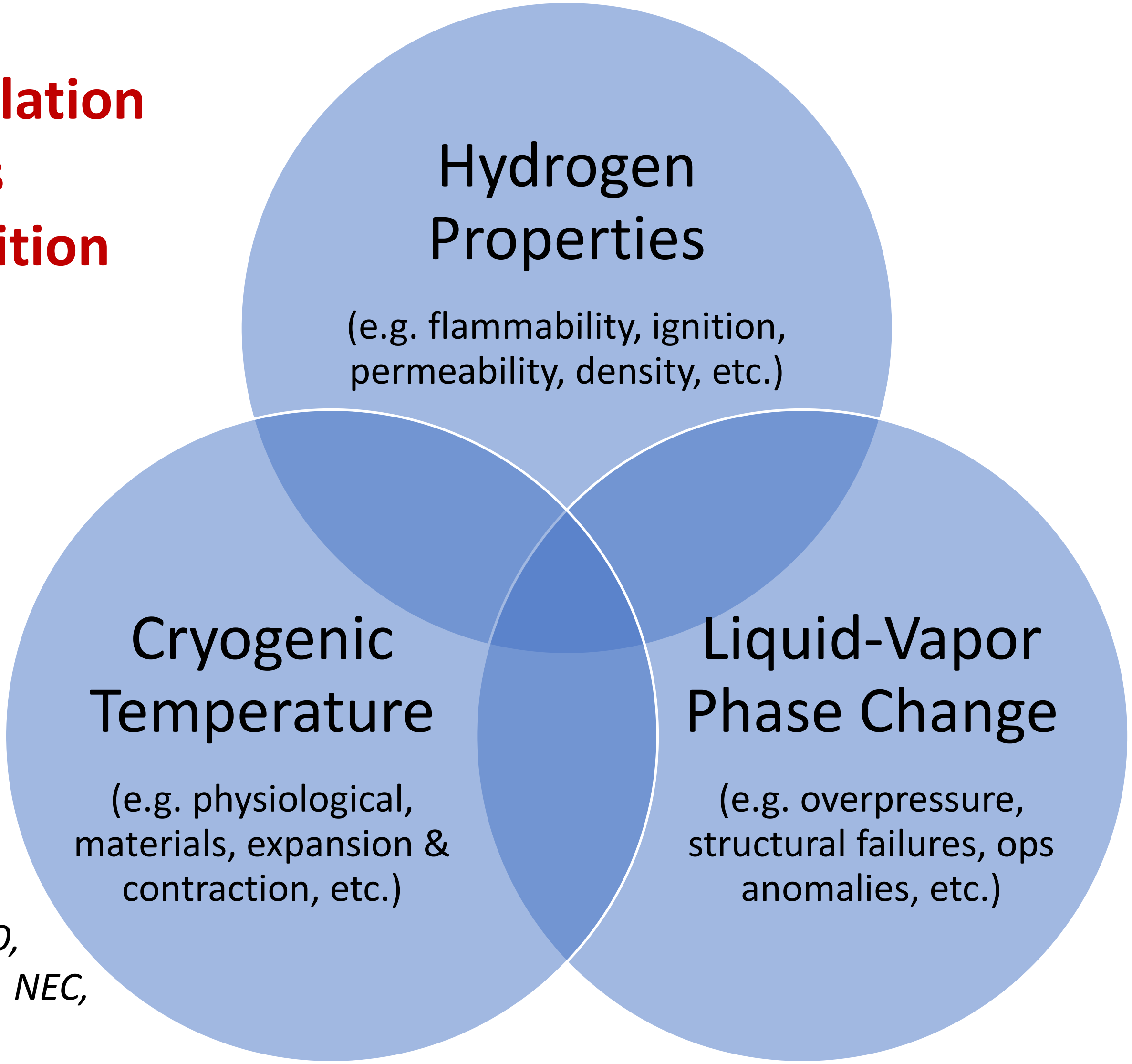
	HYDROGEN (GAS)	NATURAL GAS (GAS)
Lower heating value (Btu/lb)	51,532	21,300
Density at standard conditions (lb/gal)	0.0007 (0.59 for LH2)	0.005 (3.5-4.0 for LNG)
Autoignition temperature in air (°F)	1,050–1,080	1,004
Volume concentrations for flammability in air (%)	4.1–74	5.3–15
Diffusion coefficient in air (in.^{2}/sec)	0.0946	0.0248
Toxicity to humans	Non-toxic, simple asphyxiant	Non-toxic, simple asphyxiant

