Liquid Hydrogen Safety

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Regulations and Compliance

- OSHA - The Occupational Safety and Health Administration (OSHA) requirements for hydrogen systems in CFR 1910.103.
- NFPA - NFPA 2: Hydrogen Technologies Code, 2023 Edition - Chapter 8 Liquefied Hydrogen
- CGA G-5.3-2017: Commodity Specification For Hydrogen – 7th Edition
- NASA - SAFETY STANDARD FOR HYDROGEN AND HYDROGEN SYSTEMS.
- DOT guidelines
- Industry best practices

Hazards Associated with Liquid Hydrogen

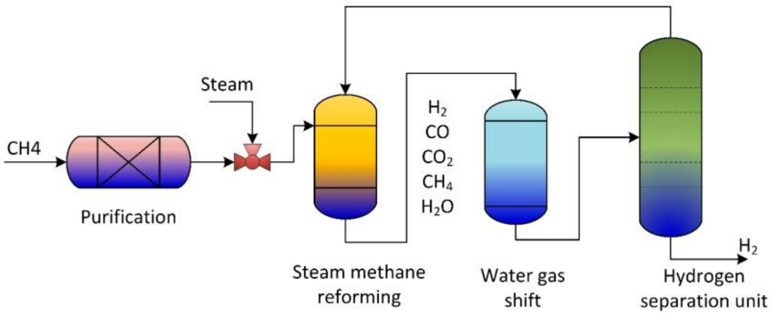
- Flammability and explosion risk
- Extreme cold leading to cryogenic burns and material embrittlement
- Asphyxiation hazard in confined spaces
- High expansion ratio – **(1:848 from liquid to gas)**

Properties

Molecular weight	2.016
Boiling point at 1 atm	-252.9 ^{0}C
Freezing point at 1 atm	-259.3 ^{0}C
Critical Temperature	-240.2 ^{0}C
Critical Pressure	12.7 atm
Liquid density at BP and 1 atm	70.8 kg/m3
Gas Density at 20˚ C and 1 atm	0.0838 kg/m3
Specific Gravity gas relative to air at 20˚ C and 1 atm	0.0696
Specific Gravity Liquid at BP and 20˚ C	0.0710
Specific Volume at 20¯ C and 1 atm	11.92 m3/kg
Latent Heat of vaporization	389 BTU/lb mole
Flammable limits in air at 1 atm	**4.0% - 74.2%** (by volume)
Ignition energy	~ **0.02 mj**
Auto-ignition Temperature at 1atm	510 - 571 ^{0}C
Expansion ration liquid to gas (BP to 20 degrees C)	1:845

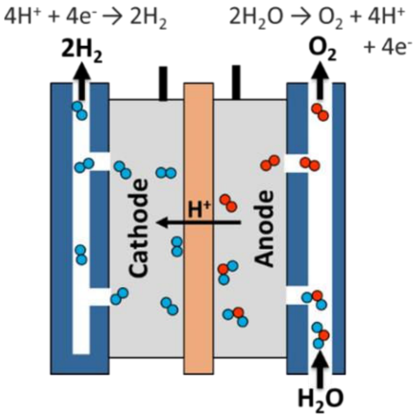
Production Methods of Hydrogen

- Steam Methane Reforming (SMR) – Converts natural gas to hydrogen & CO2



$CH_4 + H_2O \leftrightarrow CO + 3H_2$
$CO + H_2O \leftrightarrow CO_2 + H_2$

- Electrolysis – Splits water into hydrogen & oxygen using electricity.



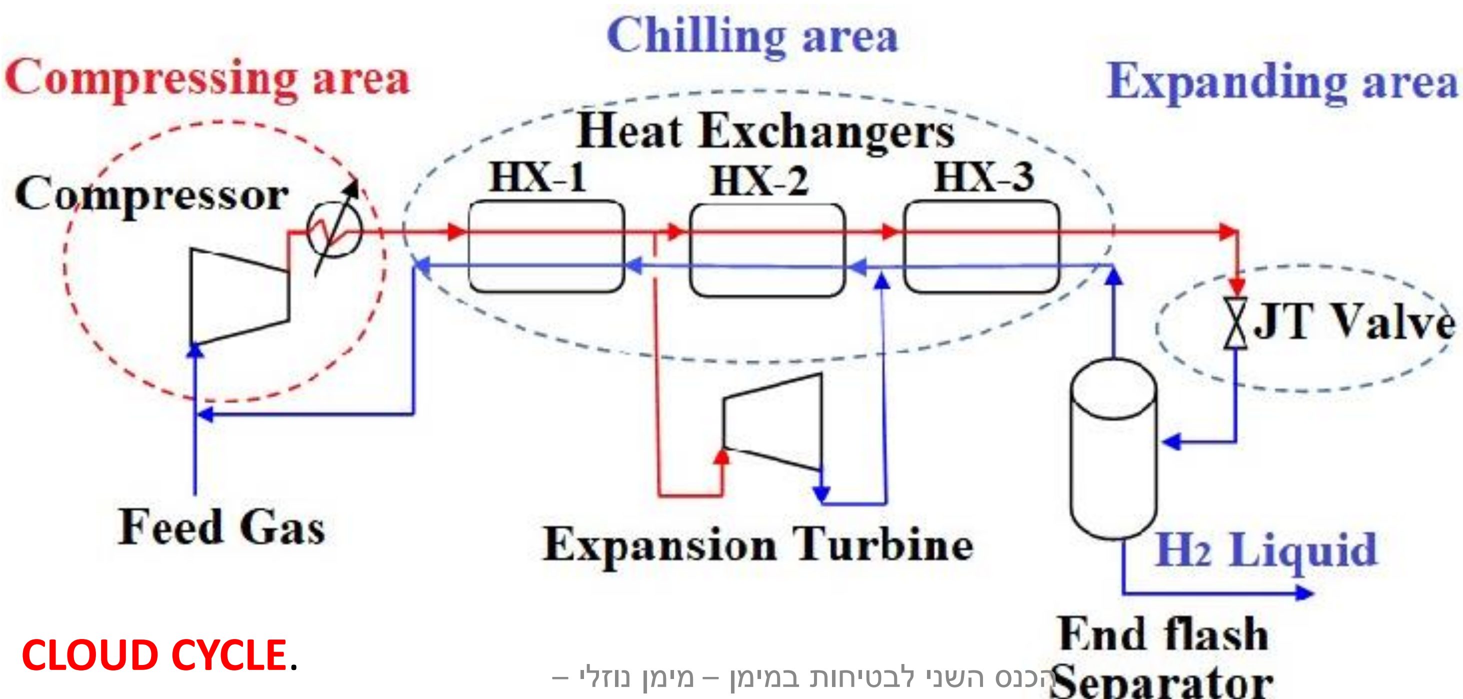
- Biomass Gasification – Converts organic material into hydrogen gas

Liquefaction Process

- Purification to remove impurities.
- Pre-cooling with liquid nitrogen.
- Cryogenic expansion & compression.
- Joule-Thomson expansion for final liquefaction.

The Joule-Thomson effect only cools hydrogen below its inversion temperature (~200 K) .

