Hydrogen liquefaction

Liquid hydrogen
North Las Vegas plant

Hydrogen as a vector of energy

Global Markets & Technologies

CSE European Cryogenic Days
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FAIR GSI HEP Tech

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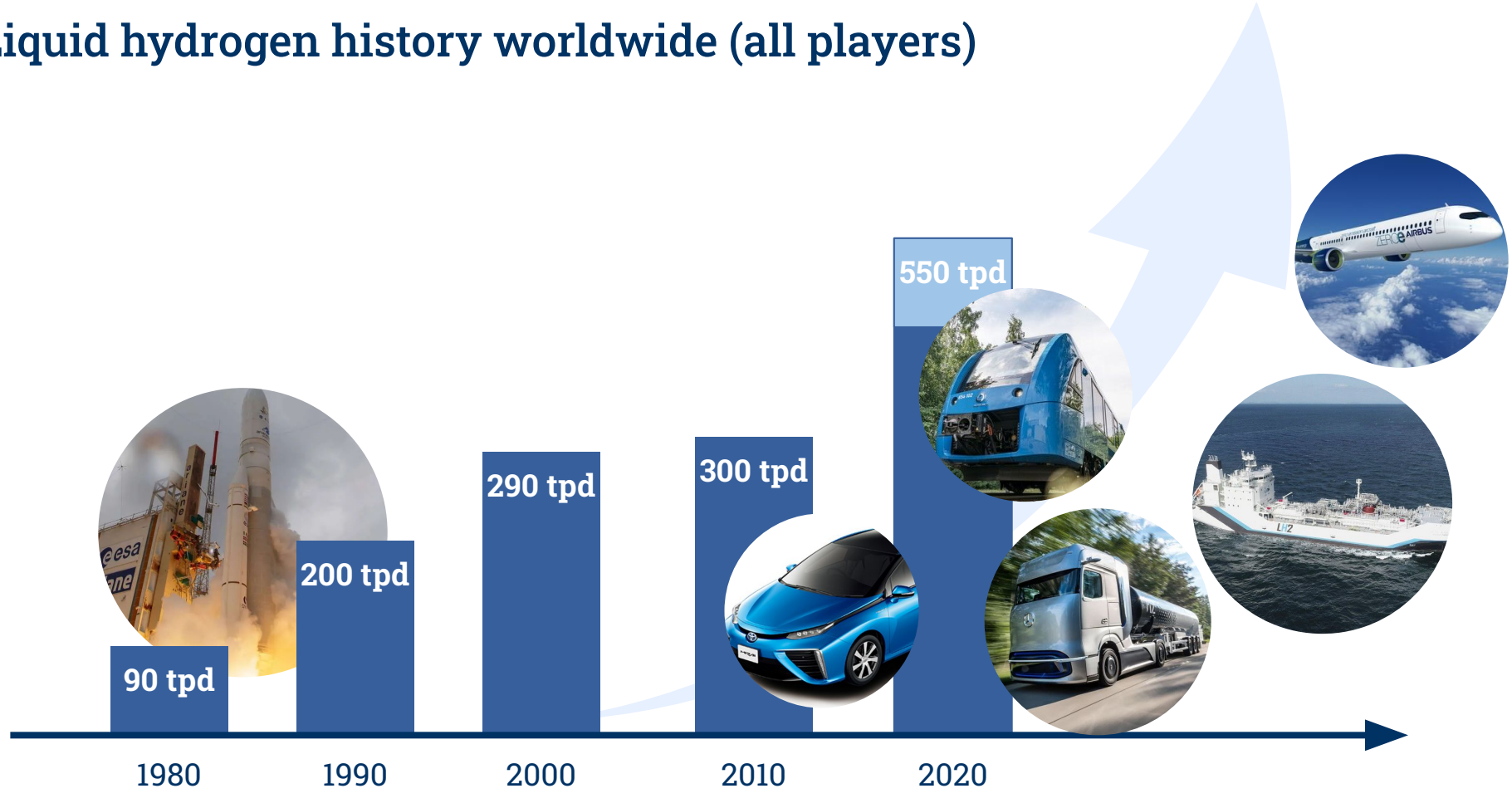
Hydrogen liquefaction