Image source: https://www.energy.gov/eere/fuelcells/safety-codes-and-standards-basics

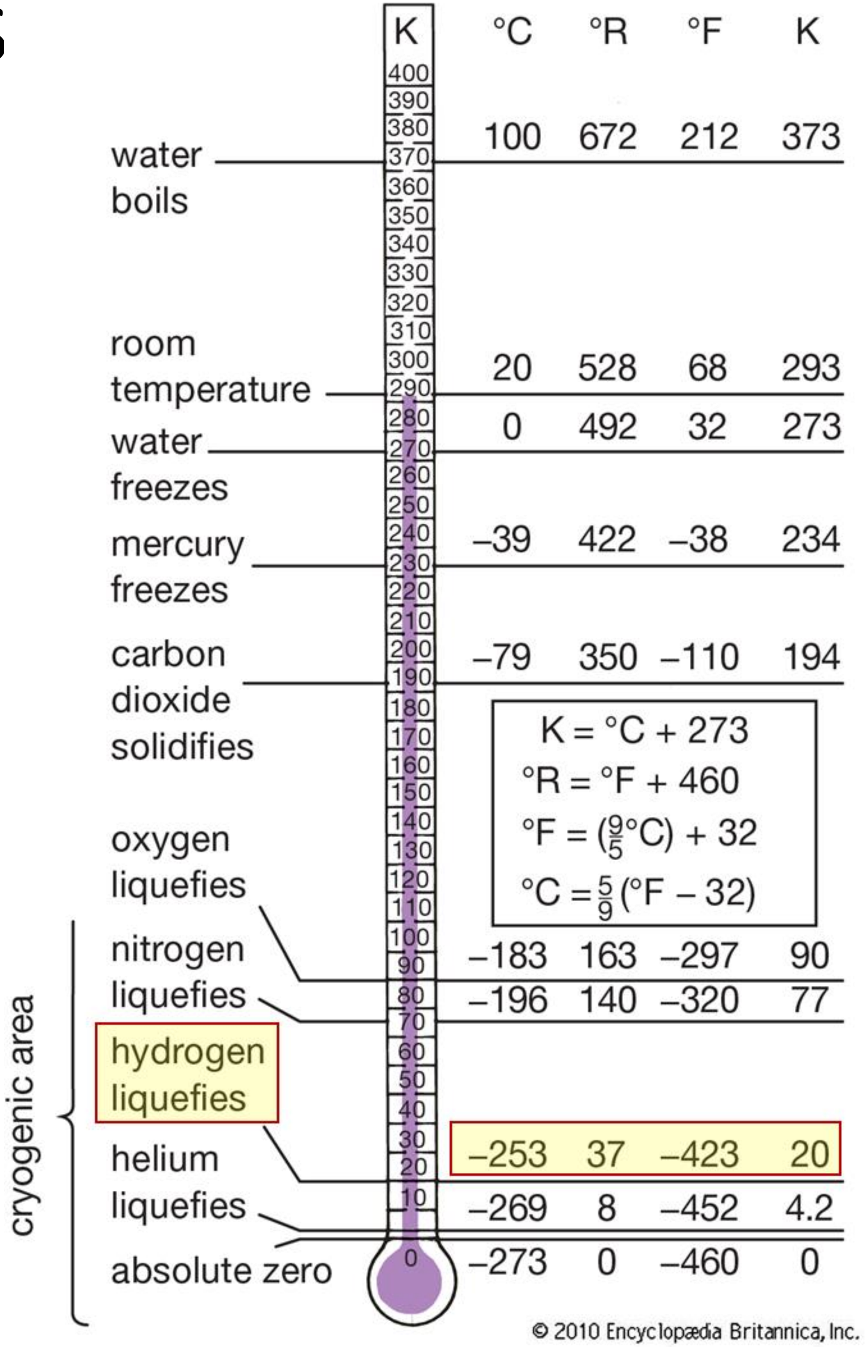
Liquid Hydrogen Safety Drivers

1. Provide ventilation
2. Prevent leaks
3. Eliminate ignition sources

Situational awareness; Plan for contingency



Codes, standards, and guidelines (e.g. [NFPA](), ISO, IECEx, ANSI, AIAA, ASME, NEC, CGA, CSA, SAE, IEEE, UL, NASA, MIL-STDs, and other national, state, local, etc.)



Some Liquid Hydrogen Safety Considerations

Safety Issue	Example Mitigations
Frostbite	Protective clothing (e.g., gloves, face shields, clean and non-static build-up clothing); design and operations
Asphyxiation	Ventilation, oxygen monitors, safety harness & lifeline to partner when entering confined or spill areas
Sensory	Awareness that hydrogen is colorless, odorless, has invisible flame in daylight (e.g. use IR for fire detection)
Materials and Construction	Suitable for cryogen hydrogen service (strength, ductility, fatigue, etc.); thermal stress, coefficient of thermal expansion of dissimilar materials; flexibility design for expansion and contraction; no buried piping
Overpressure Burst/Rupture	Secure mountings, pressure relief for all volumes that can be isolated, design for liquid warming expansion, insulation (including vacuum jacketed valves & piping for liquid lines); operational protocols, chilldown ops
Ice Buildup	Rain traps & other water build-up prevention for vents & reliefs; proper insulation on tanks & other equip.
Air Condensing	Appropriate insulation, trays, and operations to avoid surface temperatures that condense oxygen from air
Flammability/ Ignition	Prevent the "fire triangle" of fuel-oxidant-ignition; spark proof tools & electronics, purged/explosion proof cabinets, no objects above 466°C (80% of ignition temp), exclusion zones, ventilation, grounding, operations
Cold vapor/ leaks/damage	Avoid large spills and high flowrate cold venting (denser than air until it warms; flare if needed); seals design & material selection, leak detection, ventilation, automatic shutoff; physical barriers & protection
Contamination	Material cleaning requirements, no air in-leakage, supply standards, pressurant gas quality, purging, filters
Lack of planning	Safety program, training, FMEA, procedures, remote ops/valves, safe mode shutdown, first aid, emergency & fire response, evacuation, caution & warning systems, qualified personnel, design & safety reviews

