



University of  
**Nottingham**  
Energy Institute

THE 7th CLEAN ENERGY SCIENCE LECTURE  
AND SEMINAR OF THE FERF COMBUSTION INTEREST GROUP

# Solid-State Hydrogen Storage: From Discovery to Deployment

What changes when the storage material  
becomes part of the energy system?

Marcus Adams





# Contents

- The storage problem
- Brief timeline of solid-state material discovery
- What of the system engineering?
- Deployment realities and commercialisation

# The Storage Problem

Comparing hydrogen vectors: Solid-state shifts storage from an inert tank to an active reactor.



## Compressed Gas

350 – 700 bar

Volumetric Density:

23 – 40 kg H<sub>2</sub>/m<sup>3</sup>

Energy Penalty:

10 – 15% LHV

Operating Conditions:

350–700 bar | Ambient

### CHALLENGES

- Volume
- Cost of tanks
- High P (safety)



## Liquid H<sub>2</sub> (LH<sub>2</sub>)

Cryogenic (-253 °C)

Volumetric Density

≈ 70 kg H<sub>2</sub>/m<sup>3</sup>

Energy Penalty:

30 – 40% LHV

Operating Conditions:

1–10 bar | 20 K (-253 °C)

### CHALLENGES

- Boil-off
- Cost of liquefaction
- Low T (safety)



## Chemical Carriers

E.g. LOHC / Ammonia

Volumetric Density:

≈ 50 – 120 kg H<sub>2</sub>/m<sup>3</sup>

Energy Penalty:

25 – 35% LHV

Operating Conditions:

Ambient | Cracking >250°C

### CHALLENGES

- Complex Process Engineering
- Material handling
- Catalysts (noble)



## Solid-State

Hydrides

Volumetric Density:

30 – 120 kg H<sub>2</sub>/m<sup>3</sup>

Energy Penalty:

Enthalpy (possible waste heat)

Operating Conditions:

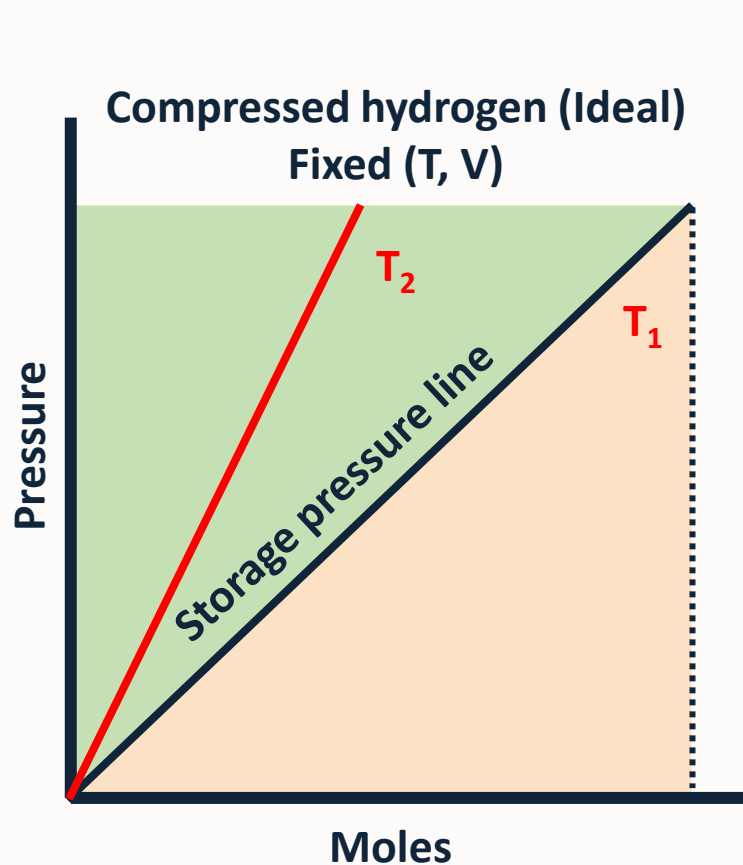
1–100 bar | 20-300 °C

### CHALLENGES

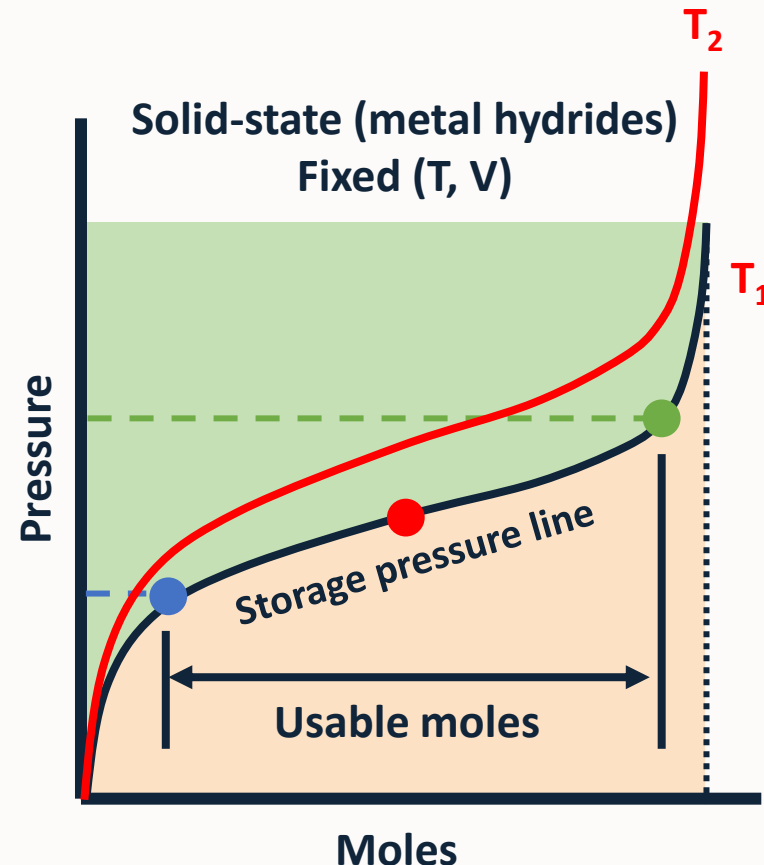
- Better materials
- Engineering scale-up
- Cost (both material & system)



# Quick overview of Hydrides



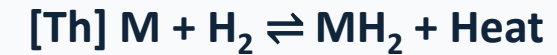
$$P = (RT/V) n$$
$$[y = (m) x]$$



$$P = \exp (\Delta H / RT - \Delta S / R)$$

The operating conditions depend:

- (1) Thermodynamics (floor) [Th]
- (2) Kinetics (added penalty) [Ki]



[Th]  $\Delta H$  &  $\Delta S$

[Th] T(8 bar) = 25 °C ●

[Th] TO CHARGE: 10 bar @ 25 °C ●

[Th] TO DISCHARGE: FC @ 4 bar @ 25 °C ●

But...

[Ki+Th] CHARGE: 20 - 30 bar @ 30-35 °C

[Ki+Th] DISCHARGE: 5 bar @ 40-80 °C

# Brief timeline of hydride discovery

## 1. ~1970S – 1980S

### AB<sub>5</sub>, AB & AB<sub>2</sub> Interstitial Alloys

#### INNOVATION

Reversible room-temperature interstitial sorption (e.g. LaNi<sub>5</sub>, TiFe, TiFe<sub>2</sub> & Ti<sub>a</sub>Zr<sub>b</sub>Fe<sub>c</sub>Mn<sub>d</sub>Cr<sub>e</sub>).

#### CONSTRAINT

- Low gravimetric capacity (≈1.4–1.9 wt% H<sub>2</sub>) due to heavy transition metal weight;
- highly susceptible to oxidation poisoning.
- Cost (£1000 / kg H<sub>2</sub>)

Working Temp:

Amb. to FC waste heat

## 2. ~1990S

### Light Complex Hydrides

#### INNOVATION

Catalysed complex hydrides e.g. Ti-doped NaAlH<sub>4</sub> unlocking high theoretical gravimetric densities.

#### CONSTRAINT

- Desorption temperatures (> 150–200°C). Low volumetric density.
- Sluggish kinetics, and capacity loss over cycling (although improved).
- Lower cost than AB<sub>2</sub>

Cap. Potential:

≈ 3-7 wt% H<sub>2</sub>

## 3. ~2000S

### Physisorption (e.g. MOFs)

#### INNOVATION

Ultra-high surface area nanostructures e.g. (MOFs) enabling fast, fully reversible adsorption.

#### CONSTRAINT

Weak Van der Waals binding energy (≈ 4–10 kJ/mol) requires liquid nitrogen cryogenic temperatures (77 K) for operation.

Thermodynamic curve not ideal for storage

Operating Temp:

< Ambient temp.