Above that, expansion would heat it up! That's why pre-cooling is critical before applying this step.

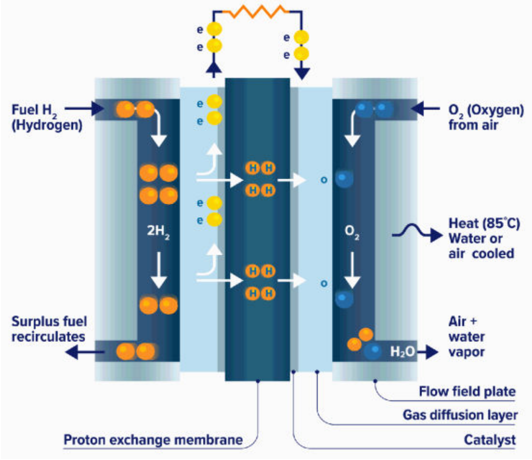


CLOUD CYCLE.

Applications of Liquid Hydrogen

- Aerospace – Rocket fuel (NASA, SpaceX, etc.).

- Fuel Cell Vehicles – Hydrogen fuel cells for clean energy.



- Industrial Use – Metal refining, ammonia production, and electronics.

- Energy Storage – Stores excess renewable energy.

Applications of Liquid Hydrogen

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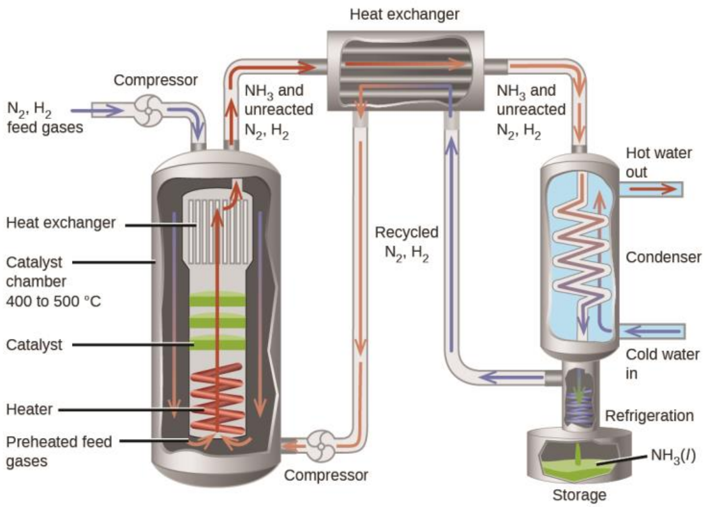


- Energy Storage – Stores excess renewable energy.

Storage and Handling Precautions

FM- DS 7-91 HYDROGEN 2024

Cryogenic Considerations
Thermal Contraction: Materials must accommodate shrinkage due to cold.

Boil-Off Management: A small amount of hydrogen inevitably evaporates; tanks include pressure-relief valves and venting systems.

Tank Shapes

Spherical Tanks: Minimize surface area for a given volume — better insulation.
Cylindrical Tanks: Easier to fabricate and transport — common for mobile or horizontal storage.

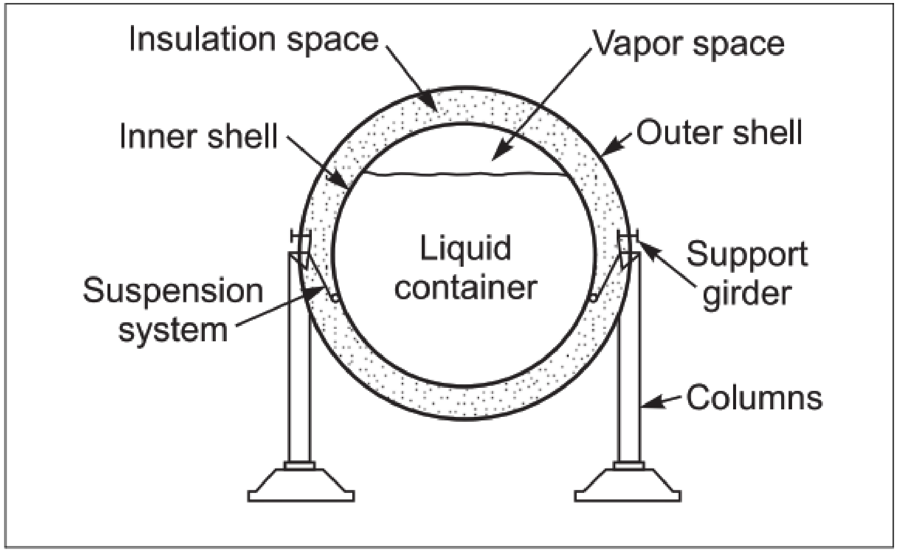


Fig. C -1 Liquid hydrogen storage vessel, inner container suspended from outer shell

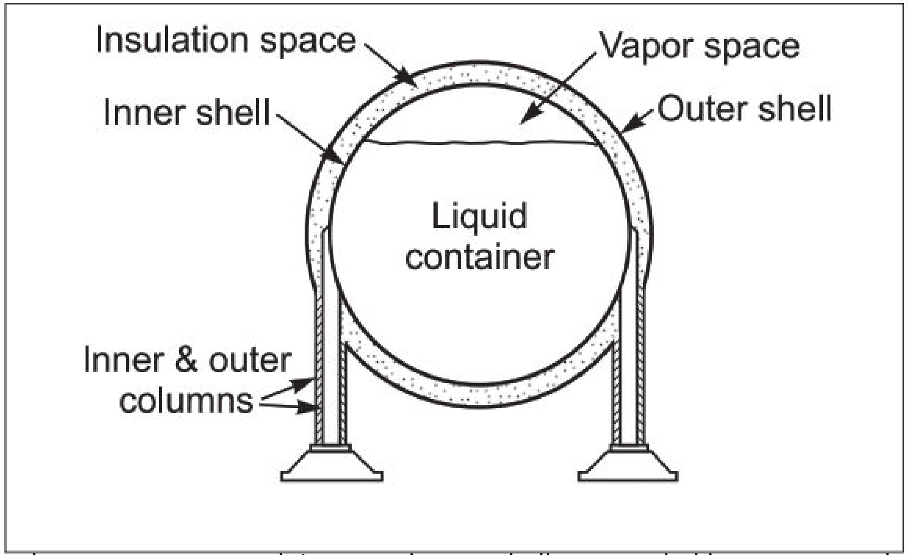


Fig. C-2 Liquid hydrogen storage vessel, inner and outer shells suspended by separate columns