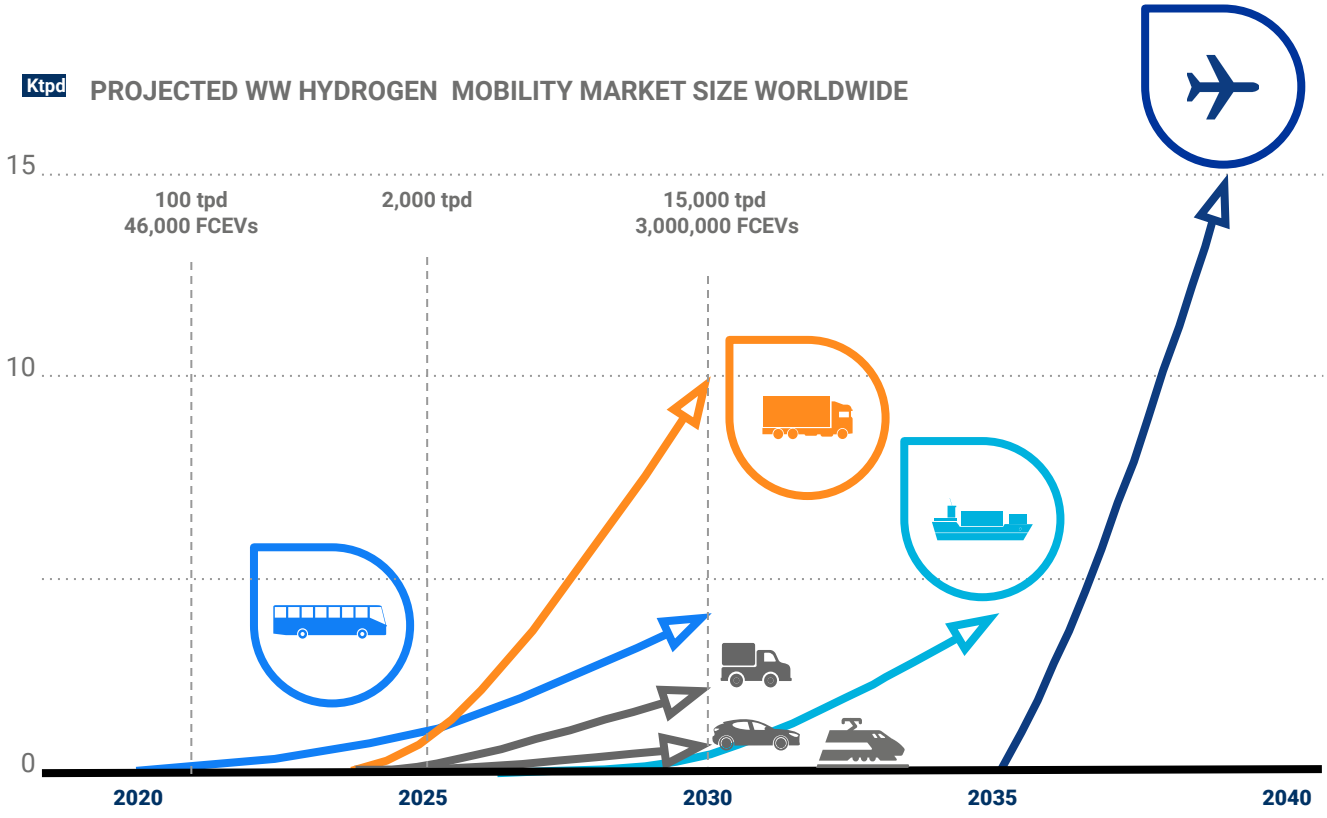
Context

Hydrogen as a vector of Energy

Liquid hydrogen history worldwide (all players)



