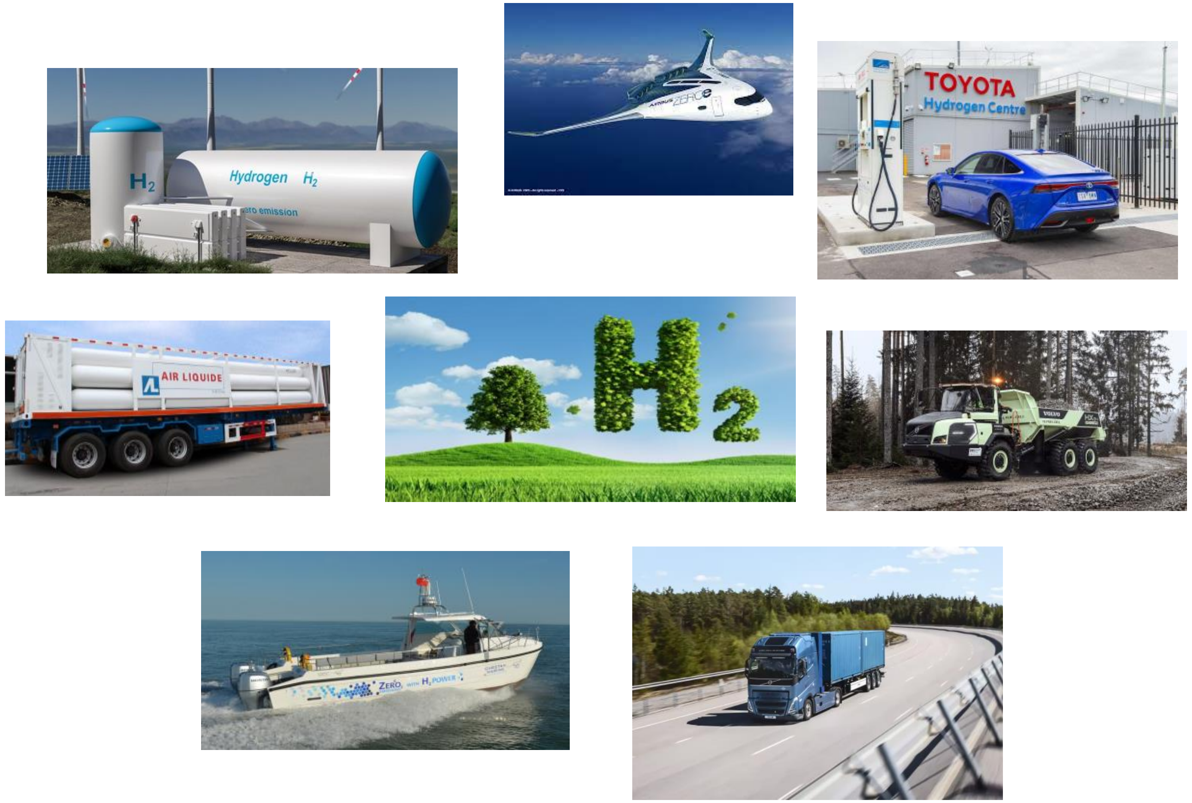
SEES SPRING MEETING 2023

Challenges for future hydrogen tank solutions in mobility – from high pressure gas to cryogenic liquid hydrogen

Christopher Cameron PhD
Senior Scientist- Structural Analysis and Modelling
RISE- Department of Polymers, Fibres & Composites
christopher.cameron@RI.SE



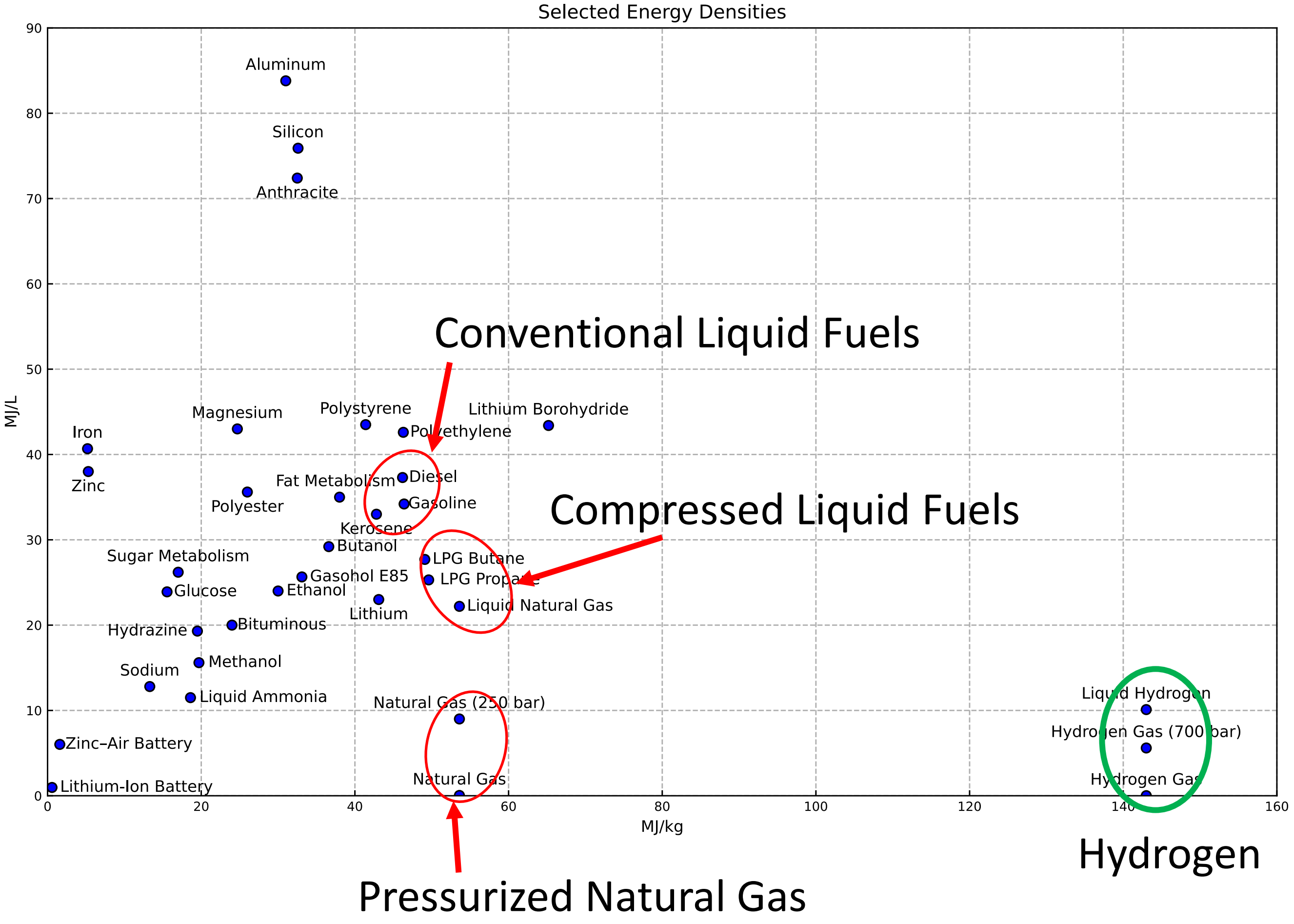
Hydrogen has the capacity to be a *sustainable energy vector* in all forms of mobility.

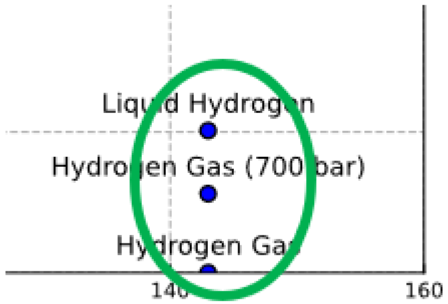
Some estimates point at 24% of Europe's energy needs will come from hydrogen by 2050. [1]

[1]Hydrogen Roadmap Europe – A sustainable pathway for the European energy transition, Ful Cells and Hydrogen Joint Undertaking, 2019

For MOBILITY applications, Hydrogen is attractive because:

- 1- Fast refueling
- 2- Zero tailpipe emissions
- 3- High specific energy density





Hydrogen

High Specific Energy *DENSITY*
(Constant energy per weight(!))