## 4. ~2010S – PRESENT

### Reactive Hydride Composites

#### INNOVATION

Thermodynamic tuning of lightweight hydride combinations e.g. (xLiH + yLiBH<sub>4</sub> + zMg(NH<sub>2</sub>)<sub>2</sub>)

#### CONSTRAINT

Complex multi-phase solid-state reaction pathways, requirement for nanoconfinement, and mass transport limitations.

(xLiH + yLiBH<sub>4</sub> + zMg(NH<sub>2</sub>)<sub>2</sub>)  
(onset < 120 °C) (3 to 4 wt% H<sub>2</sub>)

Reversible Temp:

Yet to be optimised



# Hydride discovery

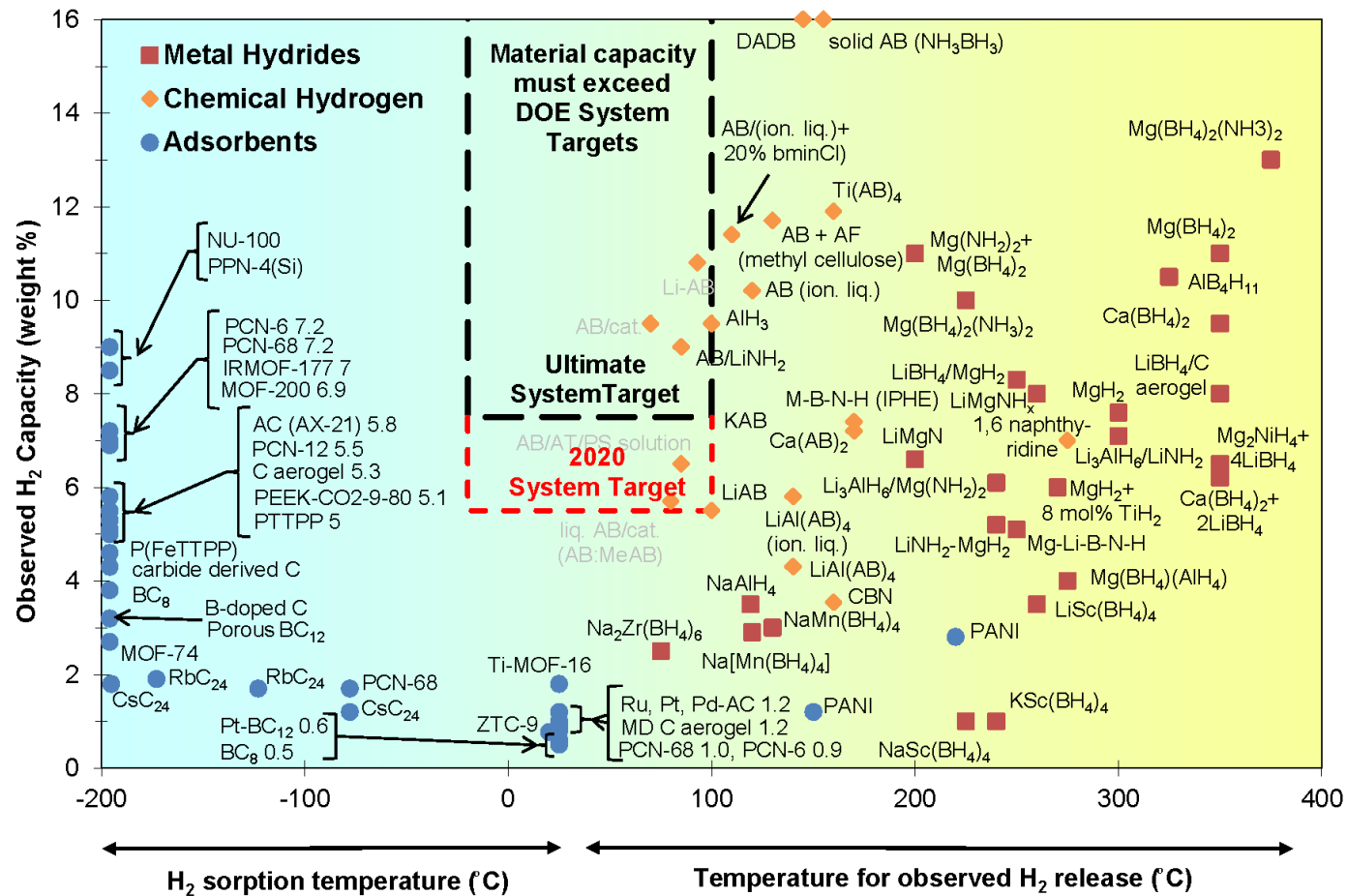


Chart shortly before 2019

Some updates since then, but generally, the target for system targets for vehicles remains elusive

There has been a research pivot away from solely focusing on this

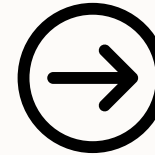
# What about system engineering?