Ready to accompany the growth of hydrogen mobility



25%
transport CO_2 impact

80+
CO_2 regulations worldwide

3 M
hydrogen vehicles by 2030

10
min to refuel a bus

50%
of hydrogen demand dedicated to transport by 2050

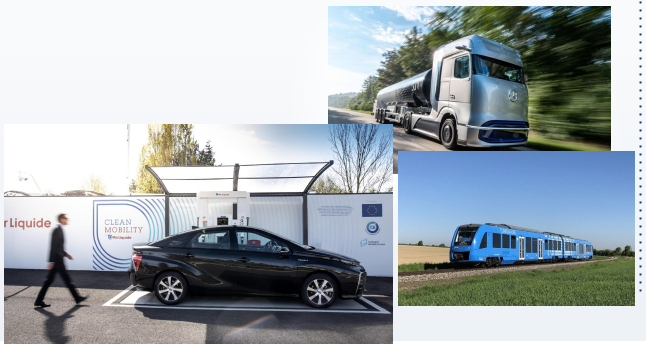
Estimates as of end of 2021

Liquid H2: a key fuel for the future of Zero-Emission transport

>50% of global H2 transport needs by 2050

Already more than **10 000** tpd by 2030

Land Mobility



Maritime

Aviation

DAIMLER faurecia FE FUEL ENERGY OBSERVER AIRBUS

Why and where does liquid H2 make the difference?

Competitiveness

Best cost from 1 tpd consumption

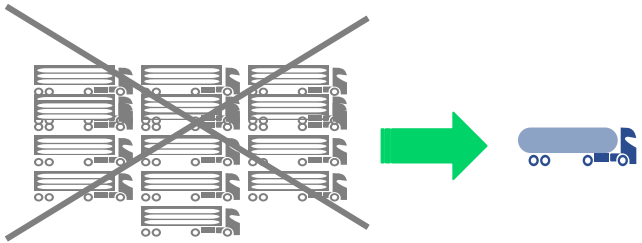
Customer eXperience

1.7 more energy than Gas H2* per unit volume

* at 700b

Decarbonize the planet

Much less trailers on the road



16 Gas H2 trailers (200b)

1 Liquid H2 trailer

Air Liquide

Hydrogen liquefaction

Air Liquide in the hydrogen supply chain

Hydrogen as a vector of Energy

Our expertise at the service of industry and mobility

Air Liquide

Air Liquide core business

Energy sourcing

Clean power, Biogas

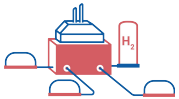
Production

Production, carbon capture

Conditioning

Liquid and gas supply chain

End-use



Industry

Mobility

Air Liquide technology leadership

LOW-CARBON & RENEWABLE PRODUCTION

Electrolysis
PEM | ALKALINE

Other technologies
E-METHANOL

Reforming
SMR | ATR

Partial Oxidation (POX)

+

Carbon Capture
The most comprehensive offering

CONDITIONING

LIQUID HYDROGEN

Liquefaction
Scaled up capacities
& Optimized payload

GASEOUS HYDROGEN

Conditioning
High-Pressure filling centers

SUPPLY CHAIN

- Liquid & gaseous storages
- GH_2 & LH_2 distribution
- GH_2 & LH_2 hydrogen stations

