Hydrogen Storage on board aeronef and ground infrastructure

Air Liquide Advanced Technologies – Workshop on aeronautical applications of fuel cell and hydrogen technologies

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Content

1. Status of hydrogen fuel cell implementation, state of the art H2 Energy. It already exists …

- 5 000 stationnary fuel cell in operation WW

- Over 4000 FC Forklift
  - 3000 aux US (Wallmart, Coca-Cola…)
  - En France: 10 chariots sur le site de Vatry d'AL

USA – Forklift

- 200 (60 from Air Liquide) refilling stations
- 50 buses et 300 FCEV Demo

London – FC Bus

Shanghai – Challenge Bibendum

→… *mostly fed with high pressure cylinders because car market is driving storage technology development*

1. Status of hydrogen fuel cell implementation, state of the art GH2-CCH2-LH2 charging stations


HRS Forklifts Vatry January 2012

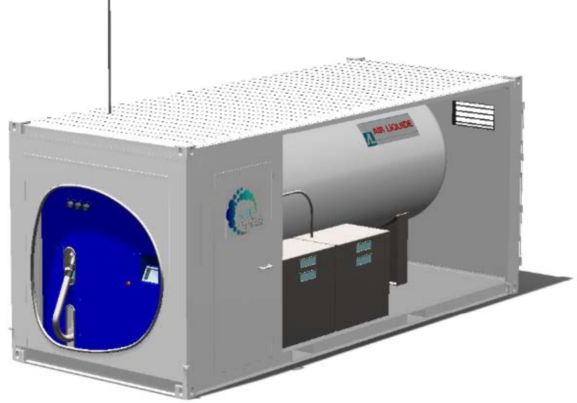

HRS Bus 200 kg/day Zurich April 2012

HRS for cars 100 kg/day
Düsseldorf June 2012

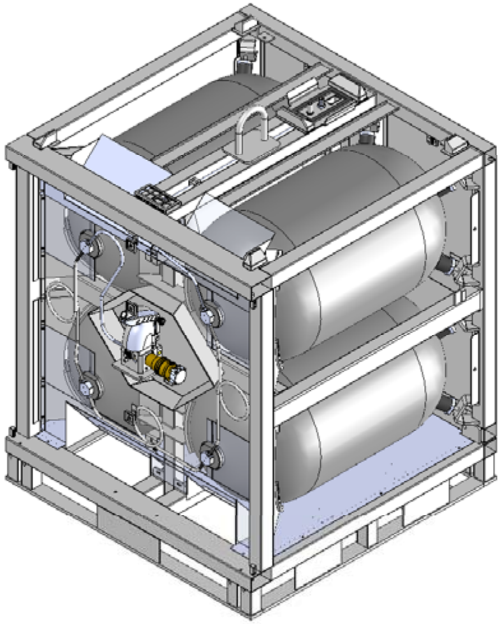

HRS Bus 200 kg/day Oslo May 2012


HRS Demo 20 kg/day
Slovenia Dec 2012

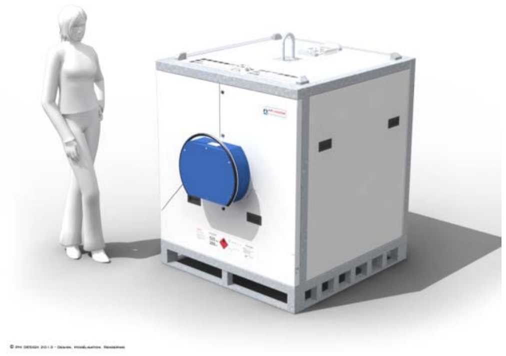
LH2-CCH2 Portable Station
Concept with Zero Boil-Off



1. Status of hydrogen fuel cell implementation, state of the art
New standardized H2 storages : H4-142 litres at 700 bars



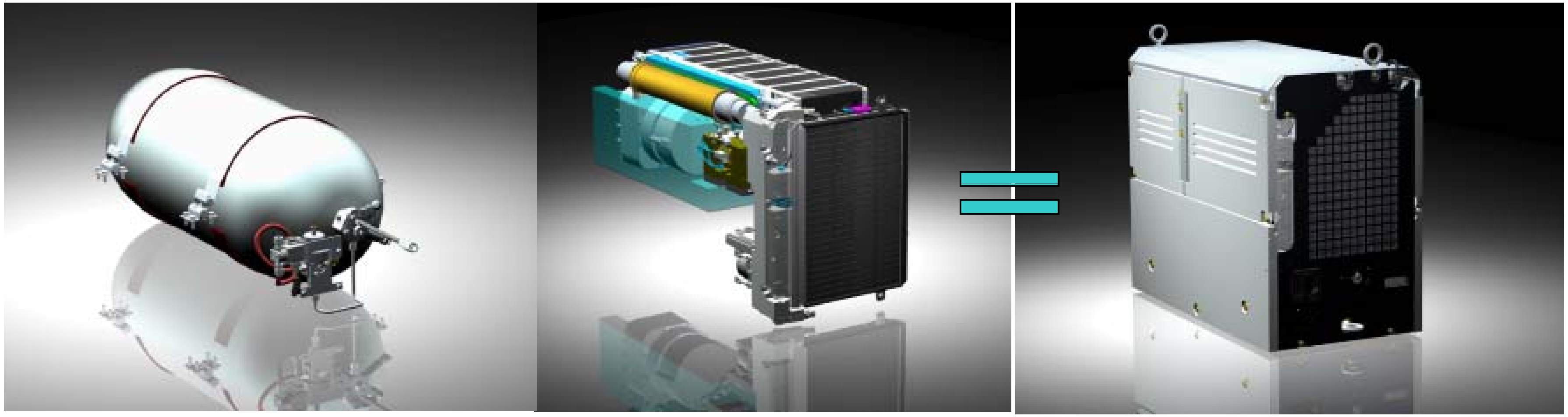
- **Type 4 cylinders individual or packaged**
- **Transportation Cost divided by 3**