Storage and Handling Precautions

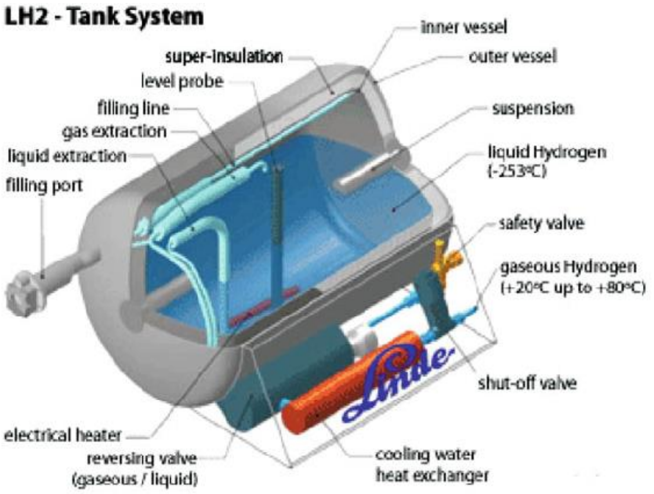
Tank Structure

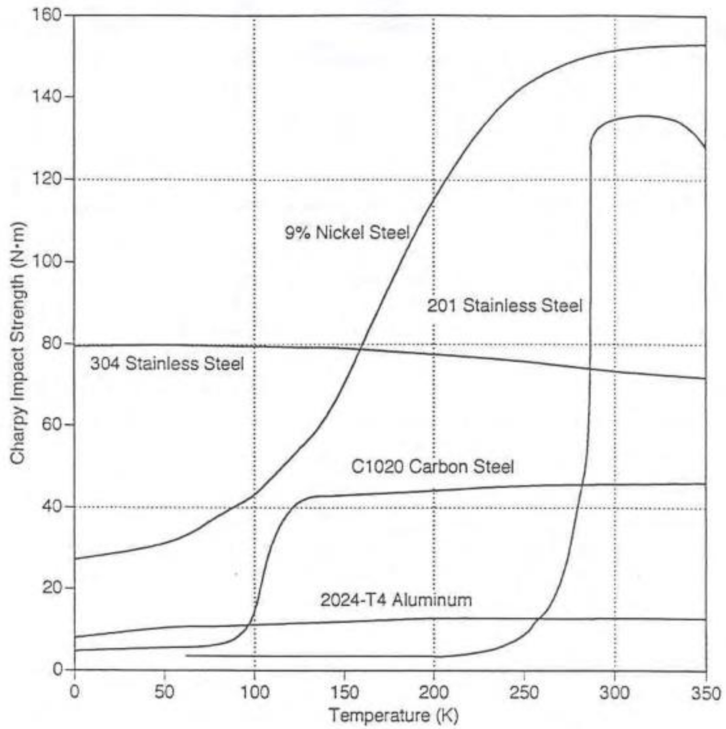
Double-Walled (Vacuum Insulated) Tank: Most LH_2 tanks use a double-walled design, where the space between the inner and outer tank walls is vacuumed and filled with insulating materials (like multilayer insulation) to prevent heat transfer.

Inner Tank: Typically made of stainless steel or aluminum alloys that can withstand cryogenic temperatures. Austenitic stainless steels (e.g., 304L, 316L) or aluminum alloys to handle the cold without becoming brittle.

Outer Shell: Metal, its main job is structural protection and housing insulation layers.

Insulation: Vacuum + multilayer insulation (MLI) or perlite powder in some designs.





NSS 1740.16

Storage and Handling Precautions

Liquid Hydrogen systems typically consist of the following components:

Liquid hydrogen storage vessel – Double wall vessel design, like a thermos bottle

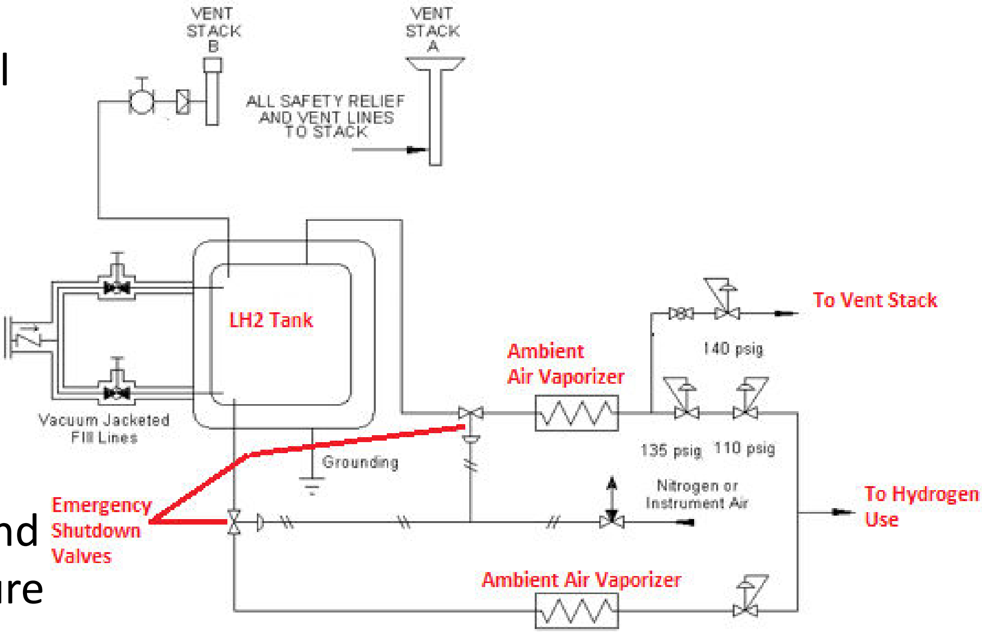
Vacuum jacketed liquid transfer lines

Vacuum pump to maintain the vacuum

Heat exchangers – typically ambient air vaporizers. These convert the liquid to gas and warm the gas to near ambient air temperature

Control manifolds that keep the pressure constant and shutoff the hydrogen flow when it gets too cold

Compressors are needed for pressures above the tank operating pressure, typically around 850 kPa (~123 psi)



Storage and Handling Precautions

Controls and safety features include:

Helium purge system to remove the air/nitrogen from liquid transfer lines prior to filling

Emergency shutdown valves on the liquid and gas product withdrawal lines

Pressure relief devices

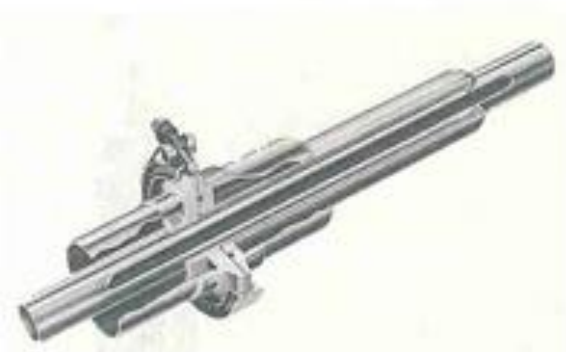
Pressure controls that are used to vent excess hydrogen at pressures lower than the set pressure for the relief devices.

Storage and Handling Precautions

Piping Systems.

Piping, tubing, fittings, and related components shall be designed, fabricated, and tested in accordance with the requirements of **ASME B31.12,** *Hydrogen Piping and Pipelines*, or other approved standards

For LH2, pipnng system is vacuum- jacketed



Bayonet joint for vacuum-jacketed transfer lines (CVI Corp., Columbus, Ohio)

Underground liquid hydrogen piping shall be protected through a corrosion-resistant outer pipe, preferably a vacuum insulation jacket.