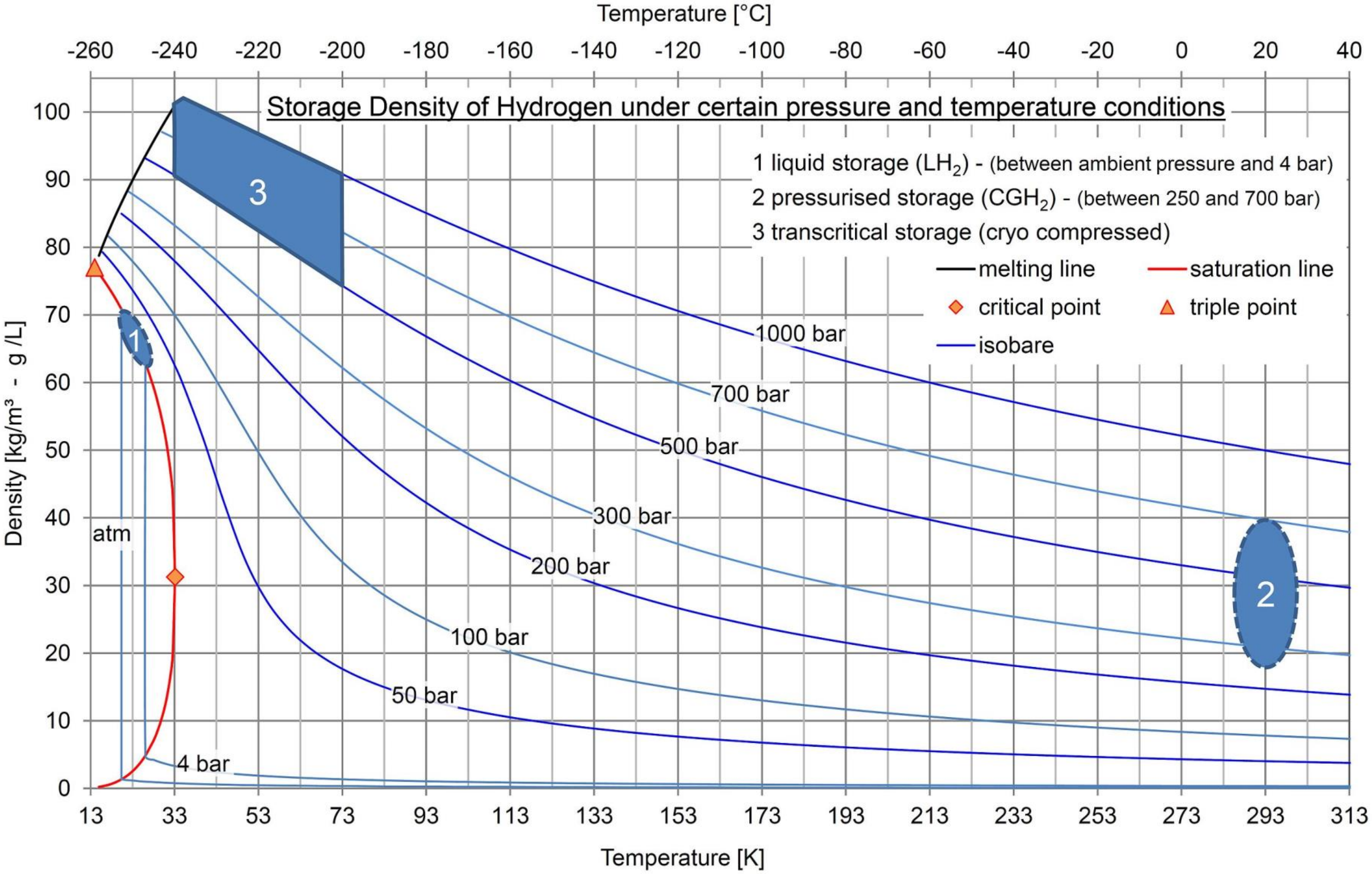
LOW energy per unit *VOLUME*

→ ***REDUCE VOLUME***

Liquify

Cryo-Compress

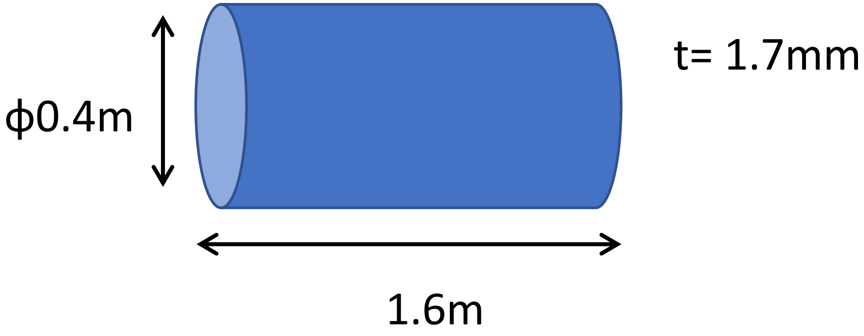
High Pressure Gas



Tank Size:

Ex: Heavy vehicle for transport

~35 MJ/L Diesel
200L Tank
→ 7000 MJ "liquid energy"
→ 170 kg Fuel, + ca 30 kg tank weight



