cryoworld
advanced cryogenics

Liquid Hydrogen Storage: Status and Future Perspectives

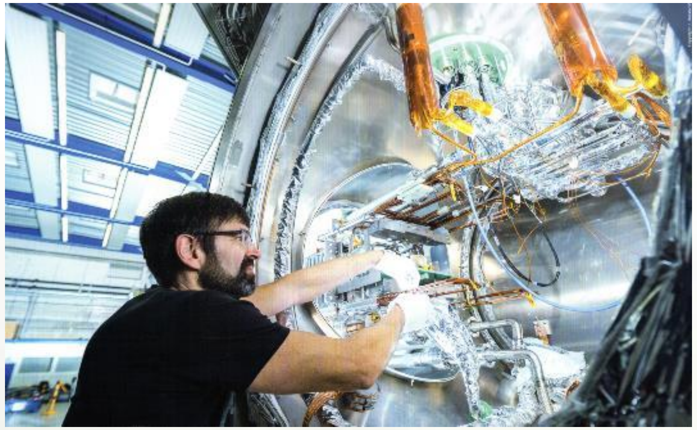
Hendrie Derking, Luuk van der Togt & Marcel Keezer

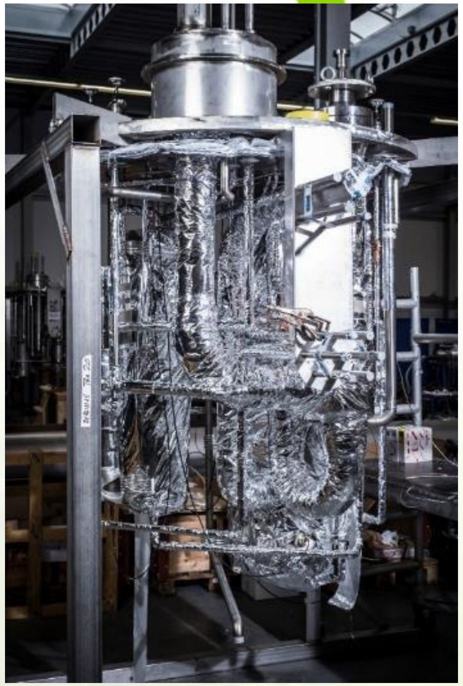
Cryoworld BV

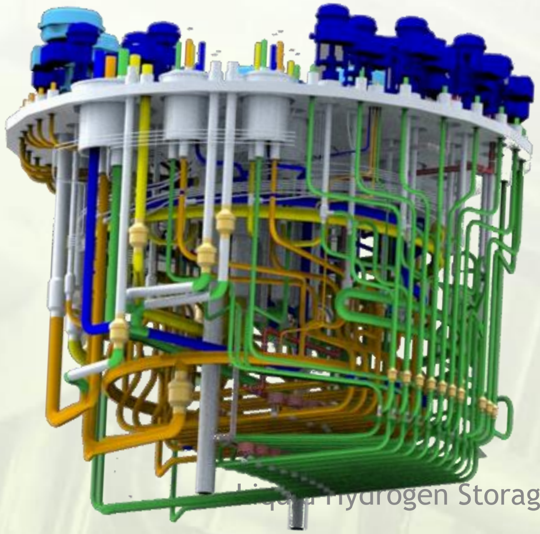
Cryogenic Heat and Mass Transfer
4th - 5th November, Enschede, The Netherlands
CHMT 2019

Cryoworld BV

Design, Engineering, Simulation, Manufacturing, Installation and Testing of high-end cryogenic systems for liquid helium, liquid hydrogen and other liquefied gases.