- **Integrated HyDeal Pressure Regulator 700/10 bar with Wi-Fi pressure sensor**

1. Status of hydrogen fuel cell implementation, state of the art
Plug&Play Integrated Fuel Cell for Fork Lift

axane + plugpower = HY PULSION



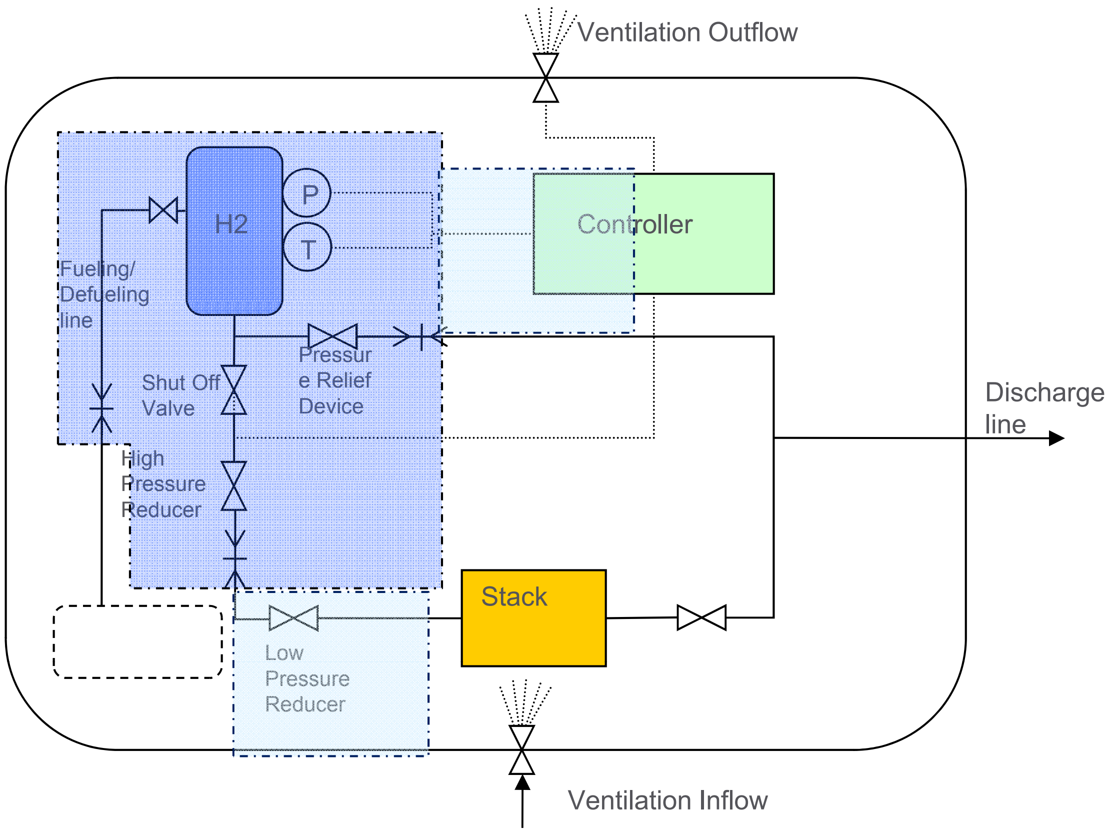
- 5 – 15 kW range; 48 V
- 350 b type III tank; 1 kg H_2
- MEA LifeTime > 10,000 hrs demonstrated in operation
- Could become airworthy with adaptations
- Suited for galley , R.A.T. for instance
- Aircraft retrofit market reachable

axane

Proprietary FC development

2. On-board Hydrogen Storage Systems

a) Hydrogen storage definition



+ Safety devices: PRD, TPRD, purge valves

+ Mechanical supporting: brackets, …

2. On-board Hydrogen Storage Systems

b) Aeronautical Technical Requirements

- **Gravimetric performance** to ensure appropriate autonomy and cost efficiency

- **Volumetric performance** to match with the integration constraints

- **Control and Monitoring** to enable the management of the system, the energy level real time monitoring, to know and deal with any potential safety issue occurring, or maintenance required action

- **Safety** and environmental compatibility
    - H2 leakage management to cancel fire and explosion risks
    - Particular risk compatibility
    - Environmental compatibility: compliance with DO160 requirements

- Hydrogen **quality**

- Maintenance and operability
    - System availability
    - Acceptable MTBF
    - Cycling
    - Refilling
    - Maintainability: LRU/SRU concept,…