Above ground piping preferred

Storage and Handling Precautions

Pressure-Relief Devices.

Pressure relief devices shall be provided to protect containers and piping systems containing LH_2 from damage due to overpressure.

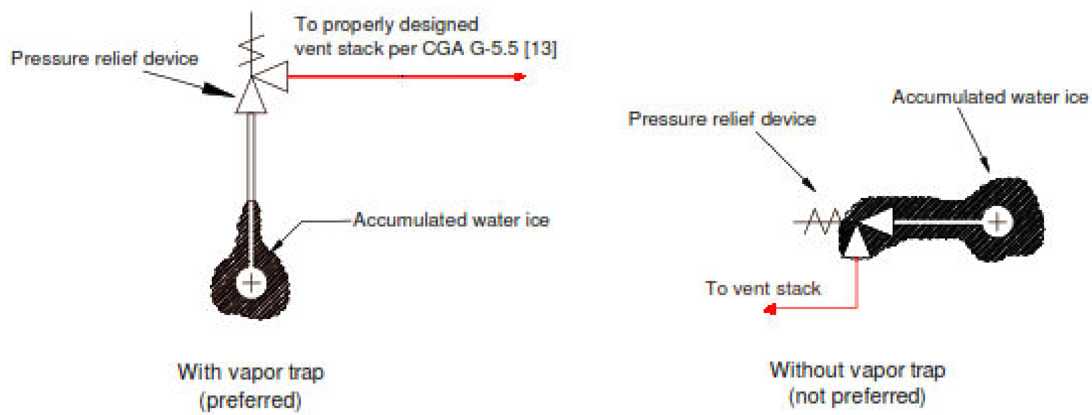
Pressure relief devices shall be designed in accordance with *CGA S 1.1, Pressure Relief Device Standards — Part 1 — Cylinders for Compressed Gases, and CGA S-1.2, Pressure Relief Device Standards — Part 2 — Cargo and Portable Tanks for Compressed Gases, for portable tanks; and CGA S-1.3, Pressure Relief Device Standards — Part 3 — Stationary Storage Containers for Compressed Gases, for stationary tanks.*

Types of PRDs include:

•rupture disks

•pressure relief valves

•breaking pin devices



Storage and Handling Precautions

Portable Tank Structure

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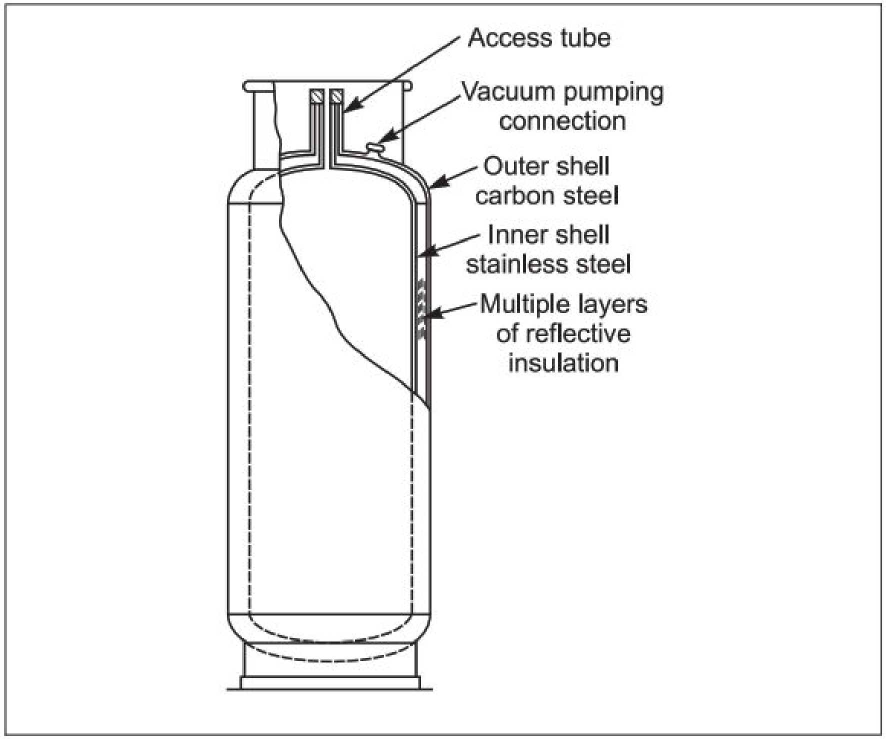


Fig .C-4 Typical Dewar flask, laminar insulated

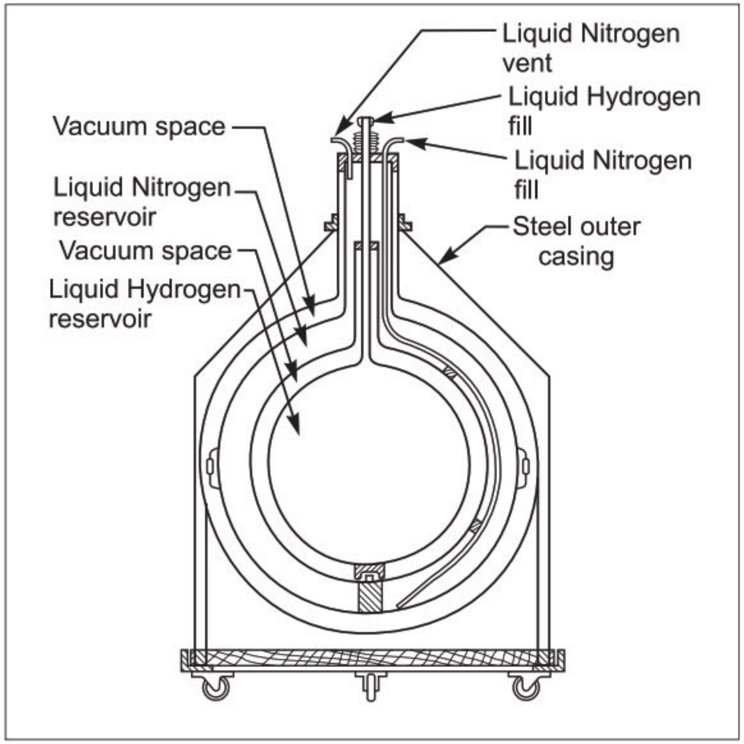
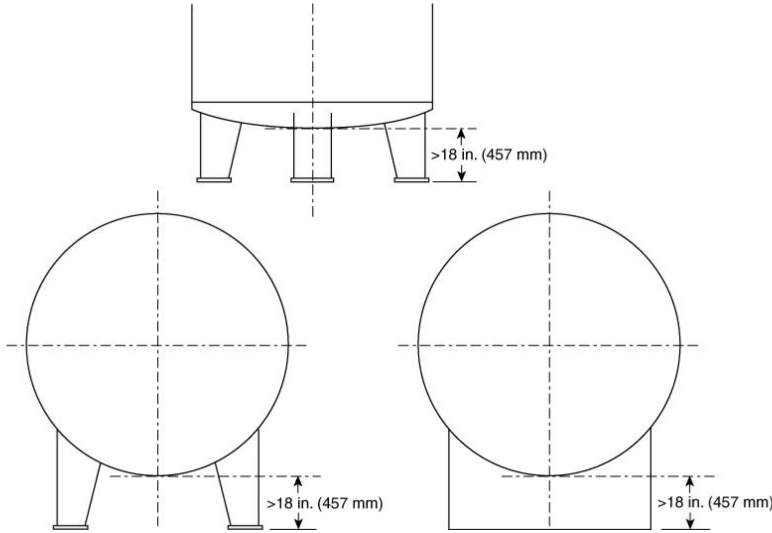