cryoworld
advanced cryogenics

Outline

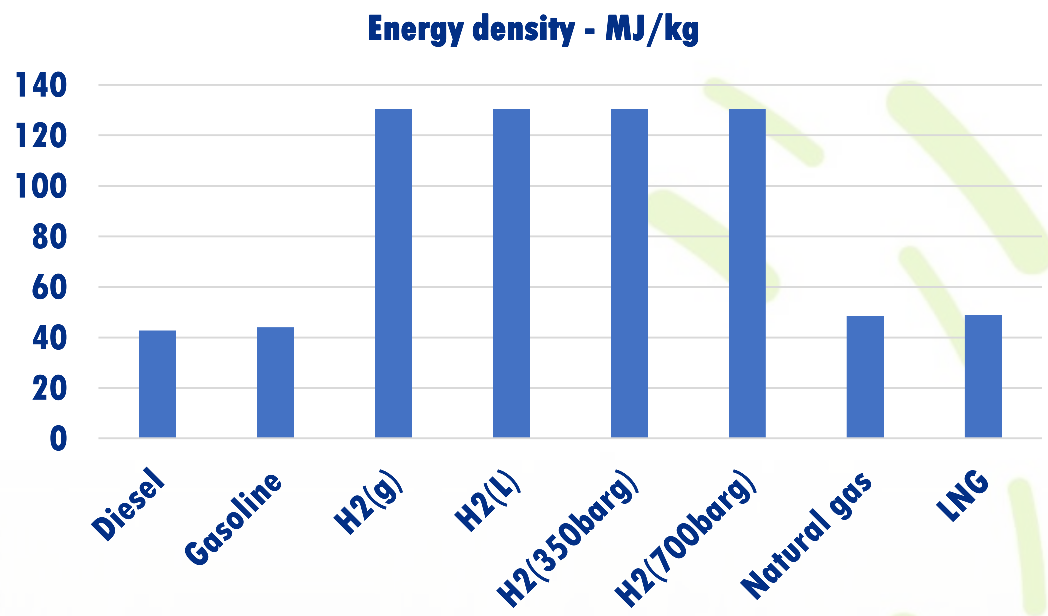
- Why hydrogen?
- Why liquid hydrogen?
- Design of liquid hydrogen storage tanks
- Performance of existing liquid hydrogen storage tanks
- Road to high performance liquid hydrogen storage tanks

Why hydrogen?