2. On-board Hydrogen Storage Systems

b) Aeronautical Technical Requirements

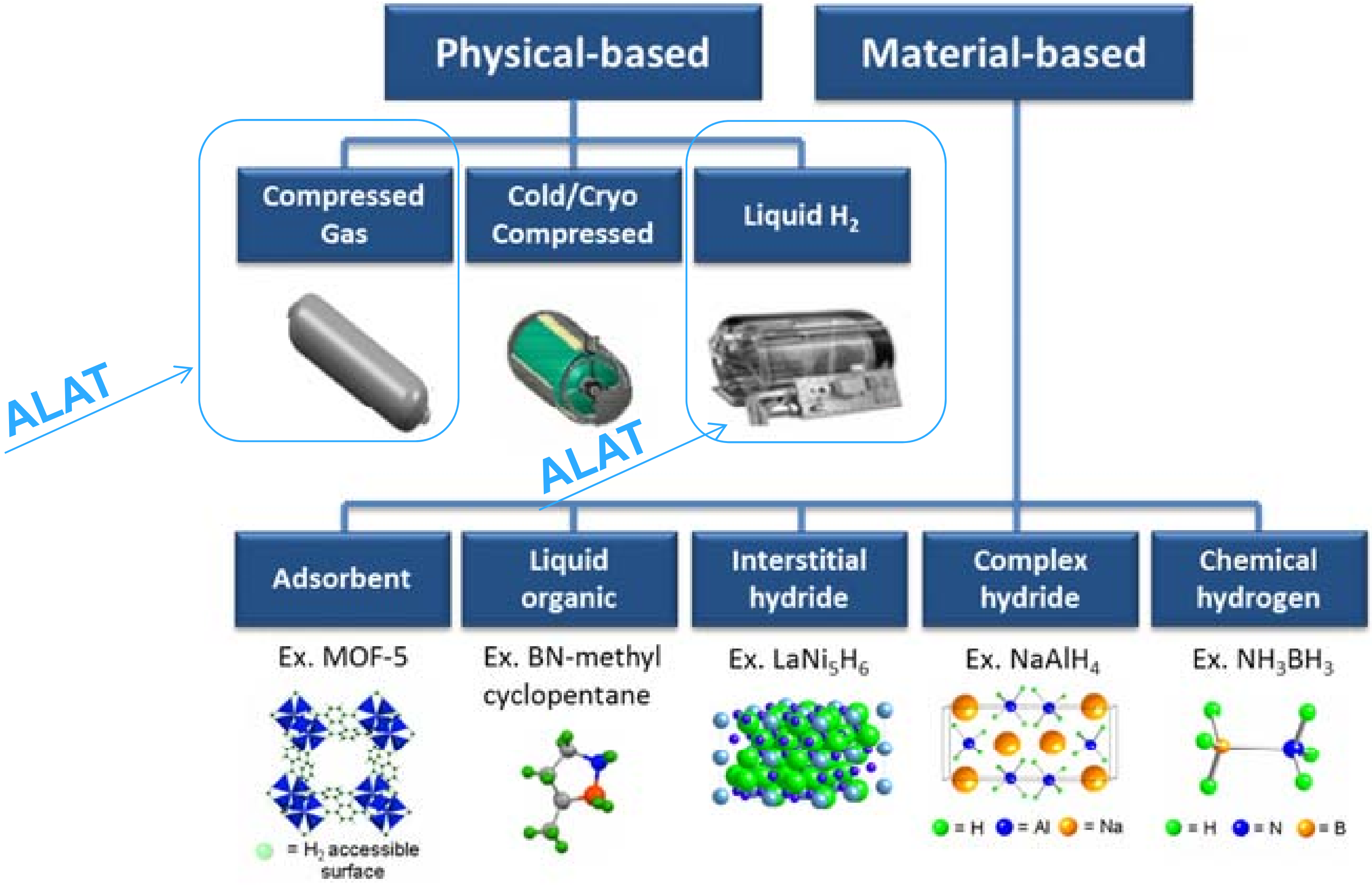
The Aircraft type and the foreseen system integration induce certain constraints:

- A **pressurized** area installation offer less H2 venting options → H2 leakages shall be extremely remote or any abnormal leakage shall be directly vented overboard
- An **unpressurized** area installation allows easier leakage management but generate more severe environmental conditions
- Depending on the application the storage device can be **located remotely** from the fuel cell inducing additional hydrogen piping → more leakage risks
- The **security** toward hydrogen access is affected by cabin integration and passengers possible access to the H2 storage system
- The **cabin integration** may also induce thermal management issues due to the heat rejection of the fuel cell → indirect impact on the storage system
- **UAV fuel cell** or propulsion systems allow important integration and safety constraints relaxations regarding the H2 storage system

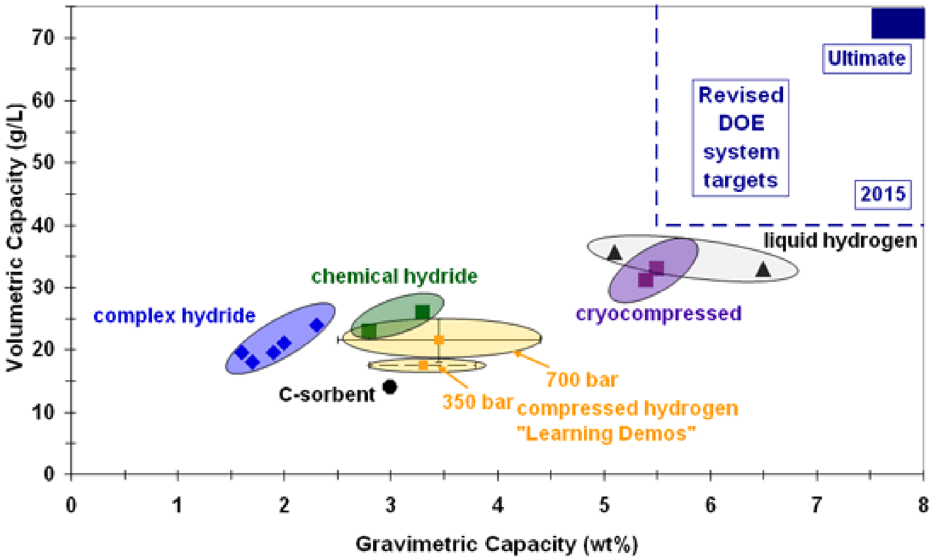
- → each targeted aircraft and application induce dedicated constraints on the hydrogen storage system.
- → the differences in terms of applicable regulations can impact the hydrogen storage system requirements.