Fig. C-3 Portable liquid hydrogen container insulated with liquid nitrogen

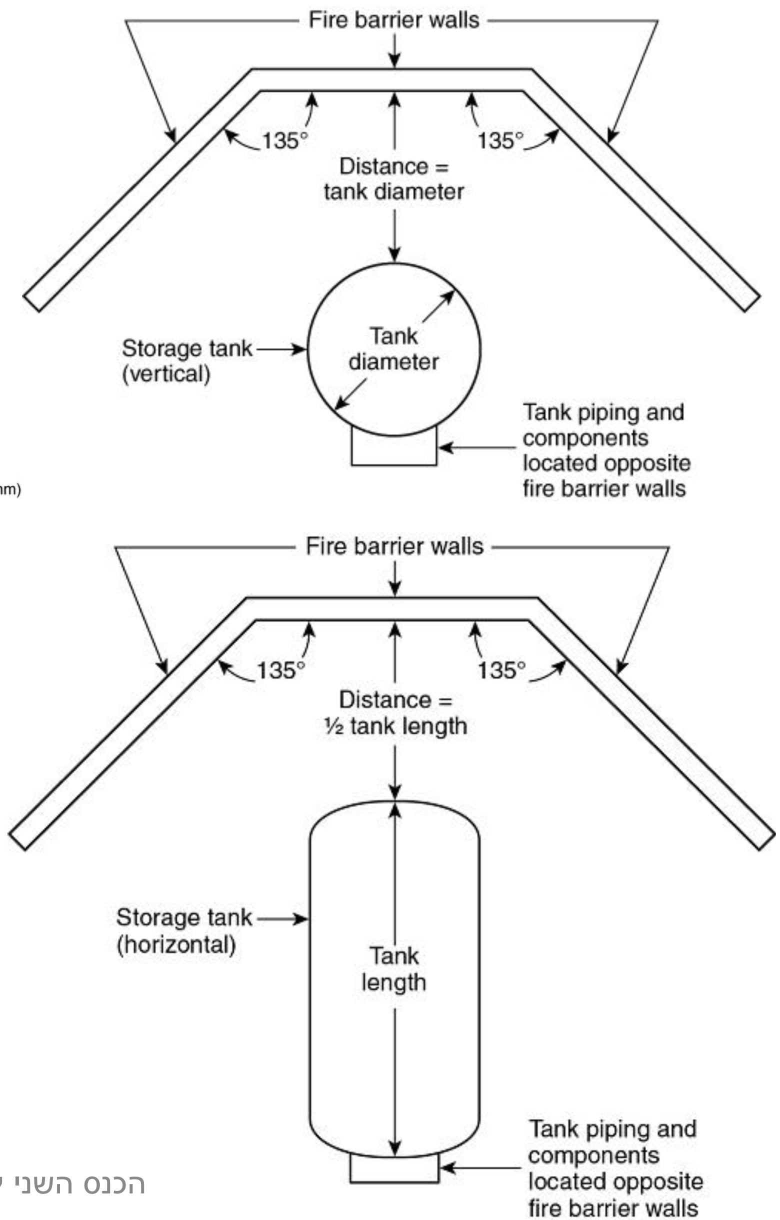
Storage and Handling Precautions



Cryogenic fluids are not diked in order that they are allowed to dissipate should leakage occur. Studies conducted by NASA (NSS 1740.16, *Safety Standard for Hydrogen and Hydrogen Systems*, 2005)

But

No sewer drains shall be located in an area in which an LH2 or spill could occur.



Storage and Handling Precautions

Table 2.1.2.6-1. Minimum Distance from Gaseous Hydrogen Storage to Exposures

	Storage Volume[1], scf (m^3)		
	<5,000 (140)	≤5,000 < 25,000 (≤140 < 710)	≤25,000 ≤150,000 (≤710 ≤ 4,200)
Exposure	*Minimum Separation Distance, ft (m)*		
Fire-resistive building	15 (4.6)	15 (4.6)	20 (6.1)
Noncombustible building	15 (4.6)	15 (4.6)	30 (9.1)
Combustible building	15 (4.6)	20 (6.1)	50 (15)
Ignitable liquids storage	15 (4.6)	15 (4.6)	30 (9.1)
Bulk flammable gas storage	15 (4.6)	15 (4.6)	30 (9.1)
Other hydrogen storage	15 (4.6)	15 (4.6)	30 (9.1)
Oxygen storage	15 (4.6)	15 (4.6)	30 (9.1)
Combustible solids	15 (4.6)	20 (6.1)	50 (15)
Air compressor intakes or HVAC intakes	25 (7.6)	50 (15)	100 (30)
Wall openings	25 (7.6)	50 (15)	100 (30)

Note 1. Volume of gas at 14.7 psig (101 kPa) and 70°F (21°C).

Table 2.1.2.6-2. Minimum Distance from Liquefied Hydrogen Storage to Exposures

	Storage Volume, gal (m^3)		
	<4,500 (<17)	≤4,500 < 9,000 (≤17 < 34)	≤9,000 ≤ 18,000 (≤34 ≤ 68)
Exposure	*Minimum Separation Distance, ft (m)*		
Fire-resistive building	20 (6.1)	50 (15)	120 (37)
Noncombustible building	20 (6.1)	50 (15)	120 (37)
Combustible building	20 (6.1)	50 (15)	120 (37)
Ignitable liquids storage	20 (6.1)	25 (7.6)	40 (12)
Bulk flammable gas storage	20 (6.1)	25 (7.6)	40 (12)
Other hydrogen storage	20 (6.1)	25 (7.6)	40 (12)
Oxygen storage	20 (6.1)	25 (7.6)	40 (12)
Combustible solids	30 (9.1)	50 (15)	65 (20)
Air compressor intakes or HVAC intakes	25 (7.6)	50 (15)	100 (30)
Wall openings	25 (7.6)	50 (15)	100 (30)

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Fire and Explosion Hazards

- Cryogenic hazard: Extreme cold can cause structural material brittleness
- Flash fire: Rapid ignition in open space
- Jet fires: From pressurized release sources
- BLEVE risk with tank failure