Hydrogen liquefaction

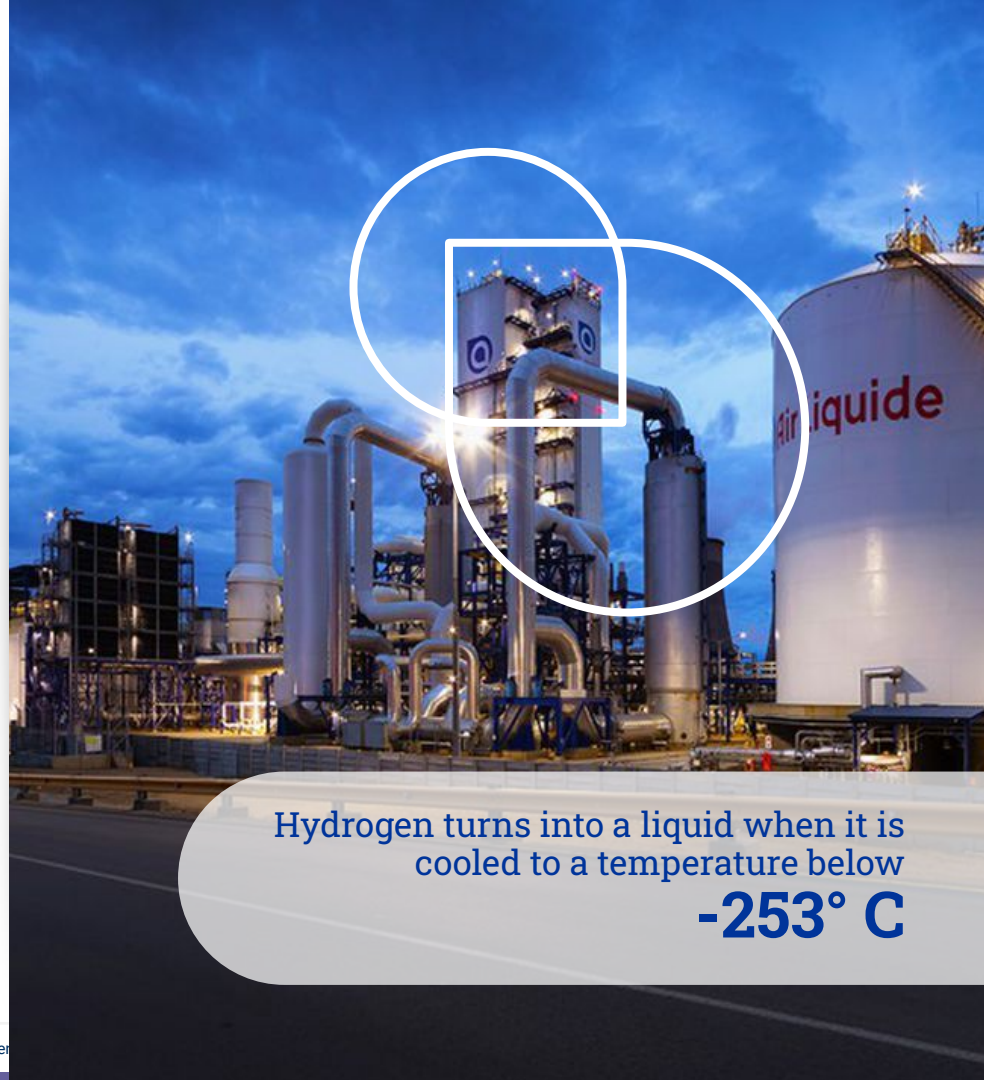
Technology

Hydrogen as a vector of Energy

Liquid hydrogen to accelerate the transition toward carbon neutrality

Conversion of gaseous hydrogen to liquid, a state-of-the-art technology to store a maximum of hydrogen in a minimal volume

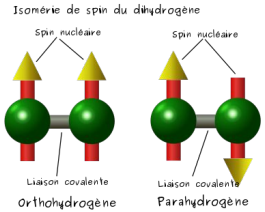
- Air Liquide has a **unique expertise** in liquid hydrogen, which requires advanced mastery of extreme cryogenics
- Already used for spaceflight since the 60s
- Particularly well suited for maritime and aviation applications + Heavy Duty road transport that will come first and be massive



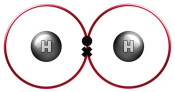
Hydrogen turns into a liquid when it is cooled to a temperature below

-253° C

Basis for designing a hydrogen liquefaction plant

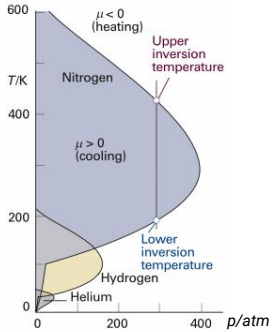


Quantum mechanics (!)