2. On-board Hydrogen Storage Systems
a) Storage technologies and state of the art performances

- Storage technologies overview (source: US DOT website)



- Status of HydrogenStorage Technologies DOE 2009



Storage System Targets	Gravimetric Density kWh/kg system (kg H_2/kg system)	Volumetric Density kWh/L system (kg H_2/L system)	Cost \$/kWh (\$/kg H_2)
2020	1.8 (0.055)	1.3 (0.040)	\$10 (\$333)
Ultimate	2.5 (0.075)	2.3 (0.070)	\$8 (\$266)
Current Status (from Argonne National Laboratory)	Gravimetric Density kWh/kg system (kg H_2/kg system)	Volumetric Density kWh/L system (kg H_2/L system)	Cost[b] \$/kWh (\$/kg H_2)
700 bar compressed (Type IV, single tank)	1.5 (0.044)	0.8 (0.024)	\$17[c] (\$566)
350 bar compressed (Type IV, single tank)	1.8 (0.054)	0.6 (0.017)	\$13[c] (\$433)

[a] Assumes a storage capacity of 5.6 kg of usable hydrogen.
[b] Cost projections are estimated at 500,000 units per year and are reported in 2007\$.
[c] Cost projection from Strategic Analysis (January 2013).

Table 3.3.2 Projected Performance of Hydrogen Storage Systems[a]

Hydrogen Storage System	Gravimetric (kWh/kg sys)	Volumetric (kWh/L sys)	Cost (\$/kWh; projected to 500,000 units/yr)	Year Published
700-bar compressed (Type IV)[b]	1.7	0.9	19	2010
350-bar compressed (Type IV)[b]	1.8	0.6	16	2010
Cryo-compressed (276 bar)[b]	1.9	1.4	12	2009
Metal hydride ($NaAlH_4$)[c]	0.4	0.4	TBD	2012
Sorbent (AX-21 carbon, 200 bar)[c]	1.3	0.8	TBD	2012
Chemical H_2 storage (AB-liquid)[c]	1.3	1.1	TBD	2012

[a] Assumes a storage capacity of 5.6 kg of usable H_2
[b] Based on Argonne National Laboratory performance and TIAX cost projections[8]
[c] Based on Hydrogen Storage Engineering Center of Excellence performance projections[9]

2. On-board Hydrogen Storage Systems

b) Storage technologies and state of the art performances

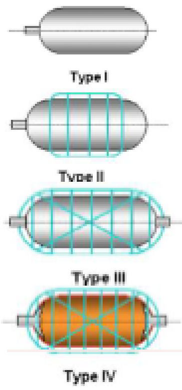
Consideration about the H2 storage technologies

- **High Pressure storage systems**
  - ➕ •High maturity (automotive industry, Hycarus project), acceptable cost, similarity to existing gaseous systems (oxygen storage)
  - ➖ •Low potential improvement with regards to gravimetric and volumetric performances, high pressure on board
- **Liquid storage systems**
  - ➕ •Very High gravimetric and volumetric efficiency, low pressure, intrinsic double wall against H2 leakage, high maturity on ground
  - ➖ •Boil-off, high cost
- **Cryo-compressed**
  - ➕/➖ •High gravimetric and volumetric efficiency, trade-off between high pressure and liquid storage performances
- **Reversible material storage**
  - ➕ •No gaseous hydrogen
  - ➖ •Low gravimetric efficiency, reversibility management on board?
- **Chemical material storage**
  - ➕ •No gaseous hydrogen
  - ➖ •Regeneration process, by-products management?

2. On-board Hydrogen Storage Systems

c) High Pressure Hydrogen Storage System

- **High Pressure GH2 Storage : 4 main types of storage technologies**



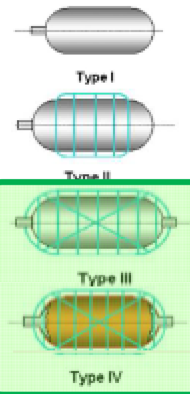
Type I	Pressure vessel made of **metal** (mainly for stationary application(SA))
Type II	Thick **metallic** liner hoop wrapped with **a fiber-resin composite** (SA)
Type III	**Load-sharing** liner fully-wrapped with a **fiber-resin composite** (portable applications (PA))
Type IV	**Non load-sharing** liner fully-wrapped with a **fiber-resin composite**.

- **Type I and II** have too limited volumetric and gravimetric capacities
- **Type III** exhibits:
  - Good gravimetric capacity (350bar) or lower gravimetric capacity (700bar)
  - Low volumetric capacity (350bar) or high volumetric capacity (700bar)
  - No permeation
  - Limited pressure cycling
  - Possible liner corrosion
- **Type IV** exhibits:
  - Good gravimetric and volumetric capacities
  - High pressure cycling
  - Permeation
  - Possible liner clogging
  - Limited operating temperature range

→ Different kind of advantages which makes type III and type IV potentially suited for different areonautical applications

c) On-board Hydrogen Storage Systems
c) High Pressure Hydrogen Storage System

- **High Pressure GH2 Storage : 2 relevent storage technologies**



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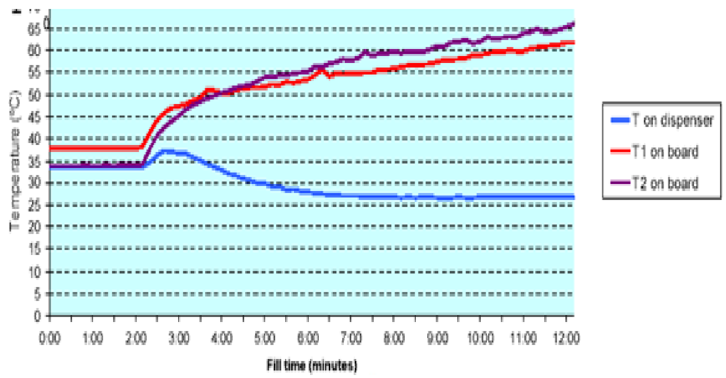
Type IV	**Non load-sharing** liner fully-wrapped with a **fiber-resin composite**.