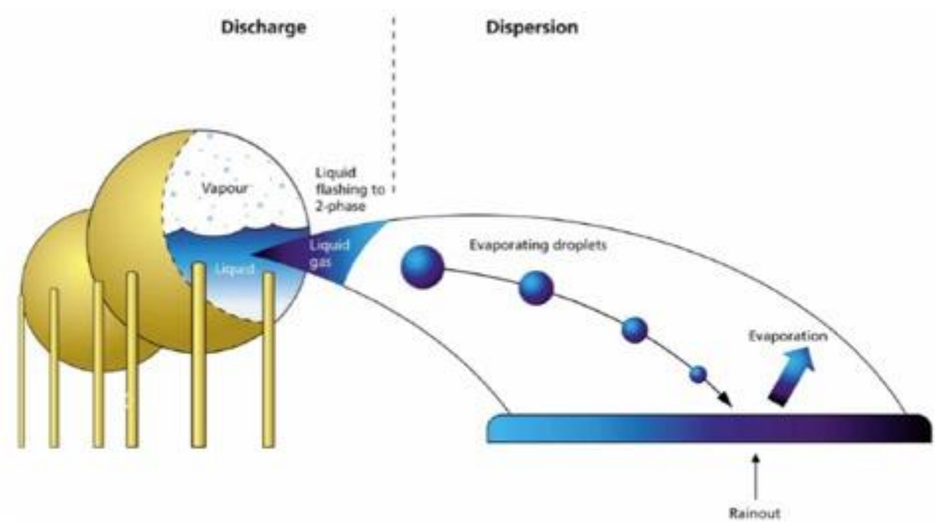
Fire Behavior of Hydrogen

- Fast flame propagation
- Hard-to-detect flame (invisible in daylight)
- No smoke or soot—less warning
- Radiant heat is low, but high flame temperature (~2045°C)
- Explosive if confined

HAZARD ANALYSIS

Four stages of scenario –

* Leak from 1" pipe (full bore)
* Vapors Flash (91%) → dispersion
* Droplets create a pool (size of pool varies)
* Pool evaporates → dispersion



Loc calcs.

LH2 Release rate from 25.4 mm broken pipe.

Leak from hole in horizontal cylindrical tank

Max Average Sustained Release Rate: 7.03 kilograms/min

Isenthalpic Flash Fraction		
Input Data:		
Ambient temperature:	298	K
Boiling point temp. at pressure:	20	K
Heat capacity:	4.5	kJ/kg-K
Heat of vaporization:	1371	kJ/kg
Calculated Results:		
Flash fraction:	0.912	

Evaporation rate @ max pool size.

Puddle Diameter: 2.3 meters

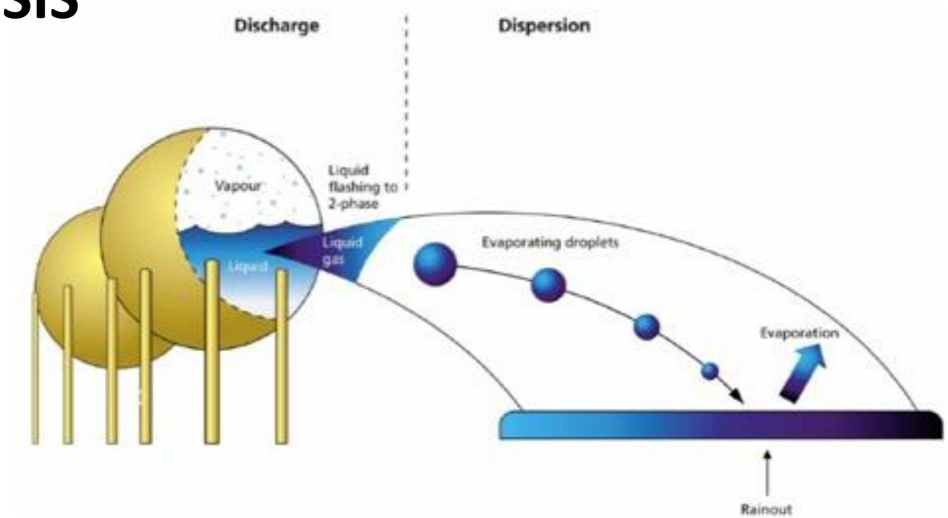
Average Puddle Depth: 2 centimeters

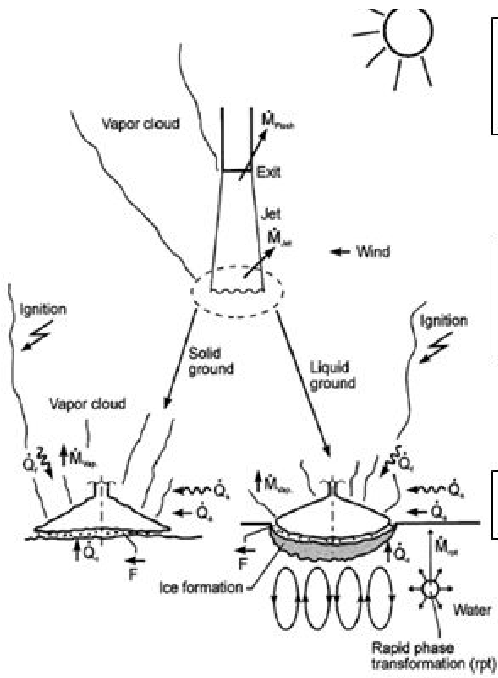
Ground Type: Concrete Ground Temperature: 20° C