## Compact Tank Engineering

- 1 Containment
- 2 Kinetics

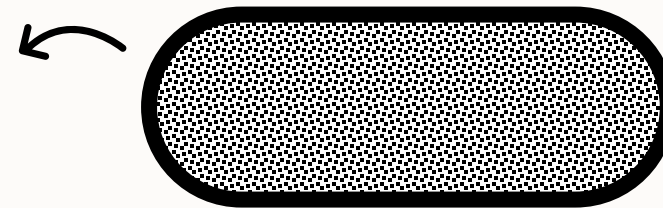
Hydride kinetics  
are a function of  
heat transfer

Want fast  
discharge/charge?  
**Remove/input heat fast**



Tank thermal  
design is central

Powder in a gas cylinder, good?





# Thermal resistance

## Thermal conductivity

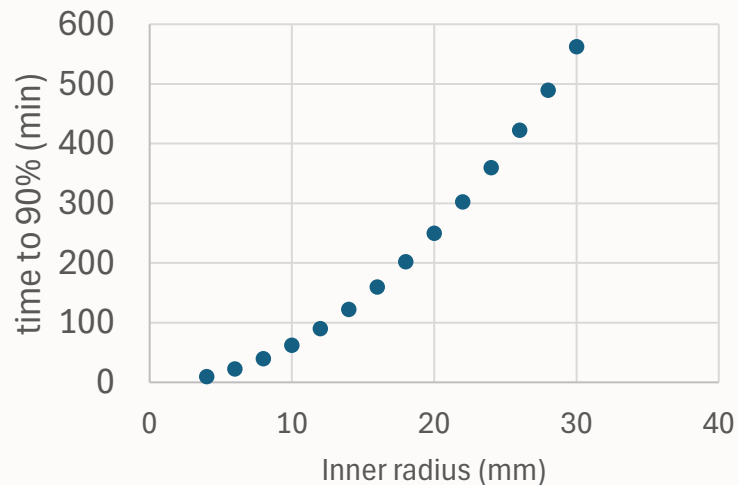
Bare tube

$$time \propto \frac{R^2}{\left(\frac{k_{eff}}{\rho C_p}\right)}$$

Inner tube radius

Effective thermal diffusivity of packed hydride

$$\frac{t_2}{t_1} = \left(\frac{R_2}{R_1}\right)^2 \longrightarrow t = t_{ref} \left(\frac{R}{R_{ref}}\right)^2$$

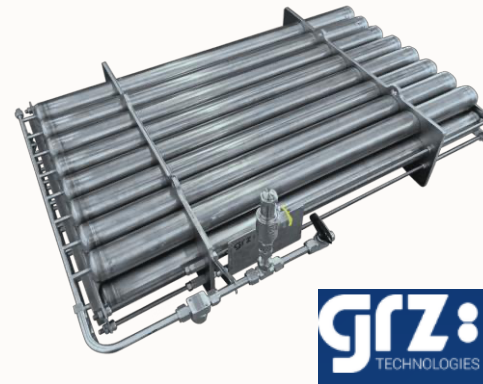


## Thermal contact

Compacts?