1 proton **1** electron
14 x lighter than air
71 kg/m^3 at boiling point (at 1 atm)

Extremely light



Specific properties

Very **low inversion temperature**
202 K (at 1 atm)
H_2 warms if expanded at constant enthalpy

1.0080 1

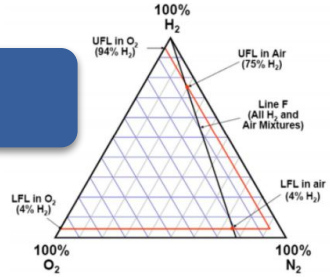
H_2

Hydrogen

Deep cryogenics

Boiling point: 20.3K (at 1 atm)

Safety

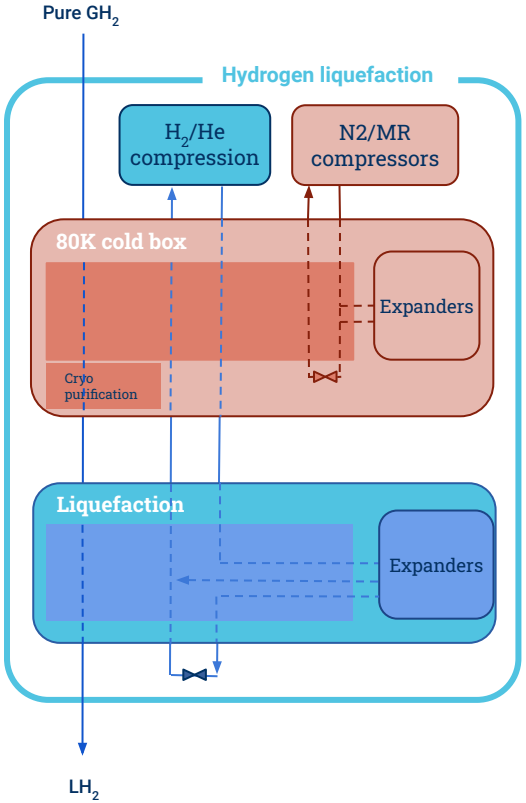


Fast growing market

Design for **scale-up**

Hydrogen liquefaction technology

- Capacity: **1 ⇒ >100 tpd**
- Production: **LH_2 > 95% para-H_2**
- Highly efficient technologies, relying on decades of operational experience
- Tailored solutions at each step (liquefier, storage, trailers, stations)
- Purification and liquefaction process derived from Helium liquefaction
- Low maintenance costs & high reliability
- Solutions for efficient **LH_2** boil-off management