→ **Diffent refilling pressures from 350 bar to 700 bar**
→ **Different life cycle management**

- **Filling patterns depend on cylinder technology**



→ **For faster flow, GH2 needs to be cooled down before refilling the storage device**

- **Conclusion**

  - TRL6 to be demonstrated through Hycarus Project in 2016 → TRL6 will be valid for one vessel technology in cabin integration
  - Regulation to be defined (cf SAE WG80 and FAA ARC) → impact on gravimetric performances
  - Components to be developed to comply with qualification and certification requirements
  - Limited gravimetric and volumetric performances potential of improvement; unsuited to large hydrogen consuming targeted applications
  - High pressure on board aircraft remains an issue towards safety considerations (cf oxygen bottles)
  - Hydrogen charging is mature and depends on the storage pressure and the charging duration

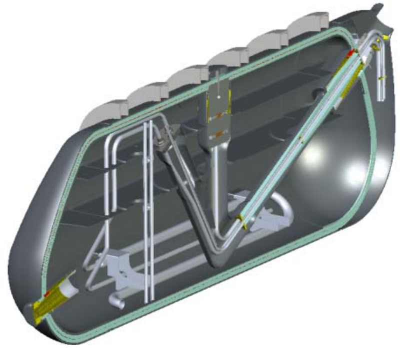
2. On-board Hydrogen Storage Systems
e) Liquid Hydrogen Storage System

- A lot of developments done for the automotive industry in the 2000s
- Hundreds of kilograms storable in an aircraft

12 kg Air Liquide tank

Gravimetric index 15% demonstrated

Any shape

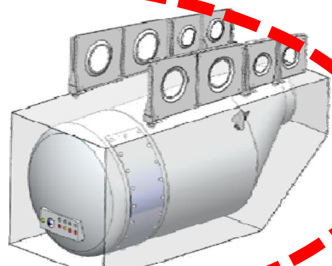


Air Liquide tank

Cryogenic valve

Liquid H2 coupling for charging

A liquid H2 tank fitting in an aircraft tail cone may look like this



50 kg Air Liquide tank

2. On-board Hydrogen Storage Systems
e) Liquid Hydrogen Storage System

Stringent safety tests performed for the automotive industry on LH_2 tanks

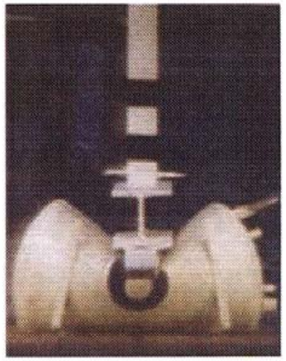
Liquid tanks are low pressure systems (below 10 bar)

They have a vacuum insulation which can be considered as a double containment

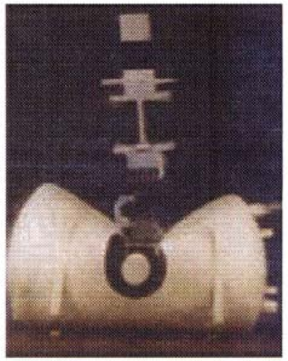
Safety of Cryogenic Fuel Tanks

Simulation of Road Accident:
Crash of a HD-vehicle into a passenger car at 60 km/h

LH_2 tank and drop weight
5 ms pre-impact



Maximum deformation of the LH_2 tank 30 ms post-impact



Lasting deformation of the LH_2 tank

Spill-over tests

Boil-Off considerations

- Example: a tank containing 50 kg of liquid connected to a 100 kW fuel cell
  - Temperature = -253°C; 4 hours of autonomy at full power (400 kWh stored)
  - Wort case boil-off rate: 2% =1kg per day = 0,5 Nm3/h

- 3 possible solutions to get rid of this BOG:
  - To vent it: small line; 11mg/s or 0,15 Nl/s of gas; but not really suitable
  - Catalytic combustion: rejects H2O vapor and 1,5 kW heat
  - Feed the FC at low idle (BOG=700W) to operate the utilities (air compressor, intercooler, sensors etc.) in steady state or **reload the battery**: best solution

  - Nota: hybrid systems combining a battery and a FC are preferable
    - Taxi A320 ~60 / 100 kW@20knts (**FC**) +runway crossing (600kW **few sec., battery**)

- Over a year a car runs 300 h whilst an aircraft flies >3000 h+ ground ops
    - Boil-off is therefore predominant for cars which will not be the case for aircraft

The BOG is therefore permanently re-used

Conclusion

- **Very high gravimetric efficiency**
- **Safe**
- Ground **maturity**
- **Cost efficiency** to be improved → manufacturability to be improved
- Maturity in aeronautical use to be increased
- Not suitable for long term storage on board due to **boil off**
- Potentially very suitable to **UAV** use for propulsion: even higher gravimetric efficiency foreseen and relaxation of technical constraints → lower cost

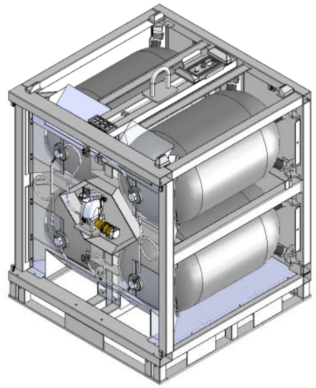
- Technical barriers to be investigated:
  - Cryogenic components to be developed to comply with **aeronautical requirements**: PRDs, pressure reducers, SOVs, sensors, filling level sensors,…
  - New **filling levels** concepts to be investigated
  - Management of **attitude** impact on the boil-off and the withdrawing of liquid hydrogen
  - **Maintainability** requirements could lead to innovative concepts (LRU/SRU architecture,…)
  - Improved operation thanks to a fast **removable** liquid hydrogen storage system
  - **How can we develop an easy and fast way to refill the LH2 tank to be operated as easily as it is done today with a car?**