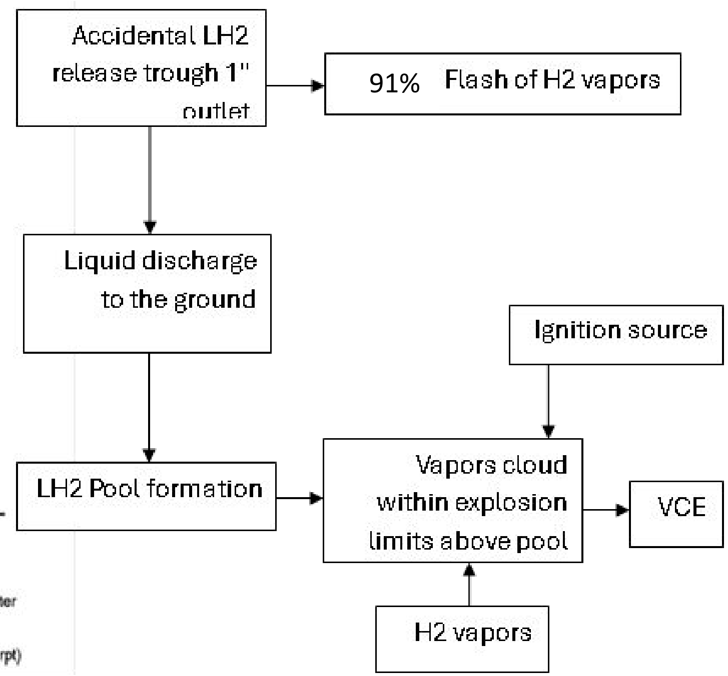
Initial Puddle Temperature: -253° C

Max Average Sustained Release Rate: 98.1 grams/secm

HAZARD ANALYSIS

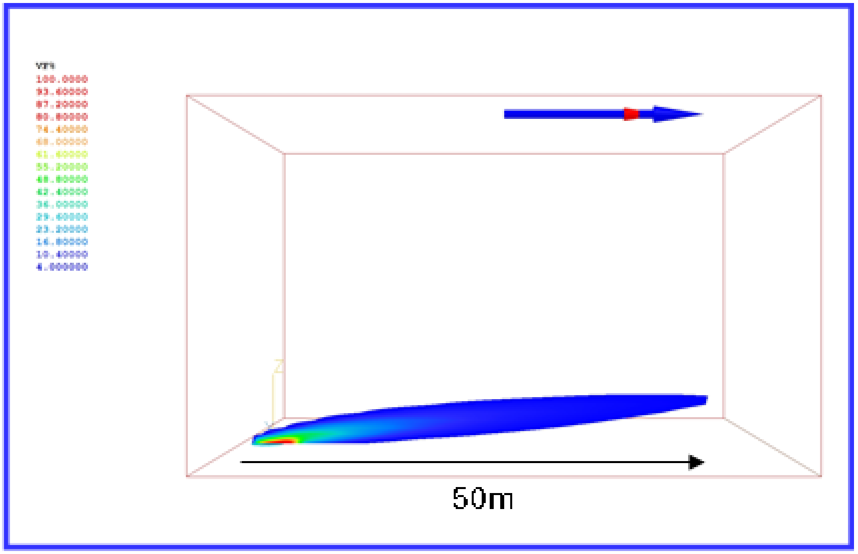




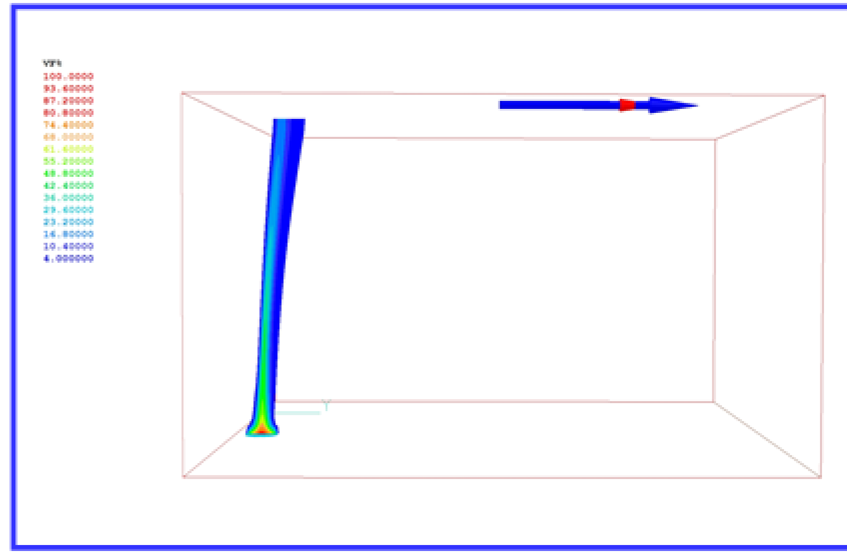


HAZARD ANALYSIS

LEL



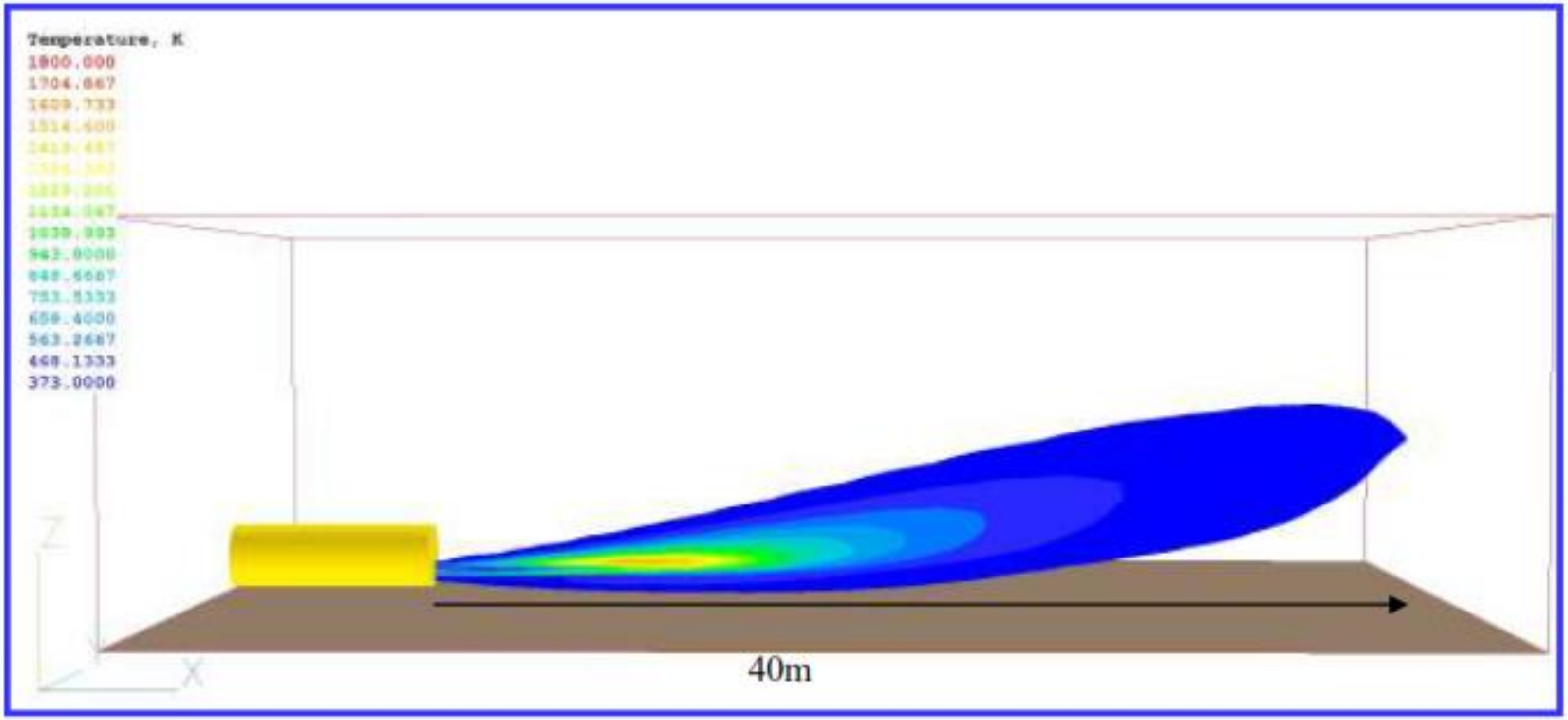
4% v/v concentration (LEL) from LH2 volatile pool (3m dia) wind velocity – 10 m/s



4% v/v concentration (LEL) from LH2 volatile pool (3m dia) wind velocity – 0.5 m/s