H_2 Liquefiers - Scaling up for mobility

LH_2 production

1 tpd | 5 tpd | 25 tpd | 50 tpd | 1000 tpd

He cycle

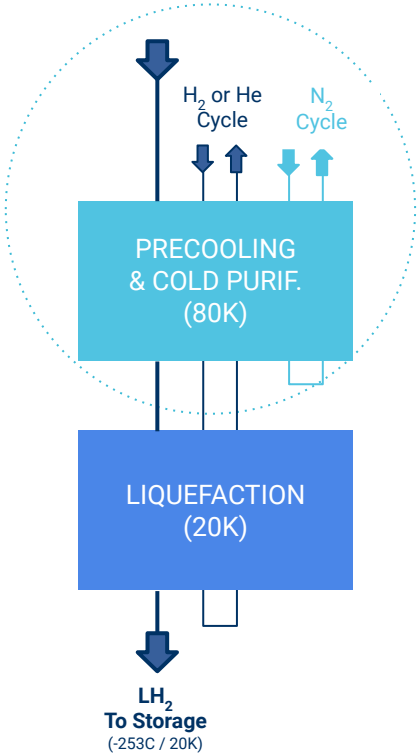
H_2 cycle

XL cycle

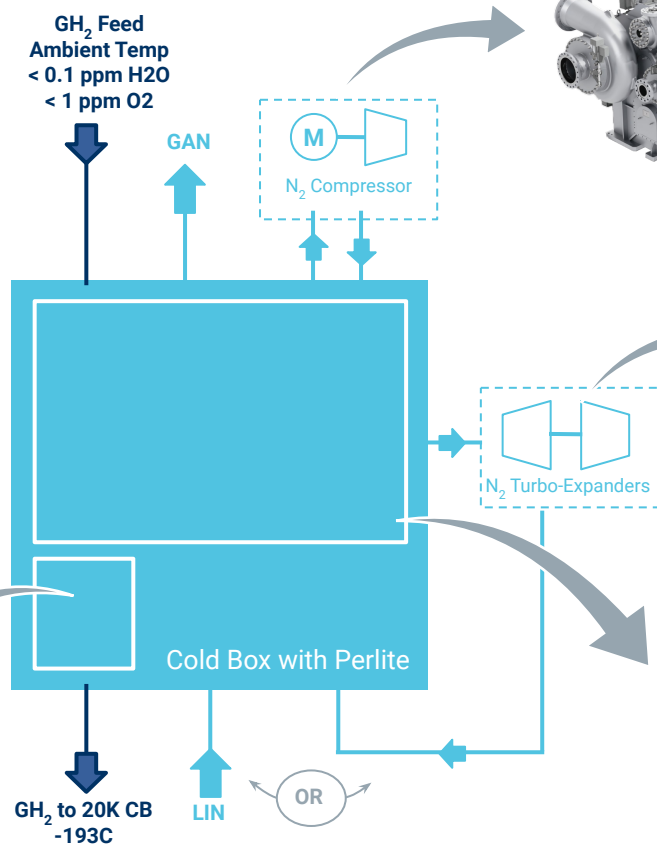
Custom-made large liquefiers

Main Air Liquide References	*China 2007-2021*	*China 2011*	*France 1988*	*Canada 1990*	*USA 2020*	*South Korea 2021*	*South Korea 2021*	*USA 2022*
LH_2 production (l/h)	600 x 4	1 500	6 000	6 000	18 000	*3 000*	*54 000*	*36 000*
LH_2 production (TPD)	1	2.5	10	10	30	*5*	*90*	*60*

Liquefaction technology
Precooling



Similar to an ASU, NLU, LNG N_2 Refrigeration Cycle



N_2 Integrally Geared Centrifugal Compressor

N_2 Expander-Boosters

Liquefaction technology

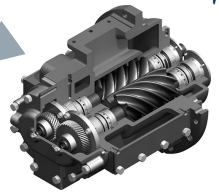
Liquefaction - Deep cryogenics

GH_2 from 80K CB
-193C

M
H_2 Compressor(s)

80K CB

From small Screw Compressors...



...to Large Reciprocating Compressor

H_2 or He Cycle

N2 Cycle

PRECOOLING & COLD PURIF. (80K)

LIQUEFACTION (20K)

LH_2 To Storage
(-253C / 20K)

Ortho

Para

ortho/para conversion

Air Liquide world-leading experience down to 4K
Leverage large H_2 liquefaction with He experience

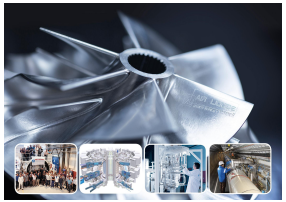
Air Liquide
Paris, July 8, 2013
Qatar: start-up of world's largest helium unit