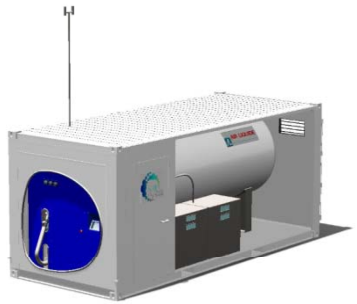
3. Hydrogen Charging Systems

a) Airport and aircraft requirements to hydrogen refilling systems

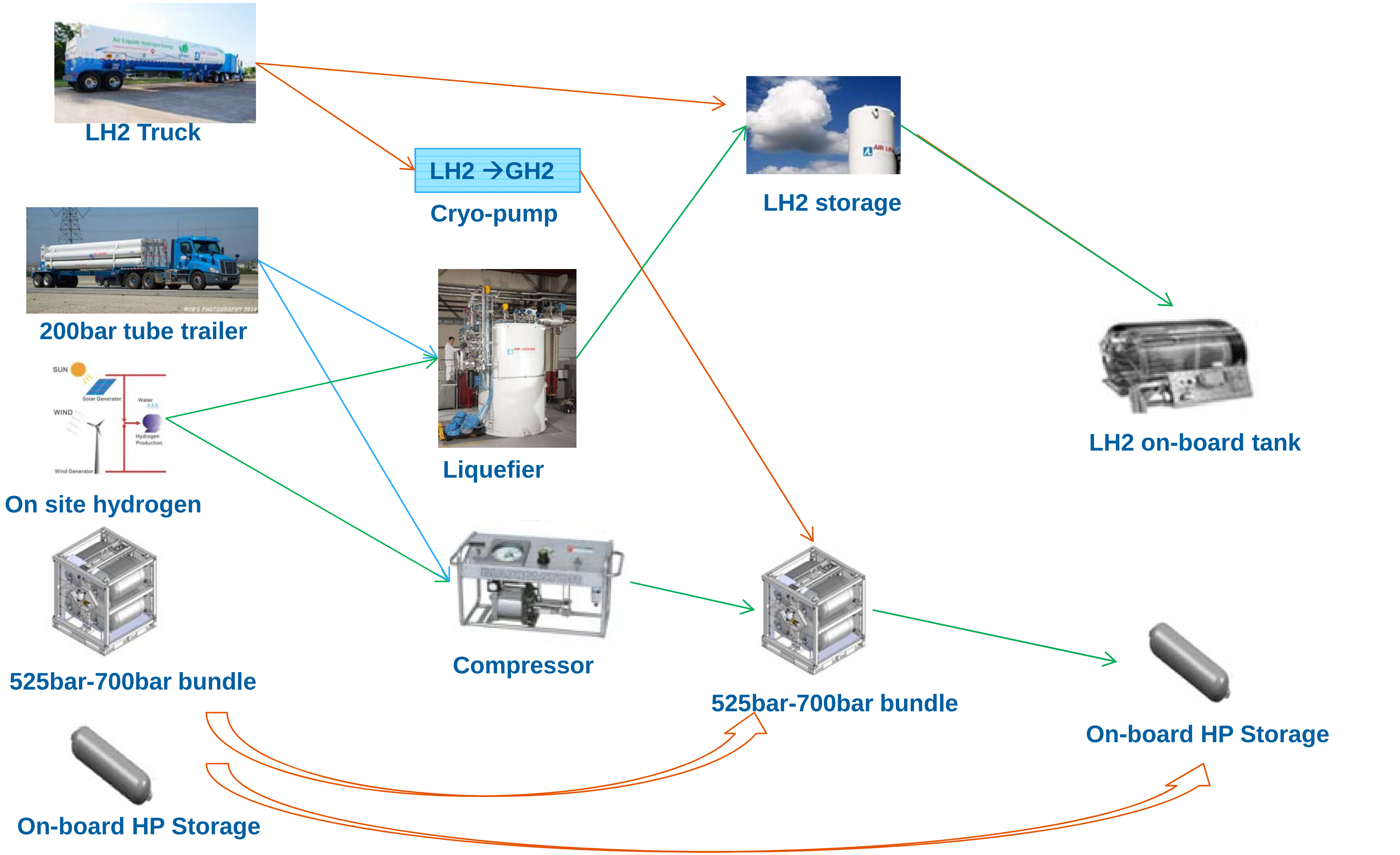
The refilling station shall comply with the following requirements (the scope is limited to physical storage solutions):

- To be able to refill the on-board storage system with:
    - 350bar or 700bar vessels
      And/or
    - Liquid hydrogen
- To ensure safe refilling next to the aircraft
  or
- To allow safe transport of the hydrogen vessel from the aircraft to the refilling station in compliance with ground /airport regulation
- To ensure the refilling within the acceptable allocated duration
- To allow the appropriate communication (control and monitoring) between the station and the on-board storage device
- To allow the appropriate hydrogen connection between the station and the on-board storage device





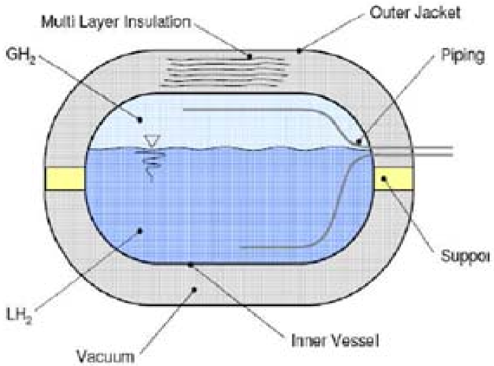
3. Hydrogen Charging Systems
b) Technological solutions for airport infrastructure