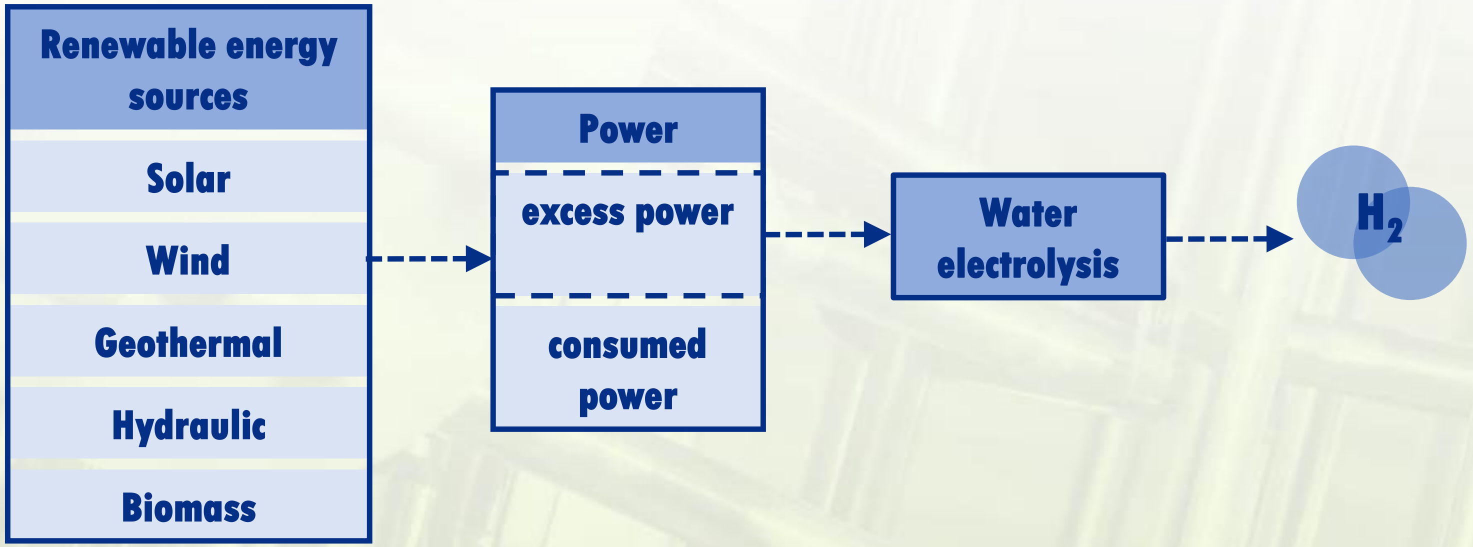
Reducing fossil fuels

Very high energy density

High potential for transportation, energy carrier and energy storage



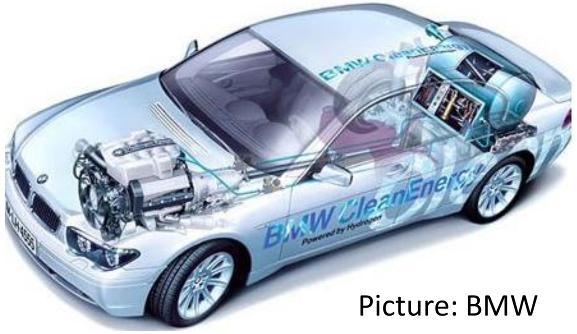
"Green" production when using renewable energy sources



cryoworld
advanced cryogenics

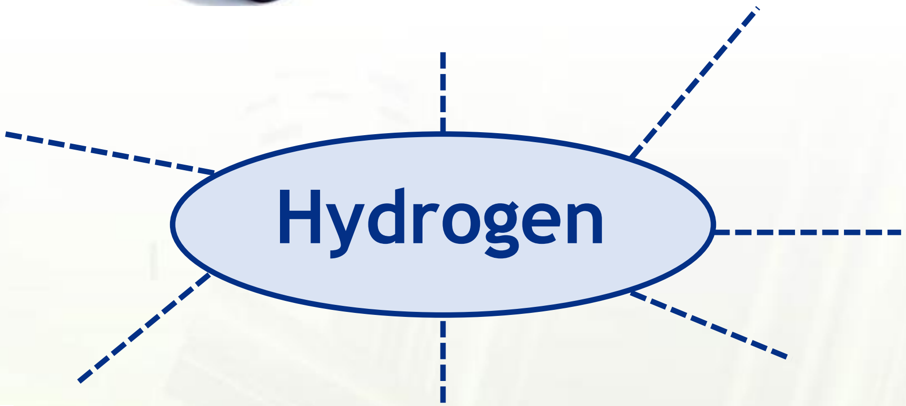
Hydrogen transportation potential

Picture: ESA/CNES/ArianeSpace



Picture: BMW

Picture: Toyota



Picture: Hyundai

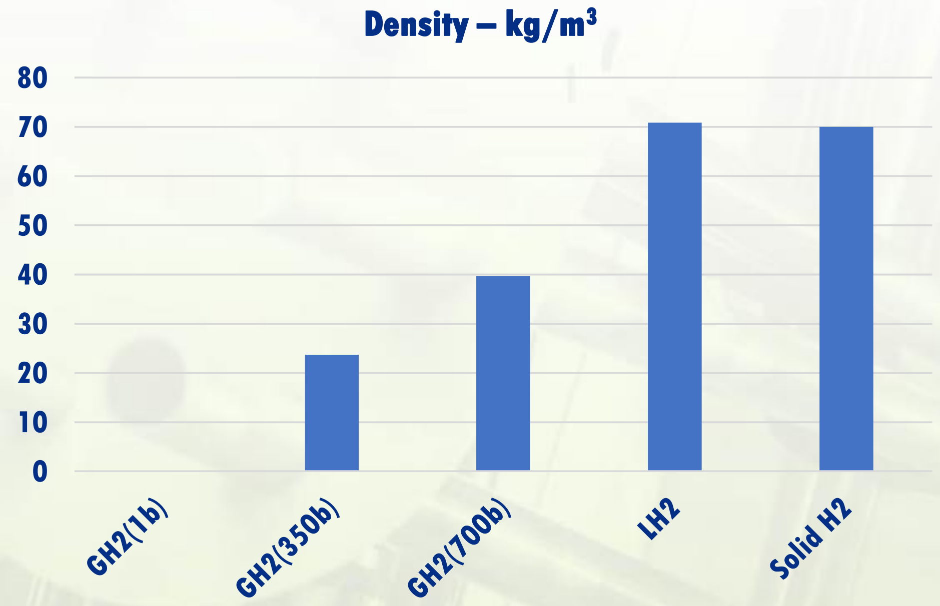
Picture: Toyota

Picture: Sandia National Lab

Picture: Airbus

Hydrogen storage

Gaseous storage	Liquid storage	Solid storage
Pressurized to 700-900 bar Storage at room temperature	At atmospheric pressure Storage at 20.4 K In slush to increase density	Physisorption in porous materials Adsorbed on metal hydrides Complex compounds Metals and complexes with water