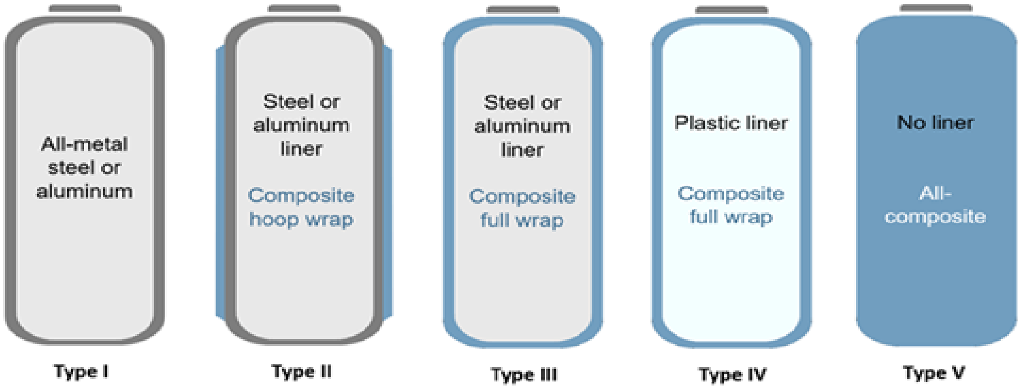
7000 MJ H2 → 48 kg H2

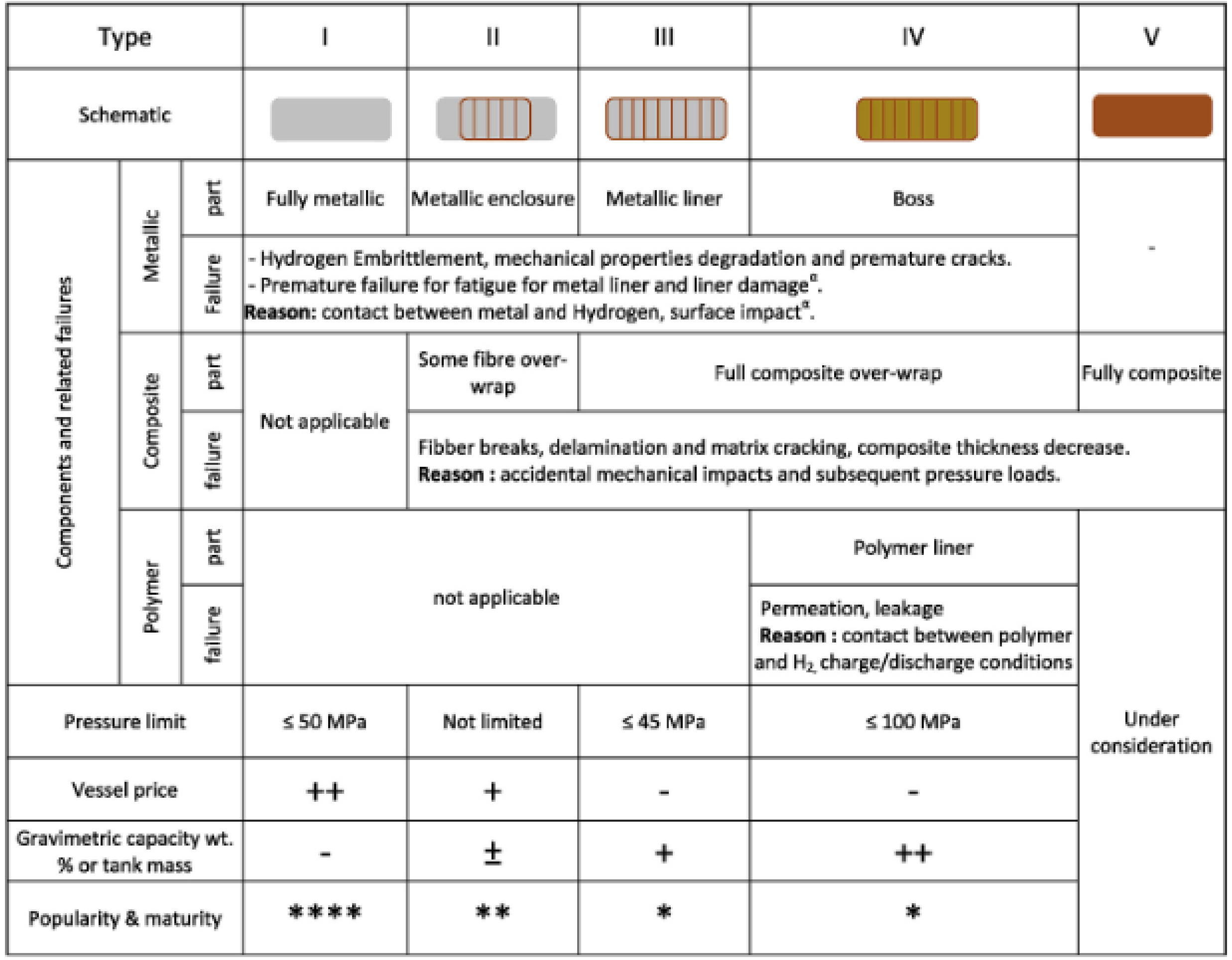
Liquid Hydrogen: ρ ≈ 68 kg/m3
→ 0.7 m3 or 700 L of tank volume…

Cryo-Compressed: ρ ≈ 90 kg/m3
→ 0.5 m3 or 500 L of tank volume…

High Pressure Gas (700Bar): ρ ≈ 30 kg/m3
→ 1.6 m3 or 1600 L of tank volume…

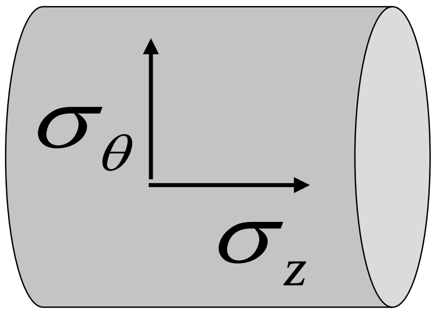
Tank Types:





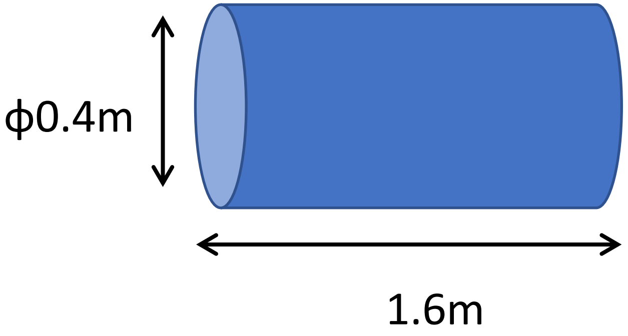
Type			I	II	III	IV	V
Schematic			▭	▥	▥	▥	■
Components and related failures	Metallic	part	Fully metallic	Metallic enclosure	Metallic liner	Boss	-
		Failure	- Hydrogen Embrittlement, mechanical properties degradation and premature cracks. - Premature failure for fatigue for metal liner and liner damage$^{\alpha}$. **Reason:** contact between metal and Hydrogen, surface impact$^{\alpha}$.				
	Composite	part	Not applicable	Some fibre over-wrap	Full composite over-wrap		Fully composite
		failure		Fibber breaks, delamination and matrix cracking, composite thickness decrease. **Reason :** accidental mechanical impacts and subsequent pressure loads.			
	Polymer	part	not applicable			Polymer liner	Under consideration
		failure				Permeation, leakage **Reason :** contact between polymer and H_2 charge/discharge conditions	
Pressure limit			≤ 50 MPa	Not limited	≤ 45 MPa	≤ 100 MPa	
Vessel price			++	+	-	-	
Gravimetric capacity wt. % or tank mass			-	±	+	++	
Popularity & maturity			****	**	*	*	

Tanks & Pressurization:

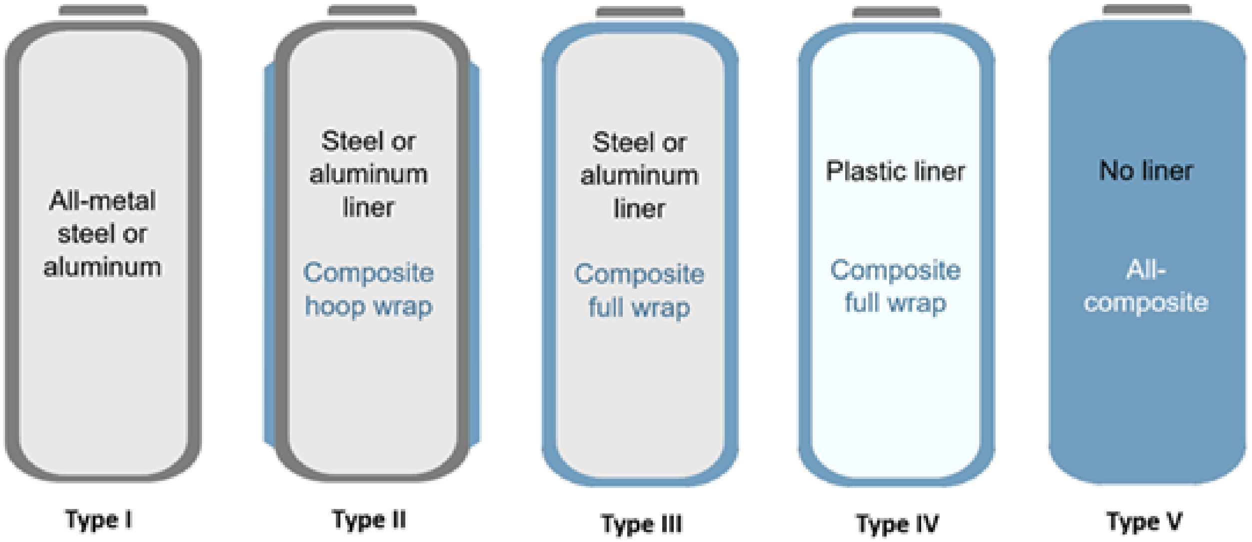


P= 750 Bar

$$\boxed{\sigma_\theta = 2\sigma_z = \frac{p\,D}{2t}}$$



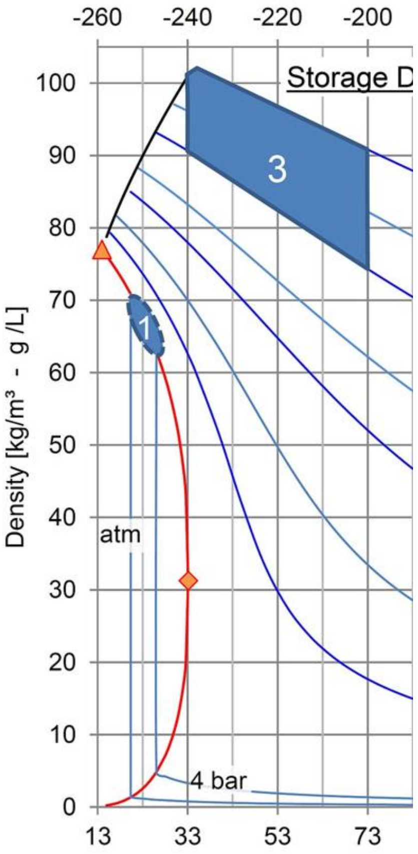
t=?