Vacuum insulated Cold Box

LH_2 to Storage
-253C

H_2 Expanders

H_2 Gas Bearing Expanders



Vacuum CB with Multi Layer Insulation

Focus on ortho/para conversion

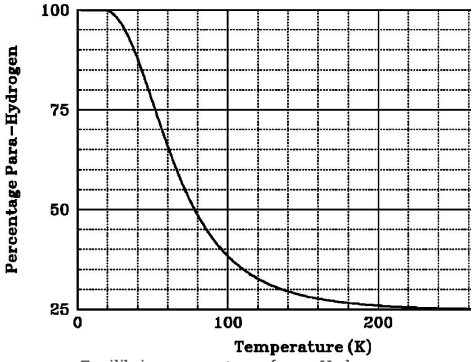
Hydrogen exists in **2 forms of spins isomers**

➔ At ambient temperature **25% para-H_2**

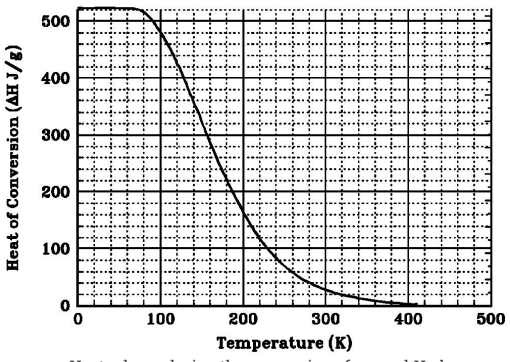
Conversion of ortho-H_2 to para-H_2 is **exothermic reaction** with a **slow kinetic**

➔ ortho/para conversion represents **~10% of the liquefaction duty**

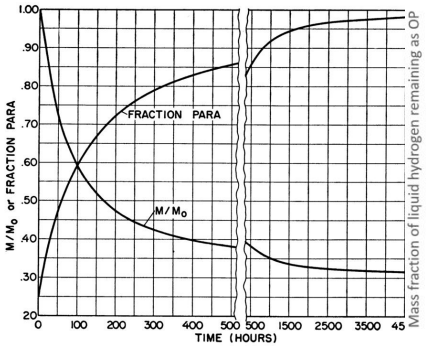
To **minimise storage boil-off losses**, the conversion is accelerated with a **catalyst** during the liquefaction process



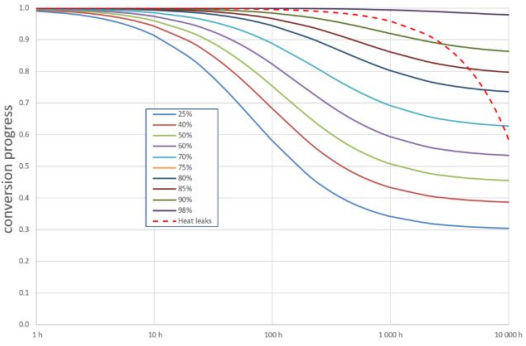
Equilibrium percentage of para-Hydrogen versus temperature