Liquid versus high-pressure gas storage

	Liquid storage	High pressure gas storage
Density	70.9 kg/m3 @ 1 bar, 20.3 K	39 kg/m3 @ 700 bar, 293 K
Safety	Low pressure system with low enthalpy Spill can lead to floor accumulation Intrinsically safe due to vacuum jacket Boil-off	Huge amount of potential energy Spill can lead to jet No safety barrier
Energy needed	~12 kWh/kg for liquefaction big expensive system boil-off during no use	~ 6 kWh/kg for compression small less expensive system No loss during no use
Handling	Liquid to liquid: by pumping or by gravity Liquid to HP gas: by efficient pumping Very fast filling Simple logistics	Gas to gas: pressure will balance Slow filling Complex logistics
Storage	Single tank	Long thick walled cylinder bundles
Cost of storage system	€300 / kg Long lifespan	€900 / kg Relatively short lifespan

Liquid hydrogen storage tanks

Aviation	Ground-based
Relatively small tank size	Large tanks
Low weight	Weight not very important
Non-vacuum insulated	Vacuum-insulated
Higher evaporation could be accepted	Zero boil-off
Materials	
• Aluminium alloys	
• Composites	
• Fibre reinforced polymers	

Liquid hydrogen storage tanks

Picture: NASA

NASA, 3800 m^3, 270 t

Boil-off ~12% H_2

Picture: Kawasaki

JAXA (Kawasaki), 540 m^3, 38 t

Picture: Linde


Picture: Linde

LH_2 truck, < 50 m3, < 3.5 t

Largest storage tanks constructed for space applications.

Spherical shape to optimize surface area to volume ratio.

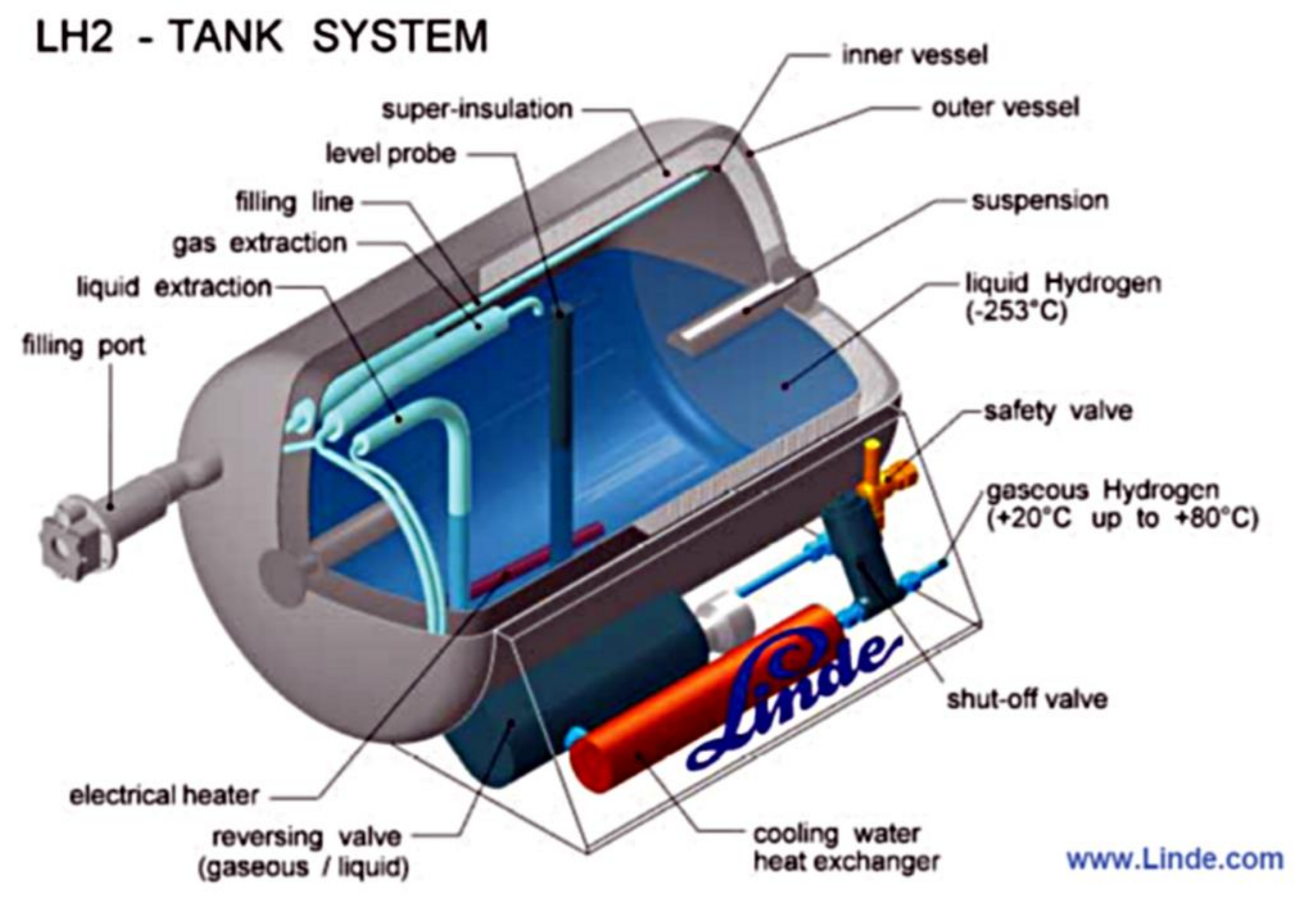
Most tanks made with perlite insulation.