Steel:
σ_y=355 MPa
t ≈ 22 mm
m = 390kg

Composite:
σ_f =625 MPa
t ≈ 12 mm
m = 50kg

Tanks & Temperature:



Liquid Hydrogen: 20K (-253°C)

Cryo-Compressed Hydrogen: 33-73K (-240 °C to -200 °C)

Thermal stresses

Max stress for CFRP
cross-ply layup

$$\sigma_{2T} \approx E_2 \alpha_2^* \Delta T$$

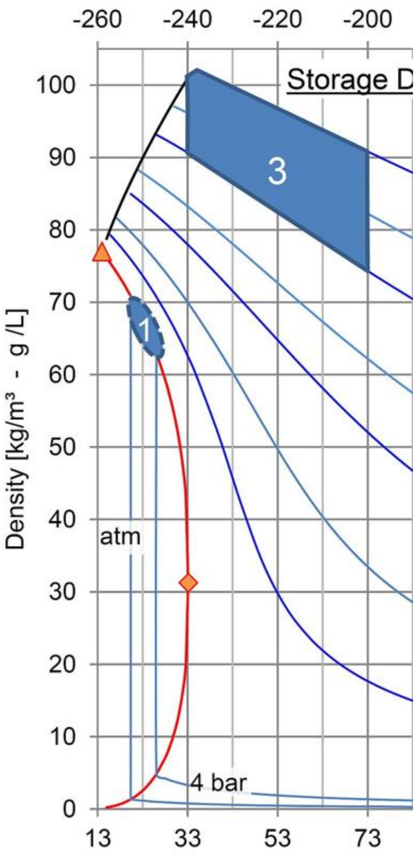
where $\alpha_2^* = \alpha_2 - \alpha_{Lam}$
Example:
$E_2 = 10\text{GPa}$
$\alpha_2 = 27 \cdot 10^{-6}/\text{K}$
$\alpha_{Lam} \approx 2 \cdot 10^{-6}/\text{K}$
$\Delta T = 363\text{K} - 20\text{K} = 343\text{K}$
$\Rightarrow \sigma_{2T} \approx 86\text{MPa}$

For low temperatures, special materials may be required (thin-ply laminates) to withstand thermal stresses.

LH2→ Higher thermal stresses , lower pressure

CCH2 → Lower thermal stresses, high pressure

Tanks & Temperature:



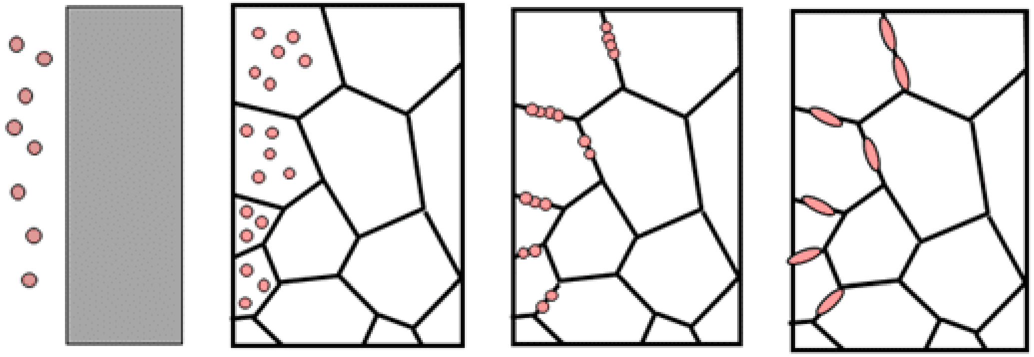
Miss-match in α_2 between tank + liner/boss/fittings → further thermal stresses

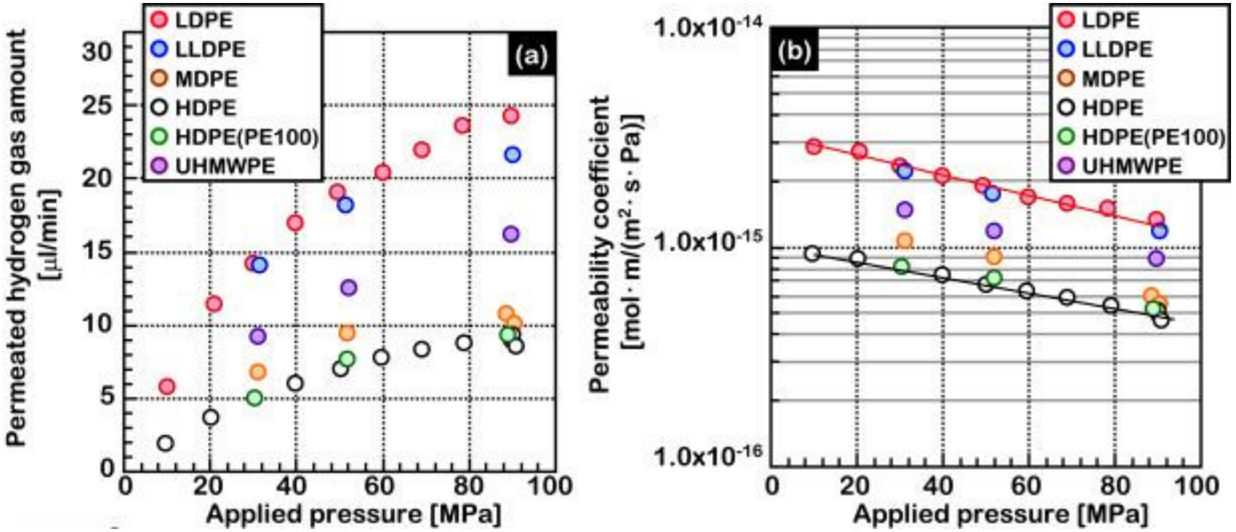
Insulation: CRITICAL factor for minimizing Boil-off of LH2, maintaining CCH2.
→Often vacuum insulated, requires a "double tanks" system

For large tanks, buckling of outer tank walls can be a challenge

Material Behaviour:

Metallic components:
Hydrogen Embrittlement (regardless of temperature)





Polymeric components:
Hydrogen permeability affected by chemistry, pressure, temperature, etc

Material Behaviour:

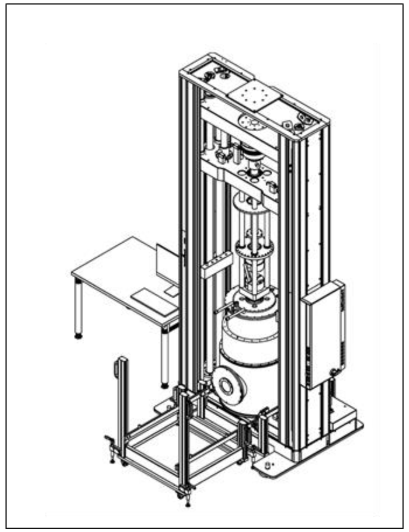
Cryogenic behaviour:
Facilities for material characterization at 20K are LIMITED

These test facilities are EXPENSIVE (large investment + large operating cost+ large safety concerns)

Cryo-temperatures effect STIFFNESS and STRENGTH of composite materials.