Components, Subsystems and Safe Operations

Photos Source: Tom Tomsik, NASA

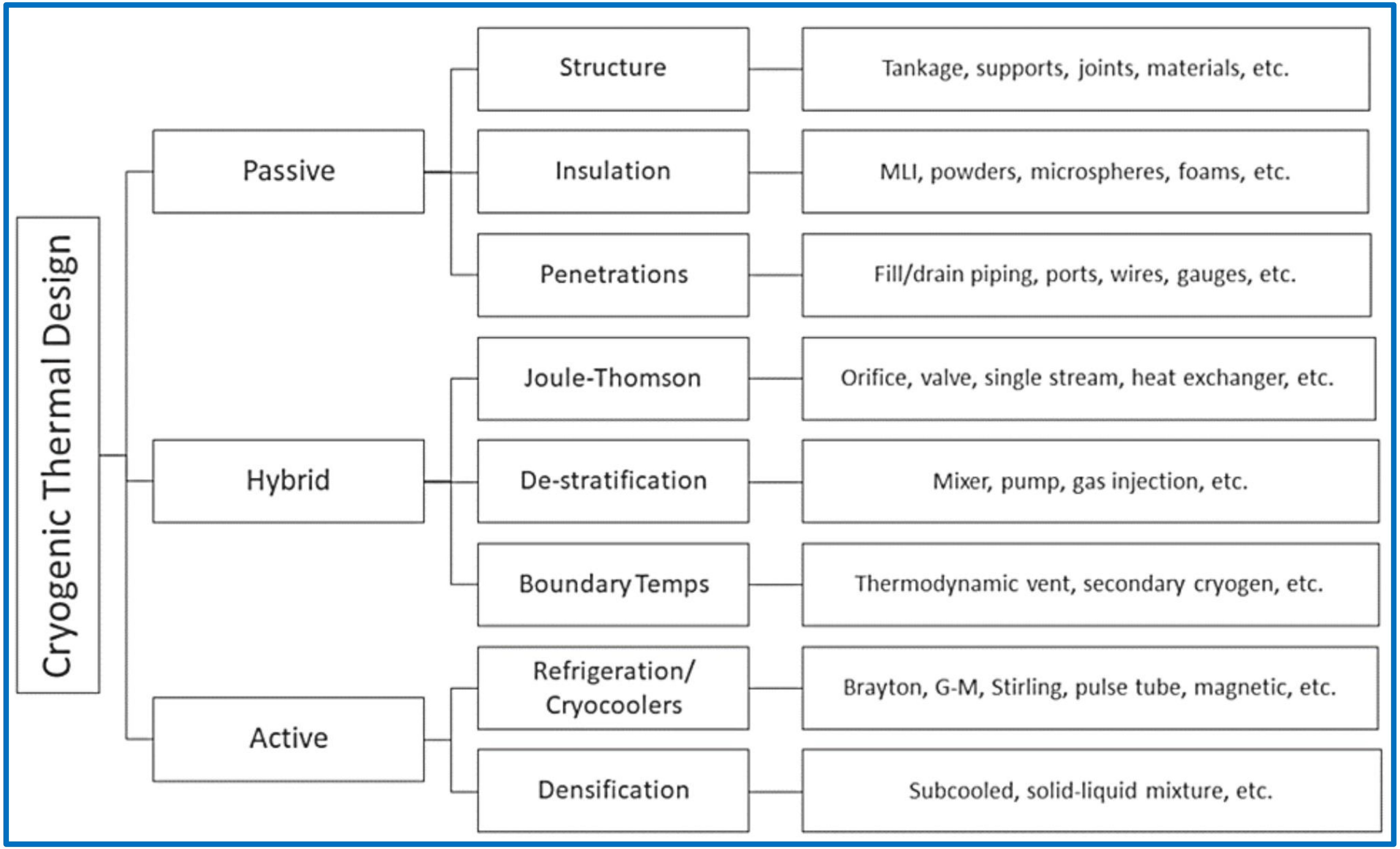
Design, Fabrication & Construction:

- Materials selection (H2 compatibility, nonlinear properties in cryo range)
- Vacuum jacketed dewars, piping and valves (maintain & monitor)
- Compatible sensors (temperature, pressure, liquid level, flow rate)

Safe Operations:

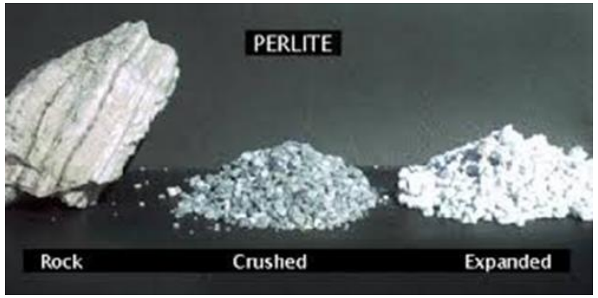
- Hydrogen delivery & storage (support systems, procedures)
- Preparation and check-out (reviews, check sheets, cold shock, leak testing, LN2 system tests, purging)
- Control of system pressures caused by heat leak; and designed for LH2 transfer (autogenuous or helium)
- Thermal management of the inherently large temperature differentials is paramount
- ***Thermodynamics is in the driver seat***

Cryogenic Thermal Design Options (No H2 Losses)