Boil-off rates of 1 - 5% / day.

cryoworld advanced cryogenics

Heat flow into liquid hydrogen storage tank

- Insulation: radiation, convection, conduction
- Conduction through support system
  - low thermal conductivity materials
  - high strength materials
- Conduction through interconnecting piping system
  - Small cross-section (thin walled pipes)
  - Increase length
- Radiation from warmer parts of the container
  - Shield by using baffles
  - Optimize design, avoid direct view to warm parts
- Natural convection in vapour above liquid due to heating
- Ortho-para conversion



Optimizing heat flows

No boiling takes place!

All heat entering the liquid is absorbed primarly by convection.

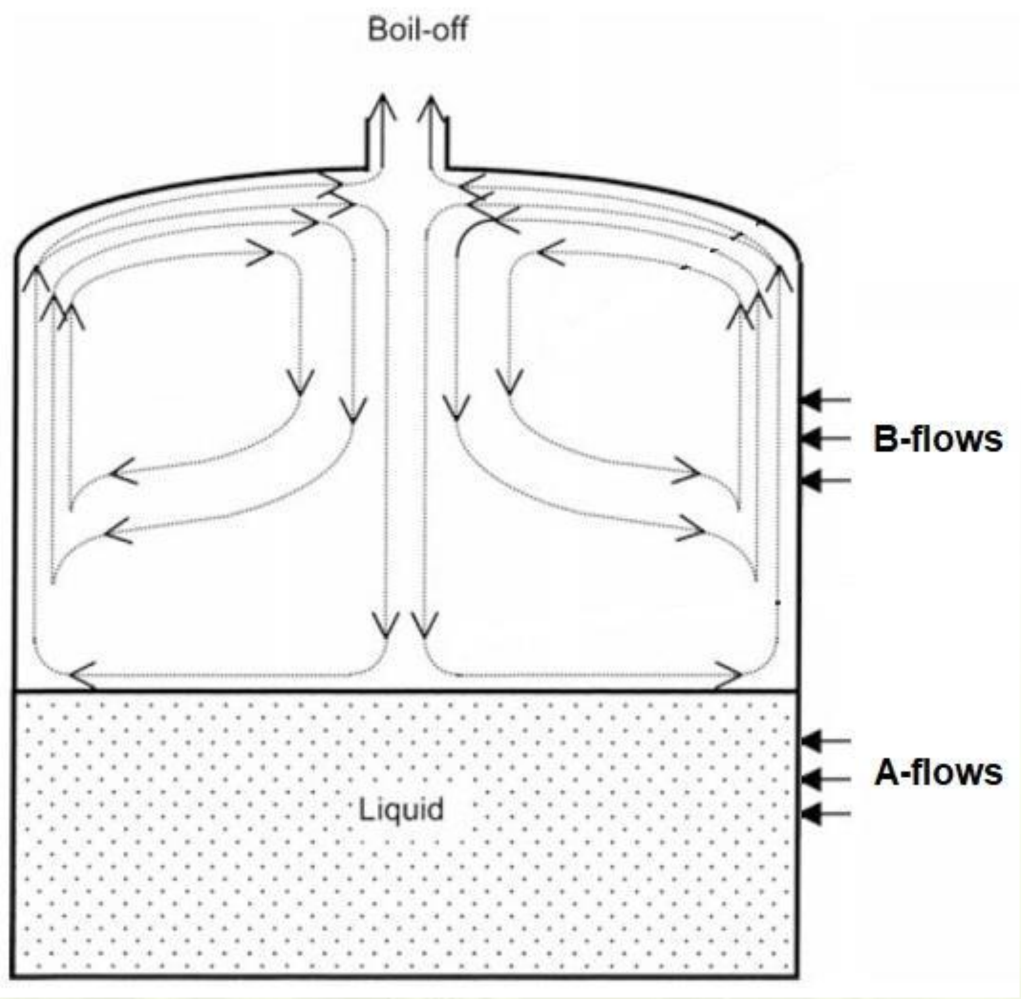
Two types of heat flows

A: heat flows adsorbed in the liquid resulting in evaporation of the liquid

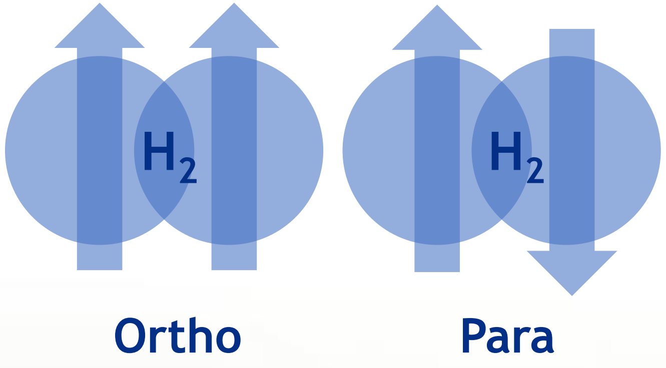
B: heat flows adsorbed in the cold vapour.

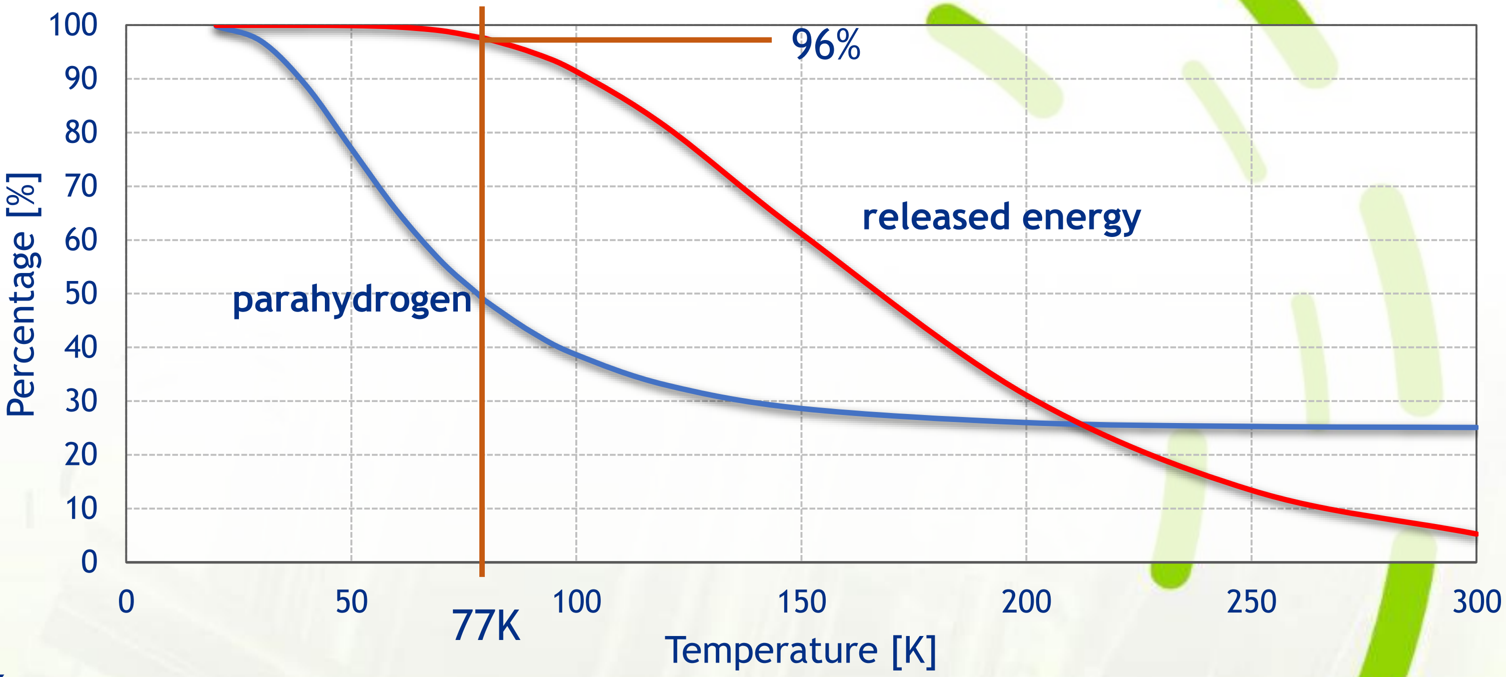
With good design, B heat flows may not contribute to the evaporation at all.