Micro-cracks
High transverse strains can lead to *microcracks*
(Very large ΔT, very high pressures, cyclic loading, etc)

Microcracks can lead degraded material properties
And provide pathways for hydrogen molecules to escape



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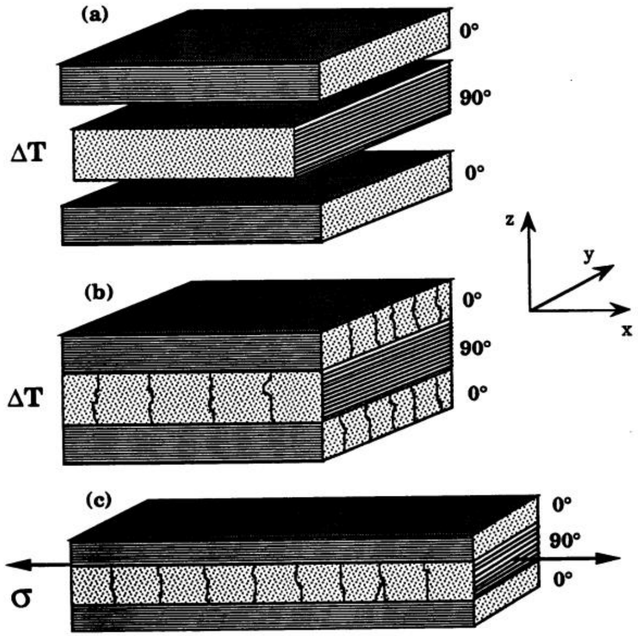
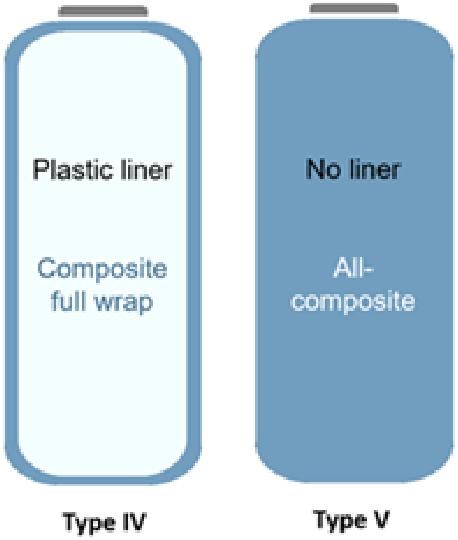
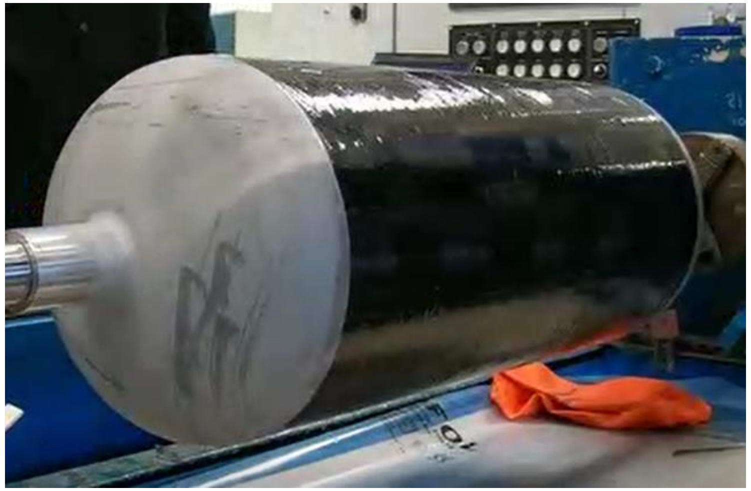


Manufacturing Methods





Type IV- Polymer Liner + Composite Overwrap

Type V- All composite, liner-less

5kg Hydrogen Tank → 10Kg CF + 5kg Resin
Production speed limited to 1-1.5m/s

→ 90 minutes to produce a single tank

Type IV tanks most promising industrial solution:
- Established technology (wet filament winding)
- User of liner provides possibilities for barrier, and “built in mandrel”

Design Methods:

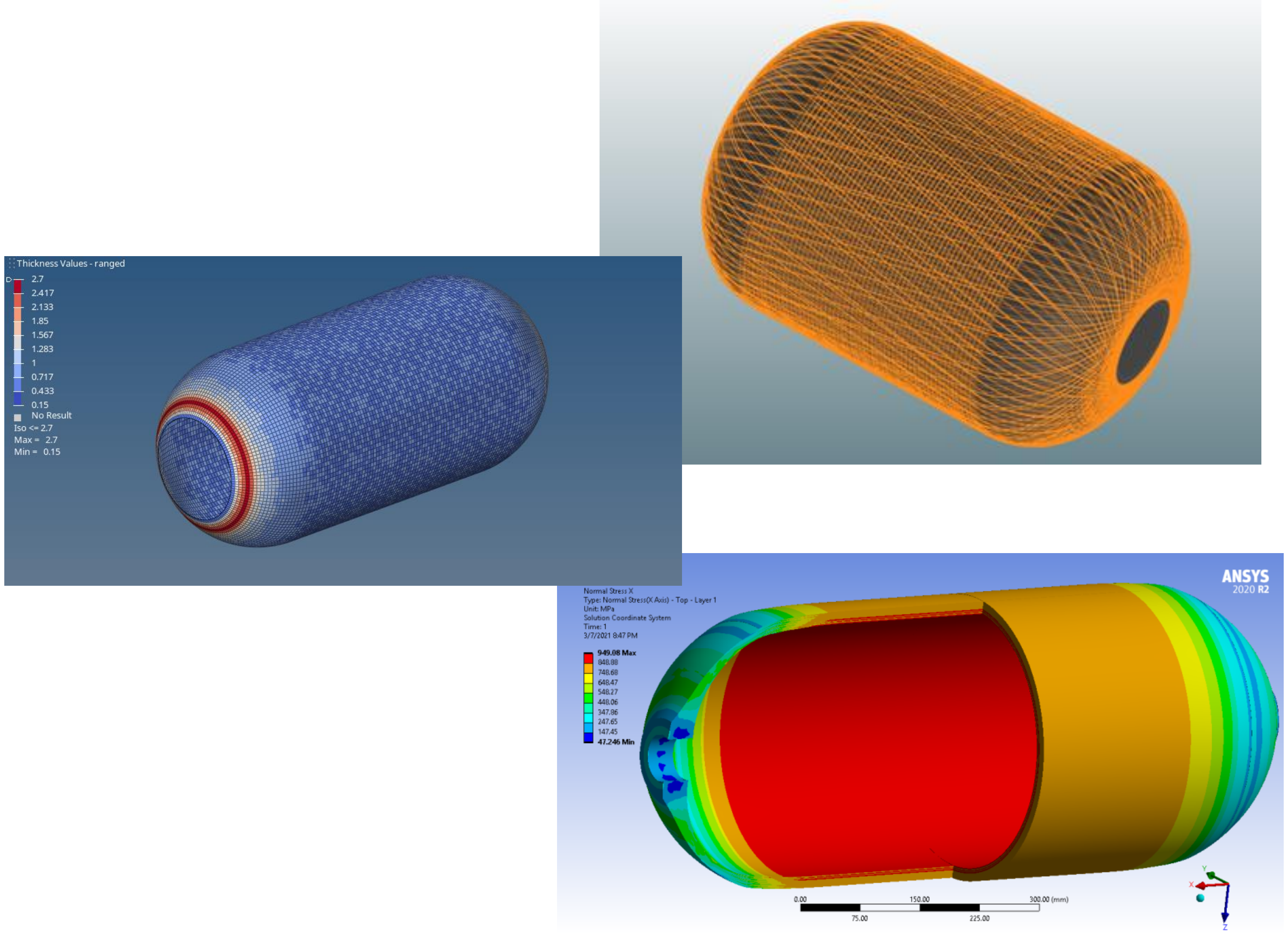
Tank geometry dictates critical manufacturing parameters.

Manufacturing process changes alter material properties

Material properties are not “constant” anywhere on an overwrapped tank

Current FE based methods are still primitive, rely on analytical simplifications for first estimates.