HAZARD ANALYSIS

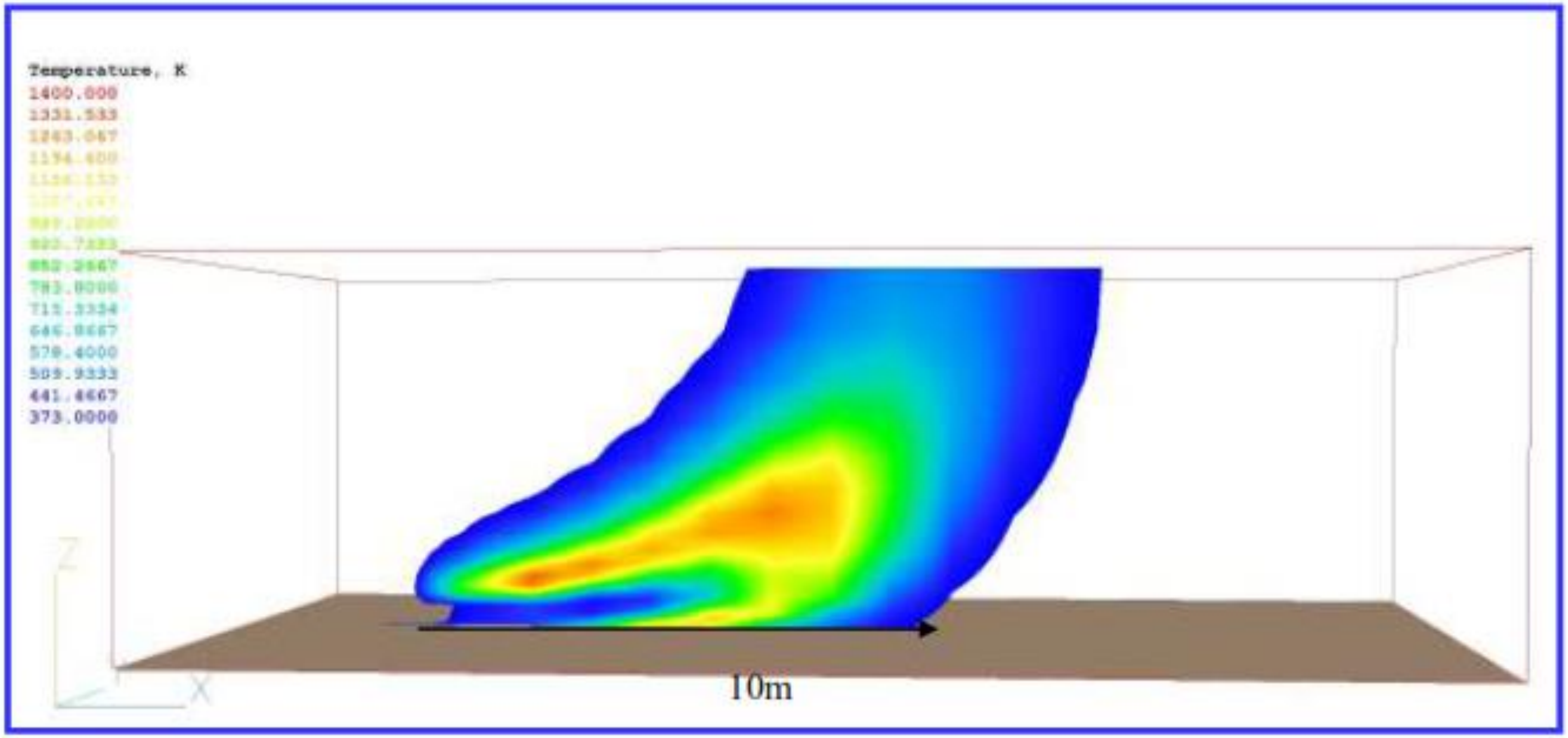
JET FIRE



100 C contour from LH2 jet fire 1" 0.82 kg/s, wind velocity – 10 m/s

HAZARD ANALYSIS

POOL FIRE



100 C contour from LH2 volatile pool (3m dia) wind velocity – 10 m/s

Fire Suppression Strategies

- The only sure way of handling a hydrogen fire is to let it burn under control until the hydrogen flow can be stopped.
- Close the block or isolation valves close to the hydrogen container by remote operation from a safe distance.
- **Use water sprays to extinguish any secondary fire and keep the fire from spreading**.
- Foam agents: Not effective for hydrogen
- Inert gas flooding: Not ideal due to re-ignition risk

Fire and Explosion Safety

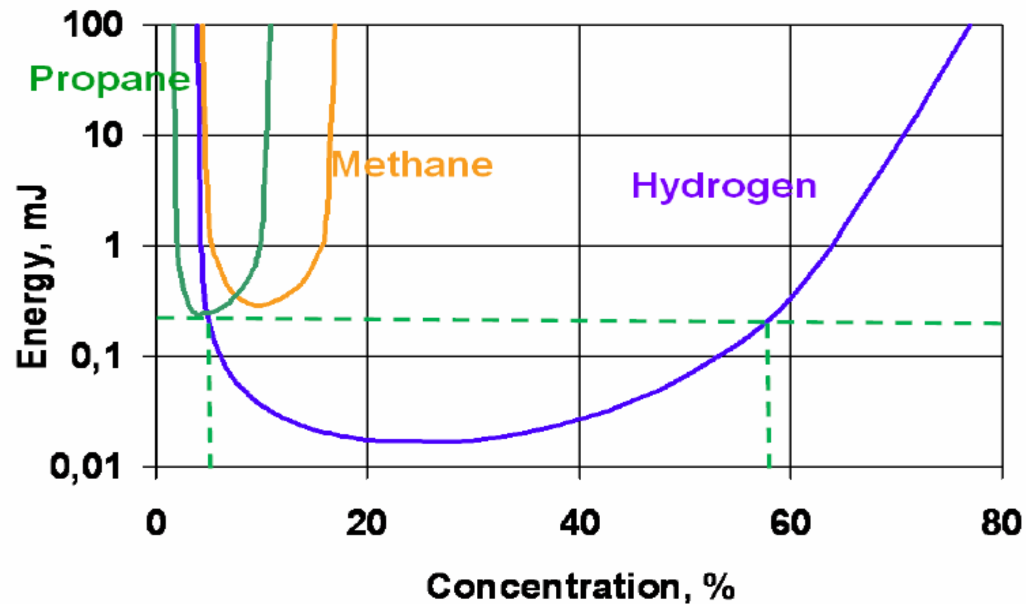
Group IIC : Hydrogen is capable of igniting from very low energy sources.

Temperature Class: T1 ≤ 450°C
Hydrogen ignites easily, but its autoignition temp is >510°C

Location	Recommended Zone
LH_2 storage tank vent areas	Zone 1 or Zone 2
LH_2 pumps and compressors	Zone 1
Filling stations or loading areas	Zone 1 (with possible Zone 2 buffer)
Control panel room (properly sealed)	May be outside hazardous zone
Open-air pipe runs (with good ventilation)	Zone 2

Fire and Explosion Safety

MIE- ~ 0.02mj =>



NFPA 2 2023 Edition: Recommends ≥ 1 ohm for conductive bonding/grounding connections.

NASA-STD 5008 : Grounding systems for hydrogen facilities must have resistance of 1ohm or less.

Personal Protective Equipment (PPE)

- Cryogenic gloves and face shields
- Fire-resistant clothing
- Proper footwear and respiratory protection
- leak detection systems
- No open flames or ignition sources nearby
- Proper grounding and bonding to prevent static discharge

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