Heat release during the conversion of normal Hydrogen



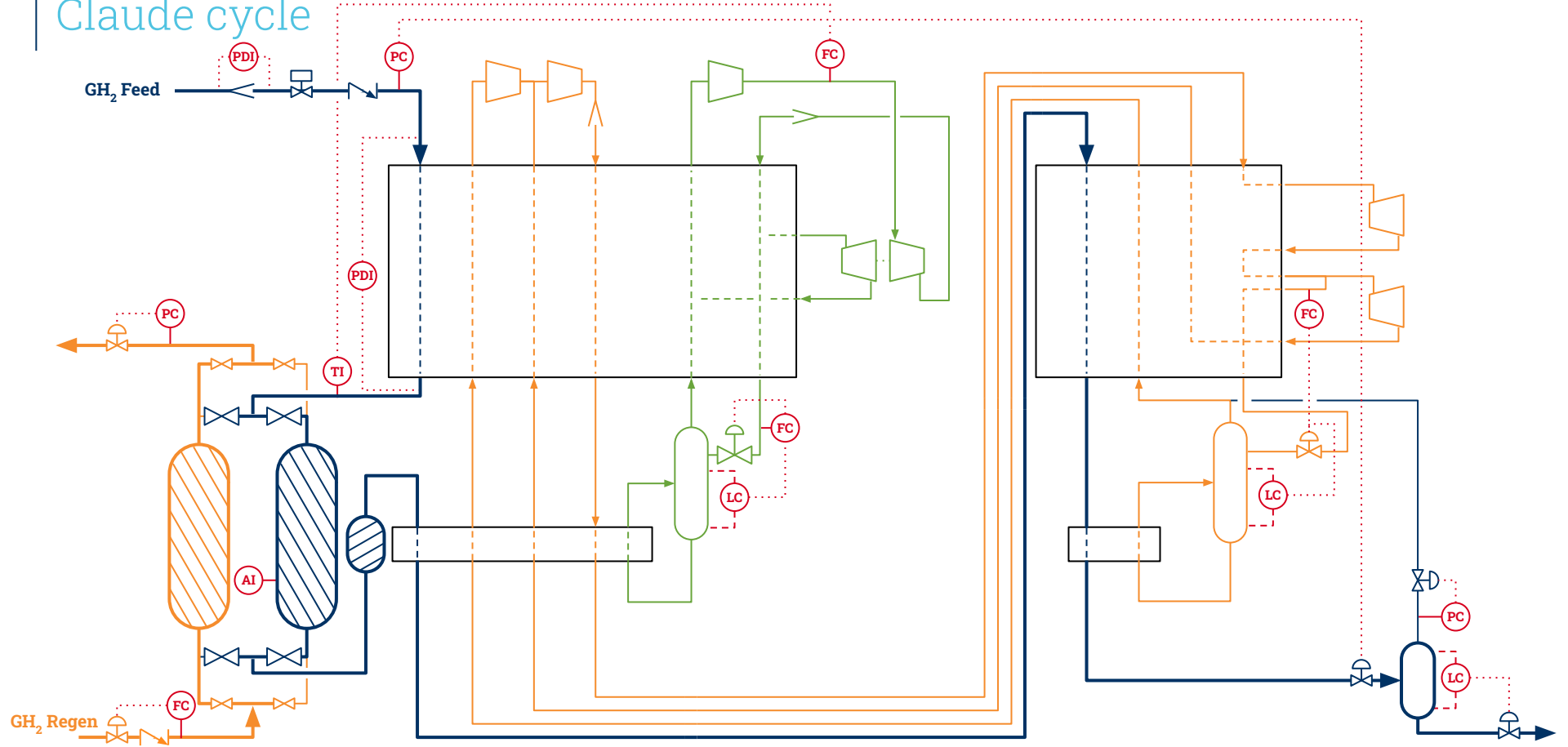
Kinetic of ortho- to para-Hydrogen conversion for uncatalyzed liquid Hydrogen.



Mass fraction of liquid Hydrogen remaining as ortho/para conversion progress for several initial para-H_2 fraction

Liquefaction technology

Claude cycle



LH_2 unit, 30 tpd - US West Coast NEVADA

Vidéo link

Production and liquefaction

Nevada, USA

The largest liquid hydrogen production and logistics infrastructure facility

Technology

- Steam methane reformer & liquefier
- Air Liquide proprietary technologies

Capacity

- 30 tonnes per day
- Air Liquide's largest liquid hydrogen production site

Markets

- Mobility market in California (for more than 40,000 FCEVs)
- Industrial use

Commissioning

- Commissioned in May 2022

LH_2 unit, 30 tpd - US West Coast NEVADA

For more information

https://engineering.airliquide.com/technologies/hydrogen-liquefaction

Thank you