There are no well developed models to predict e.g. failure onset at transition region of tank.



Health Monitoring

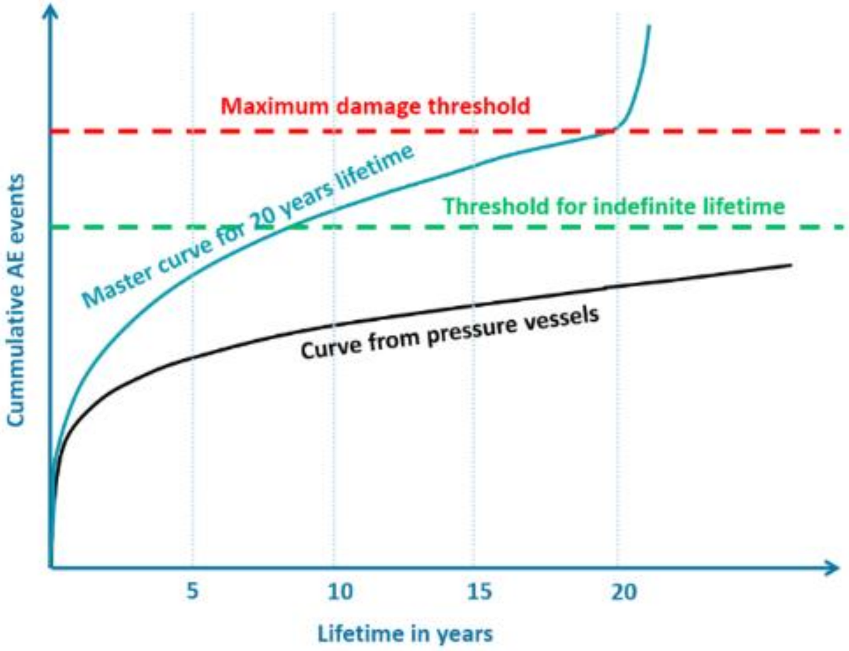
Once a tank is manufactured it needs to be monitored to makes certain it is functioning well. How can this be done?

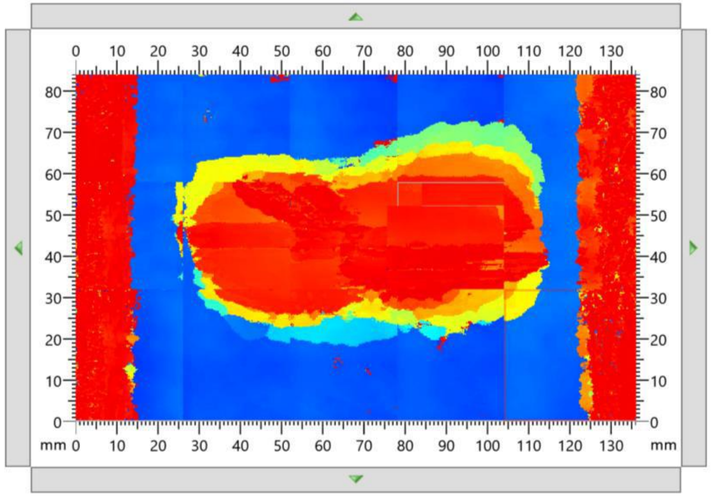
In-Situ Health Monitoring?

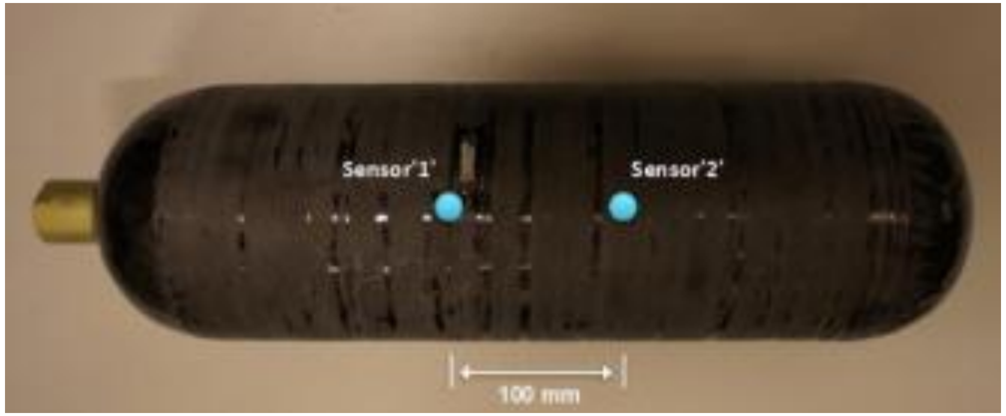
Burst pressure testing vs lifetime use?

Periodic inspection technologies?

Integrated sensors, AI, preventative maintenance?







Damage Repair

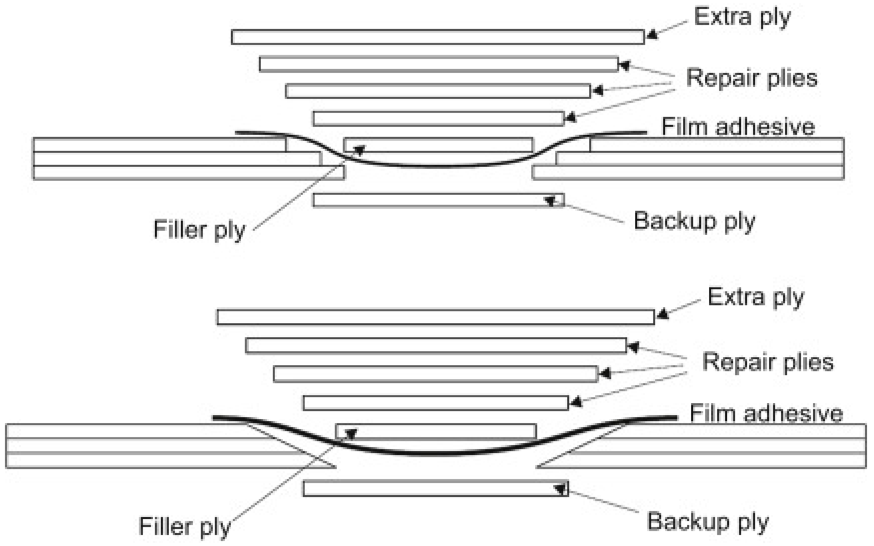
Composite tanks are expensive and time consuming to manufacture.

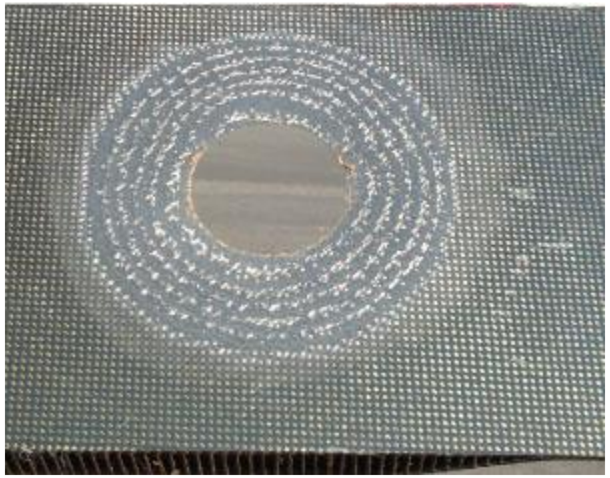
They have a very large CO2 footprint which requires a long lifetime to offset.