Effective thermal conductivity 5 – 10 W m<sup>-1</sup> K<sup>-1</sup>

$$R_{total} = \frac{1}{h_{cond}} + \frac{1}{h_{tc}}$$



Thermal expansion/contraction during cycling creates micro-gaps

$$h_{tc} \sim 200 - 1000 \text{ W m}^{-2} \text{ K}^{-1}$$



# What about system engineering?

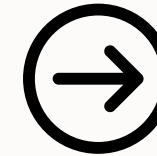
## Compact Tank Engineering

1 Containment

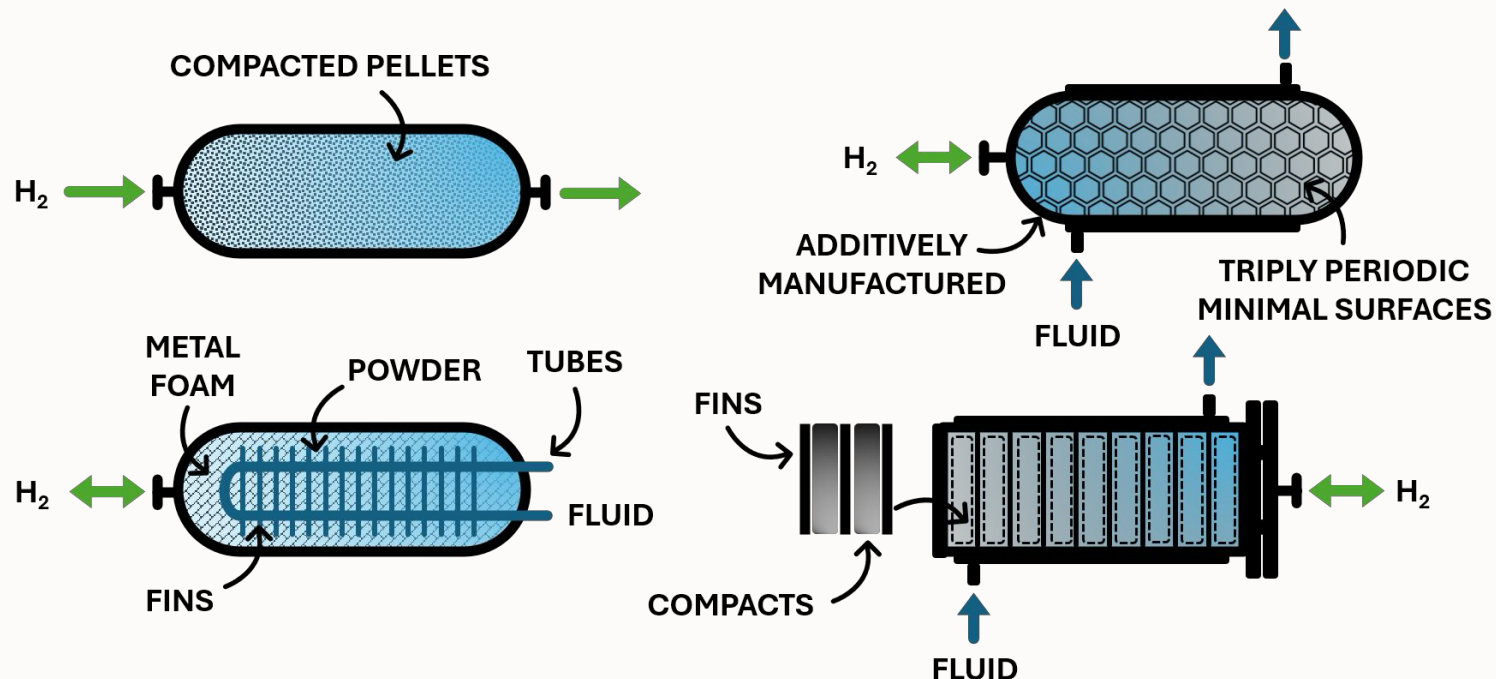
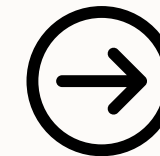
2 Kinetics