For more information: see Section 1.0, ***Cryogenic Fluid Management…***, Moran Innovation LLC, 2023

Insulation Options



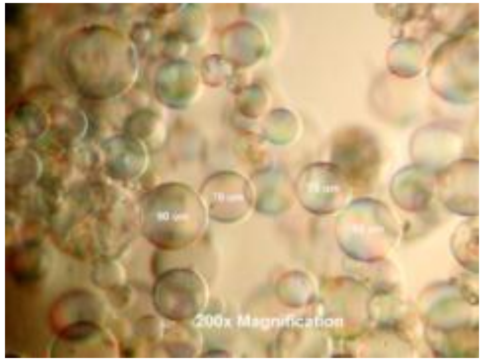
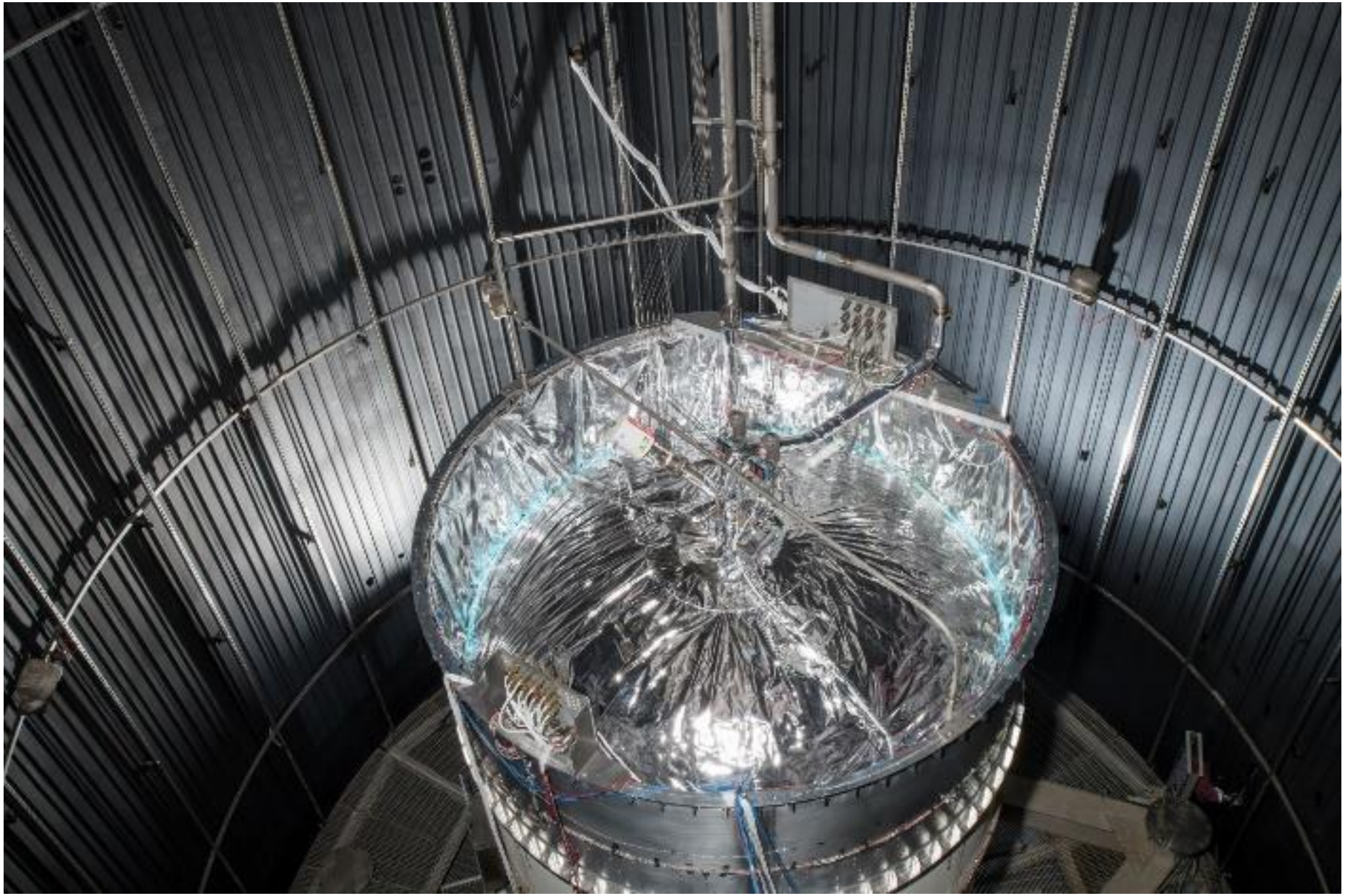