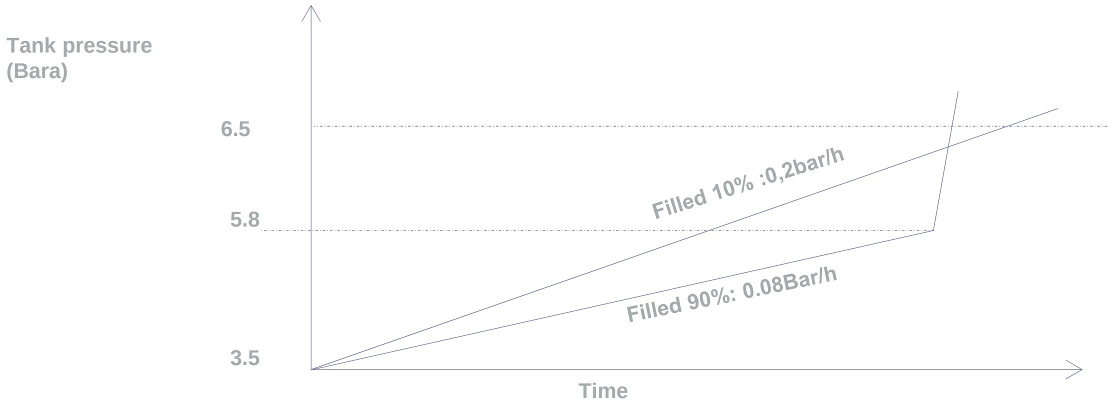


3. Hydrogen Charging Systems

c) LH2 refilling complexity

- LH2 tank are double-wall evacuated tank with Multi Layer Insulation
- Depending of heat leaks through MLI, pressure in the tank is rising when left unattended.



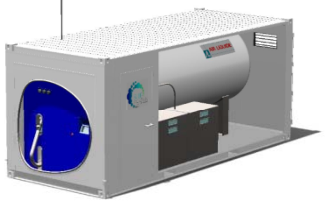


- During Operations, tank is pressurized at a pressure which depends on the Fuel cell operating pressure . Automatic Pressurization device is installed onboard the tank
- Upon refilling, Station must be capable to push liquid H2 inside the tank whatever its pressure at the time of refueling
- Station must be mobile to park as close as possible to the plane for refilling

→ The refilling station needs to be a dedicated cryogenic system ensuring LH2 conditioning in compliance with the on-board tank physical state. An advanced communication device shall allow the monitoring of the refilling. The station needs to be mobile and next to the aircraft.

LH2

LH2-CCH2



3. Hydrogen Charging Systems
d) conclusions

In order to provide a compliant hydrogen supply chain to the aeronautical fuel cell applications, the following challenges need to be addressed:

- **To provide the appropriate refilling technical solution in airport for each storage device**
- **To provide adequate amount of hydrogen to the airport with a viable logistical plan, considering the number of equipped aircraft, other vehicles, their ramp-up**
- **To deliver hydrogen to the target airport network in any required location, in compliance with any local regulation**
- **To minimize the energy consumption on / next to the airport**
- **To minimize the environmental footprint on the airport, and on the global supply chain thanks to optimized logistics and technical innovation**
- **To offer a price per Nm3 which allow the hydrogen applications total cost to be competitive; synergies need to exist with the ground application on or out of the airport.**

3. Hydrogen Charging Systems

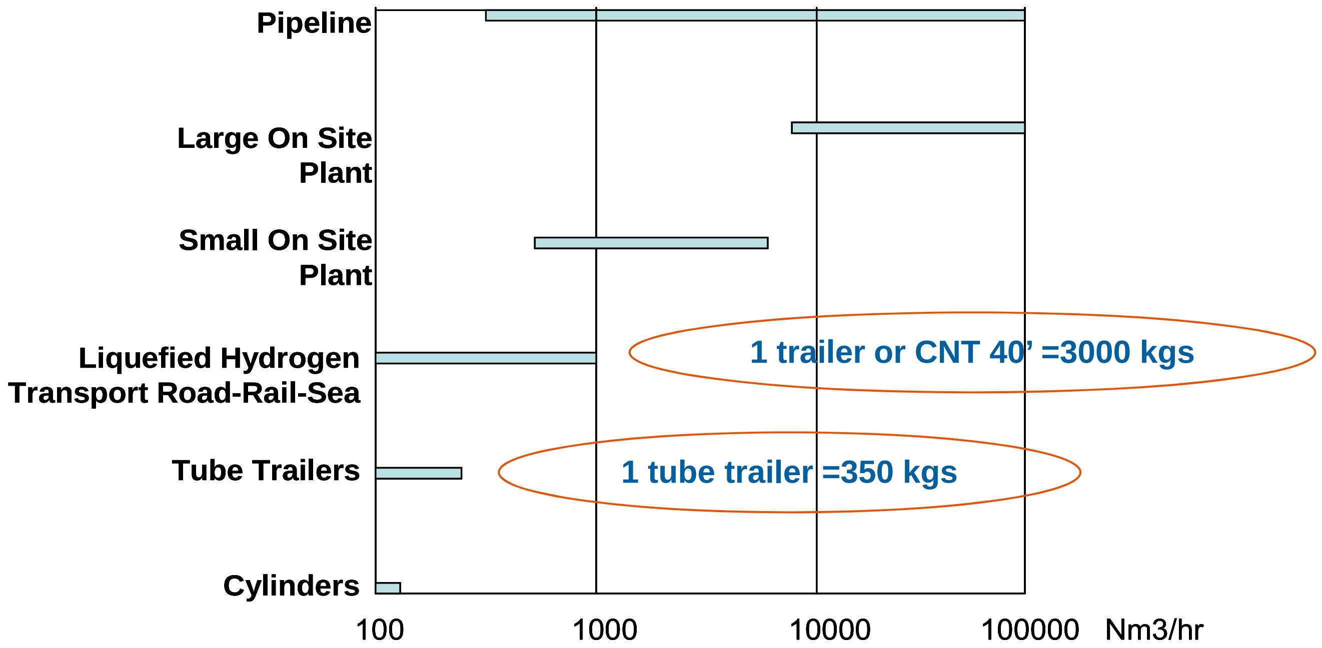
d) conclusions

Technological topics to be investigated

- To make it possible to refill the on-board storage while installed in the aircraft
- To develop mobile refilling stations to come to the aircraft
- To develop a cryo-pump to be able to design a dual station
- To develop a liquid refilling protocol to comply with the aircraft requirements