Minimize A heat flows and ensuring adsorbing B heat flows in cold vapour.



Ortho-para conversion





In equilibrium:

25% para-H_2 / 75% ortho-H_2 at RT

50% para-H_2 / 50% ortho-H_2 at 77 K

99.8% para-H_2 / 0.2% ortho-H_2 at 20 K

Energy released during full conversion at 20 K is ~670 kJ/kg.

A catalyst (i.e. Iron(III) oxide) is used to during liquefaction to speed up the transition.

A small part (~4%) of released energy still will be adsorbed in liquid.

cryoworld advanced cryogenics

Insulation

Insulation type	Examples	k-value (300 - 77 K) [mW/mK]	+	-
Insulation@atm pressure	Foams Powders Solid fibres Silica aerogels	~20 - 50	Low weight Relatively cheap Easy to produce	High heat load Need constant purging
Perlite @ 10^{-2} mbar		~1.0	Standard technology Good performance	Needs strong vacuum enclosure Heavy structure
Multilayer insulation (MLI) @ 10^{-4} mbar		0.0065 – 0.1	Excellent performance	Needs strong vacuum enclosure Heavy structure Most expensive solution

Current status

Most tanks made with perlite insulation, using LN_2 technology.

Boil-off rates of 1-5% / day.

Why LN_2 based storage tanks?

- Experience from the past, standard product;
- Latent heat of H_2 is very high.

Liquid @ 1 bar abs.

	Temperature [K]	Latent heat / mass [kJ/kg]
Hydrogen	**20.3**	**448.9**
Nitrogen	**77.2**	**199.3**
Methane	**111.5**	**511.1**
Helium	**4.2**	**20.8**

JAXA (Kawasaki), 540 m^3, 38 t

cryoworld advanced cryogenics

Reducing boil-off

The density of H2 is very low, resulting in a low volumetric latent heat!

To reduce the boil-off rate it would be better to use LHe technology:

- Multi-layer insulation in combination with high vacuum;
- Actively cooled radiation shields.

Liquid @ 1 bar abs.

	Temperature [K]	Latent heat / mass [kJ/kg]	Density [kg/m³]	Latent heat / volume [kJ/m³]	Factor of LH_2 [-]
Hydrogen	20.3	448.9	70.9	31828	1.0
Nitrogen	77.2	199.3	806.6	160769	5.1
Methane	111.5	511.1	422.6	215933	6.8
Helium	4.2	20.8	125.0	2604	0.1

Two examples

Large LHe storage @ CERN

- Volume:4 x 120 m^3
- Boil off: ~0.20 g/s or 0.12%/day

Conversion to LH_2

- 0.01%/day or 0.01 g/s

Picture: CERN

Small LHe storage @ CERN

- Volume: 5 m^3
- Boil off: ~0.036 g/s or 0.5%/day

Conversion to LH_2

- 0.04%/day or 0.02 g/s

Conclusions

- Due to high liquefaction costs, zero boil-off should be the goal for all liquid hydrogen storage tanks.
- Currently, most ground -based liquid hydrogen storage tanks have perlite+vacuum insulation without active shielding, resulting in boil-off rates of 1-5%/day.
- Boil-off could be reduced to 0.01-0.05%/day by using storage tanks based on LHe technology (MLI insulation and active shielding).
- In case of large storage tanks, boil-off gas could be re-liquefied to reach zero-boil off.

cryoworld advanced cryogenics

cryoworld
advanced cryogenics

Thanks for your attention