Image source: Wesley Johnson (NASA)

Tank Applied MLI Data from SHIIVER Tests



Tank applied MLI data from SHIIVER testing showed a heat flux lower than **1 W/m²** at both liquid hydrogen and liquid nitrogen temperatures with 30 layers (~2.5 cm) using aluminized mylar and double dacron netting at a constant layer density and a warm boundary of 300 K.

Refr: Johnson, W.L. et al., "Demonstration of Multilayer Insulation, Vapor Cooling of Structure, and Mass Gauging for Large-Scale Upper Stages: Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) Final Report", NASA/TP-20205008233, Aug 2021.

For more information: see Section 3.2, ***Cryogenic Fluid Management…***, Moran Innovation LLC, 2023

Methods to Utilize or Mitigate Boil-Off Gas

Source: Witte & Barillo, "Safety for Hydrogen Vent Systems", Feb 2, 2023.

- **Fuel cell feed**: for electrical power
- **Propulsion**: combust and/or expand through a nozzle
- **Mixing**: thermally destratifies liquid and lowers tank pressure
- **Vapor cooled shielding (VSC)**: to reduce environmental heat load into the tank
- **Thermodynamic vent system (TVS)**: uses Joule-Thomson effect to provide the cold stream from an external or internal heat exchanger
- **Zero boil-off (ZBO) system**: cryo-refrigeration to maintain or reduce tank pressure
- **Re-liquefy**: recovers vent gas using a cryocooler or other method
- **Combination** of two or more of the above

See "Hydrogen Myth Busting (Episode 3)", LH2 Era™ blog, Apr 16, 2023.