Backup slide

•State of the art of hydrogen logisitcs for industrial customers



•For aeronautical applications, logistics may also depend on:

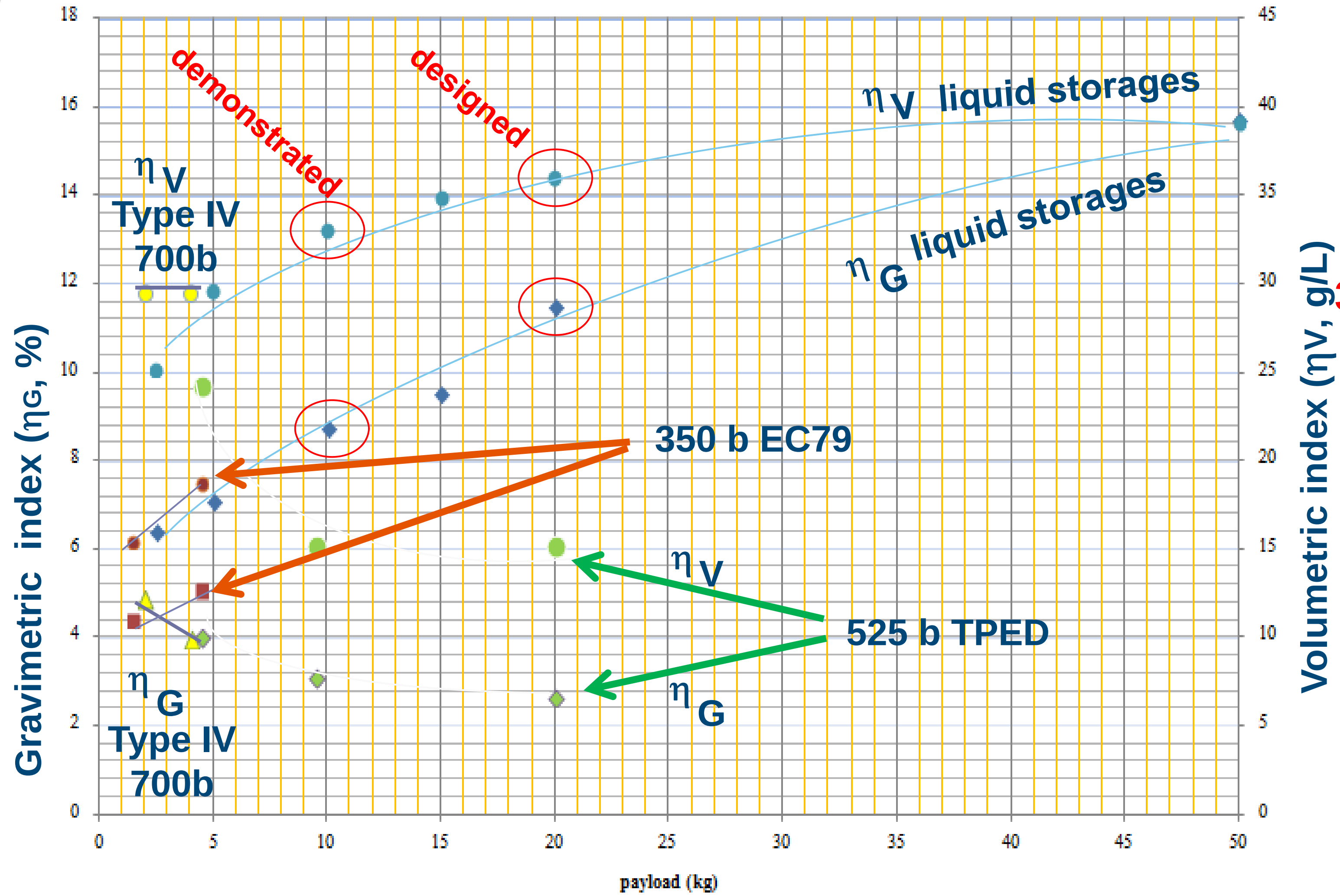
-Size and ramp-up of the application
-Infrastructure required (number of aircraft and other vehicles to be serviced per airport)
-required airports network
- Type of storages to be refilled (LH2, GH2, …)
-Refiiling Specs & procédures
-Availability of H2 to supply the airports network
-Regulations

Back-up Slide

Vehicle	Usage	Some Specs	Compressed Gas	Cryo-Compressed	Liquid	Metal Hydride	Chemical Hydrogen	Reforming
	-Populsion	-Storage efficiency -Simple operation -fast filling	★	★	★		★	
	-Populsion	-Storage efficiency -Simple operation -Costs -Zero emissions - B to C → « idiot proof »	★					
	-APU	-Storage efficiency -Simple operation -Fast filling -Lifetime -Zero emissions -B to B -WW H2 Logistics	★	★	★			
	-RAT		★			★	★	
	-Galley		★					
	-APU	-Storage efficiency -Simple operation -Fast filling -Lifetime -Intensive Logistics -Zero emissions -WW H2 Logistics		★	★			
	-RAT		★				★	
	-Galley		★					
	Propulsion, lifting	-Simple operation -Lifetime -FC off during handling? Zero emissions	★			★		

2. On-board Hydrogen Storage Systems

b) Storage technologies and state of the art performances



50kg H2
(8 hours for
100kW FC)
Liquid tank:
300kg, 1,3 m3

700b tank
>1ton, 1,6m3

350b tank
<1t; 3m3