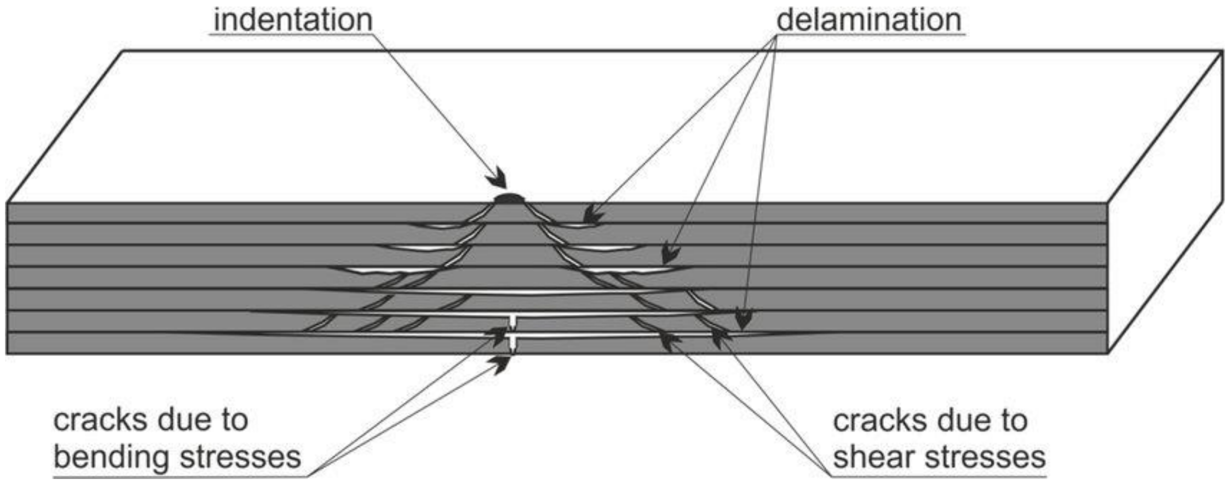
Can they be repaired?

If so how large can damage be?

How could a repair be certified?







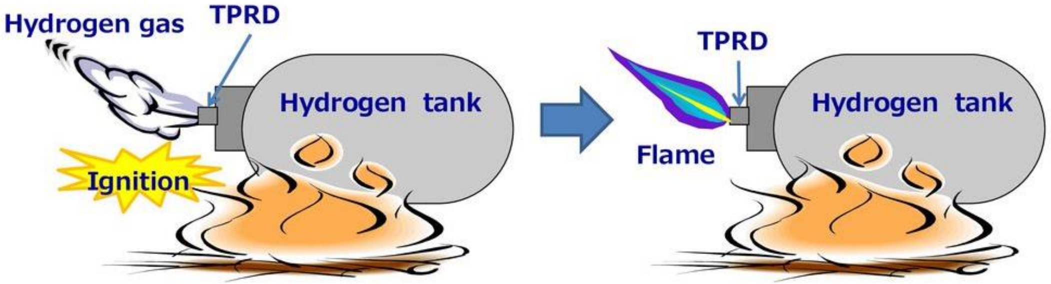
Fire Safety

Current technology relies on Thermally activated Pressure Relief Devices (TPRD) in case of vessel overheating.

What happens if these fail?

What does the safety situation look like with full scale roll-out of hydrogen powered mobility?

Electric vehicles were “feared”….now they are mainstream.



Sustainability

Lightweight gas→ High pressure required
Liquid transport→ -253°C, boil-off
Cryo-compressed→ Cold + high pressure

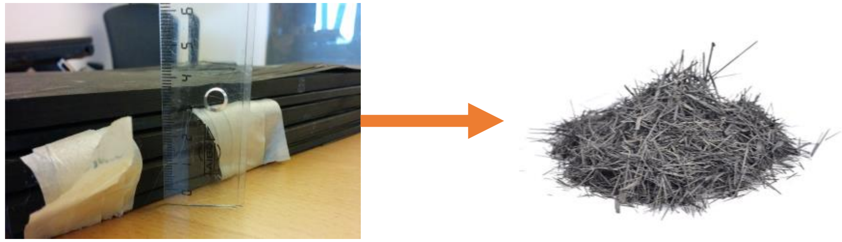
Todays most promising state of the art technologies are NOT CIRCULAR

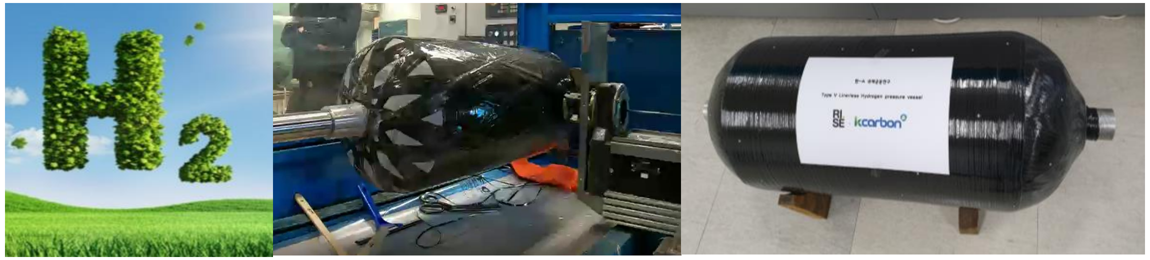
Are they SUSTAINABLE?

Material recycling?

Repurposing?

Re-Use?





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Material Availability…

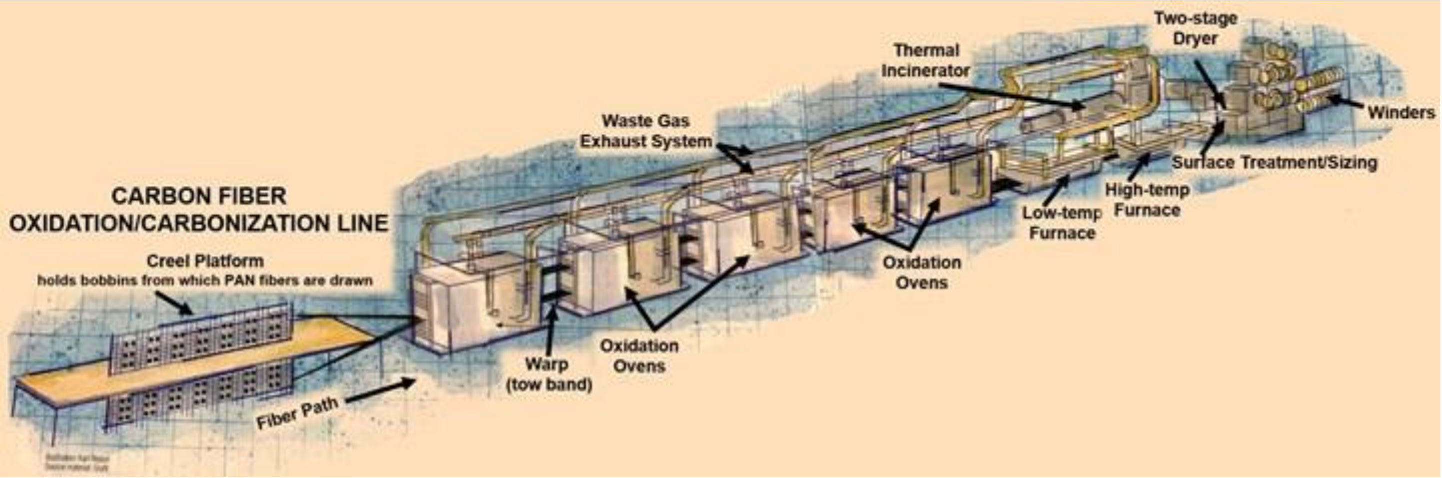
Data from 2021:

Supply from US, EU, Japan, China in 2023: **125 000** Tonne

Demand: Driven by wind turbines, investment in wind farms etc.

Estimated **Demand** 2026: **180 000** Tonne

POTENTIAL shortfall in terms of CF availability- may be a hinder to large scale tank manufacture?
Cost, availability, quality, etc…



Conclusions:
What challenges exist for widespread adoption of hydrogen in mobility?

Technical Challenges:

High pressures → high performance materials
High strength composites + polymer liners + H2 resistant steels need to be used. Some materials and technologies already exist, refinement needed for robust implementation at 700+ Bar

Liquid Hydrogen → Cryogenic materials need to be developed
Space has been using liquid hydrogen since 1960’s. Single mission ≠ 20 years of re-use (and abuse…)
ROBUSTNESS and COST will be driving factors

Leakproof Vessels → Long term
Hydrogen is uniquely challenging in keeping contained, molecules are small and react with many materials. Quality control is a first step, long term behaviour?