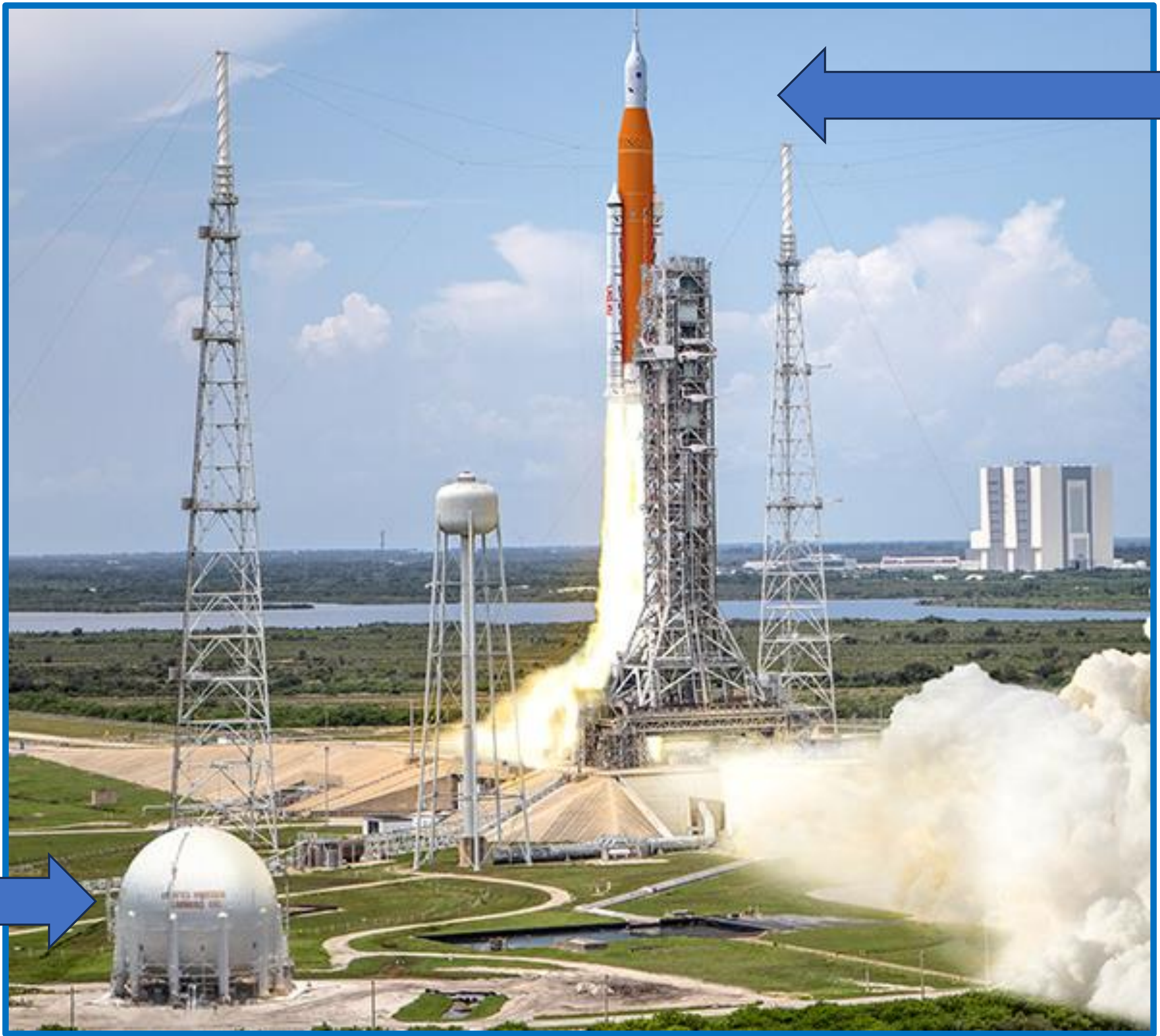
No Loss (Zero Boil-Off) Liquid Hydrogen Systems

Image credit: NASA

- Cryocoolers or cryo-refrigeration cooling loops can be used to eliminate boil-off, liquefy, and condition hydrogen
- Example system (4700 m^3 storage):
  - 1.25 million usable gallon LH2 dewar tank at NASA Kennedy Space Center
  - 50% larger than previous world record LH2 storage dewar tank used for Apollo and space shuttle launches
  - Custom internal heat exchanger with helium cooling loop
  - Interface designed for reverse Brayton cryo-refrigeration system

Refr: "KSC LC39B Liquid Hydrogen (LH2) Dewar Integrated Refrigeration and Storage (IRAS) System", Moran, 2017

Launch!



NASA Space Launch System (SLS) maiden flight was the Artemis I mission launched on Nov 16, 2022. Artemis I sent an uncrewed Orion spacecraft around the moon and back to earth culminating in a water landing of the Crew Module.