Health Monitoring →
What systems can we use to keep track of expensive vessels and make sure they are not decommissioned too early (or too late…)

Technical Challenges:

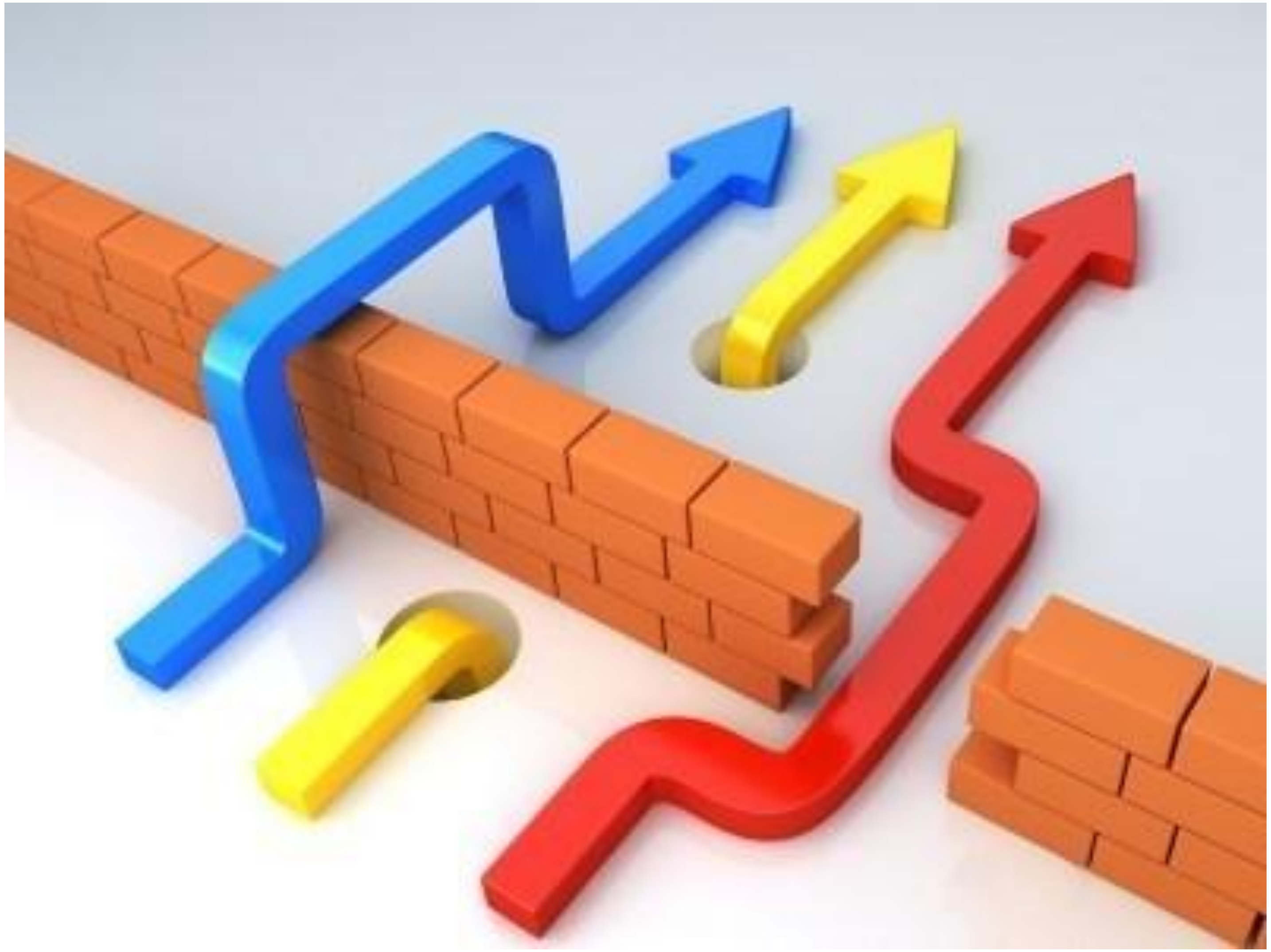
Design methods connected to Manufacturing →
How can we used advanced FE tools to predict potential areas of damage in Type IV and V vessels prior to even making them? The cost to "learn by experience" will be too high

Sustainability→
If H2 should be a "green wave", tanks cannot be the next wind turbine blade. Can we use other materials? Can we refurbish? When is a high-performance materials needed and when is virgin CF from fossil based sources *actually* the more sustainable choice?

Fire Safety →
Will widespread implementation of high-pressure or liquid hydrogen tanks lead to new safety challenges? Regulatory? Health and Safety? Is it better or worse than batteries?

Material Availability→
When CF is underproduced, and costs are excessive, how do we provide cost effective sustainable solutions?

CHALLENGES are not the same as ROADBLOCKS



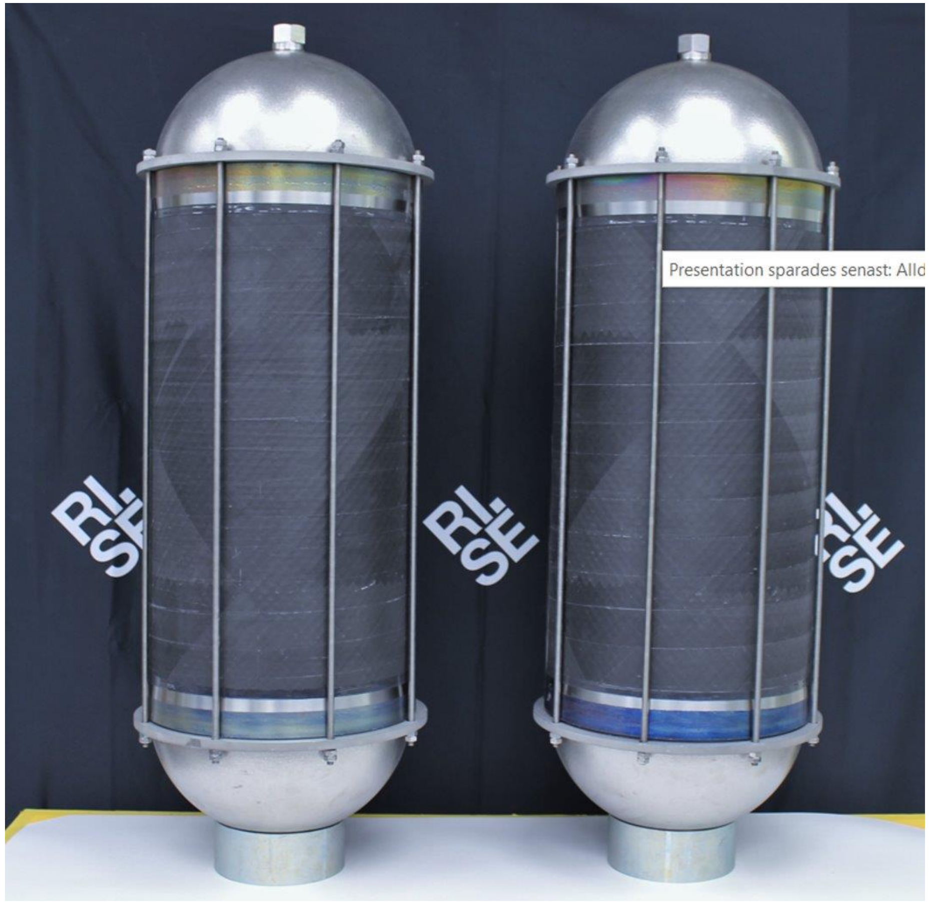
We have:

45% more researchers in 2021 than 2011 in Europe[1]

A widespread acceptance and desire for changes in mobility sector AND energy sector to eliminate reliance on fossil fuels

So many lessons learned from previous jumps in technology.

The Future for Hydrogen in Mobility is bright!



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