New 4700 m^3 (1.25 million US gallon usable) liquid hydrogen dewar tank

Image credit: NASA

20-20 Vision for the Countdown to Hydrogen™

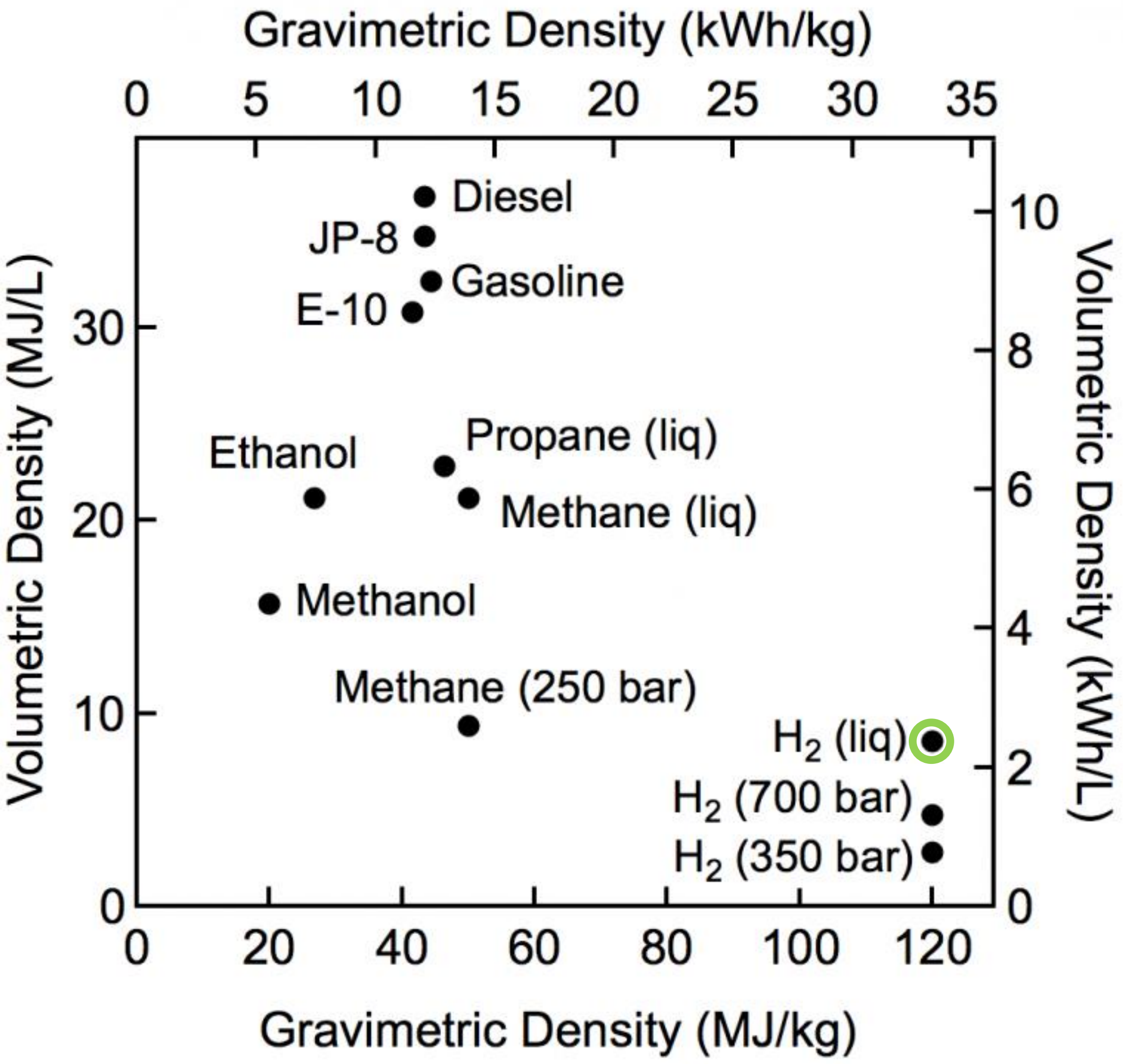


Image credit: DOE

Safety first!

- ✓**20** m/s *rise rate* of GH2 in air (at 20 C, 1 bar)
- ✓**20** K (-253 C) *LH2 temperature* at 1 bar
- ✓**5** LH2 safety tips: provide *ventilation*, prevent *leaks*, eliminate *ignition sources*, take *cryogenic* precautions, design and operate for *phase change*
- ✓**4** times the *volume* of LH2 needed to match the energy content of common liquid fuels (but don't forget efficiency!)
- ✓**3** times the energy content in LH2 compared to the same *mass* of common liquid fuels
- ✓**2** *spin states* of hydrogen (ortho and para)
- ✓**1** *proton* per atom (and 2 atoms/molecule)
- ✓**0** carbon *emissions* (and no smoke, soot, particulates, or environmental impact)