Hydride kinetics  
are a function of  
heat transfer

Want fast  
discharge/charge?  
**Remove/input heat fast**



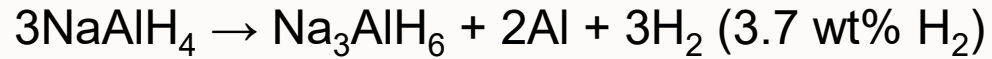
Tank thermal  
design is central



Movement of  
thermal energy

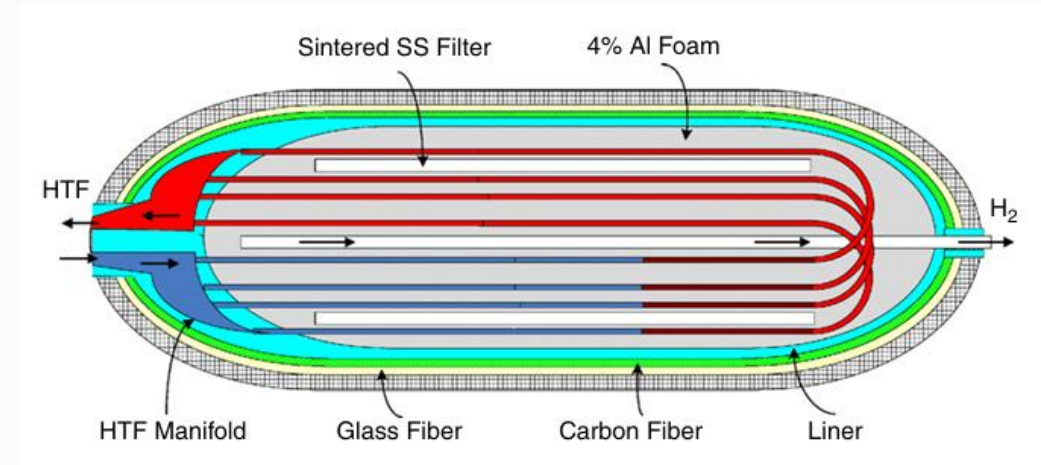
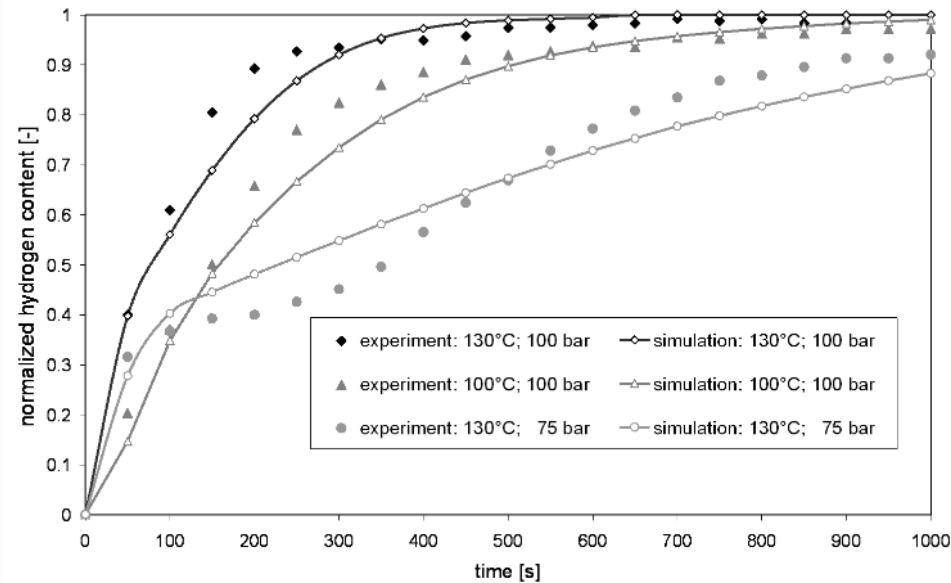
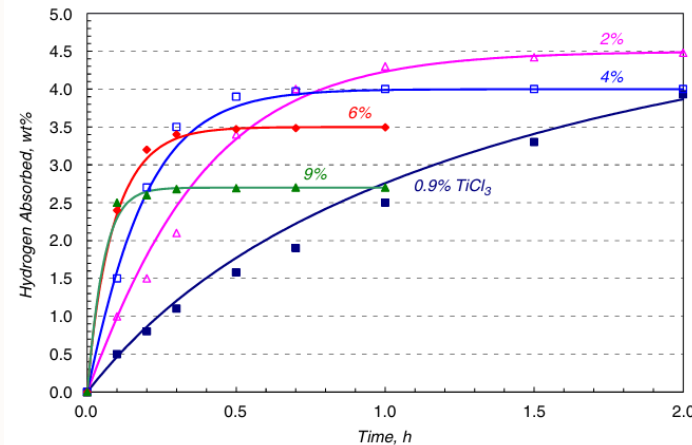
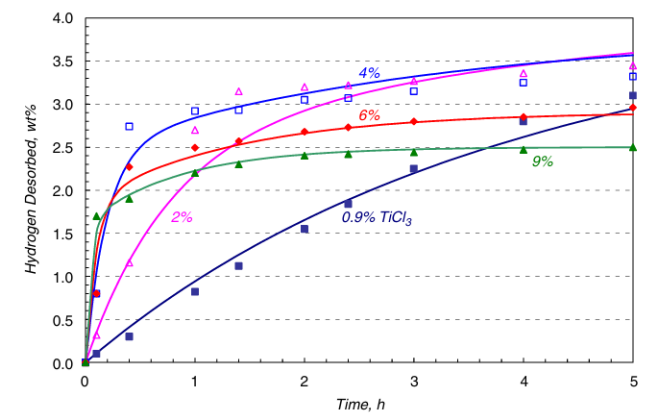


# NaAlH<sub>4</sub> past prototypes



Ti-doped Catalyst

$$\Delta H = 37 \text{ kJ mol}^{-1}$$

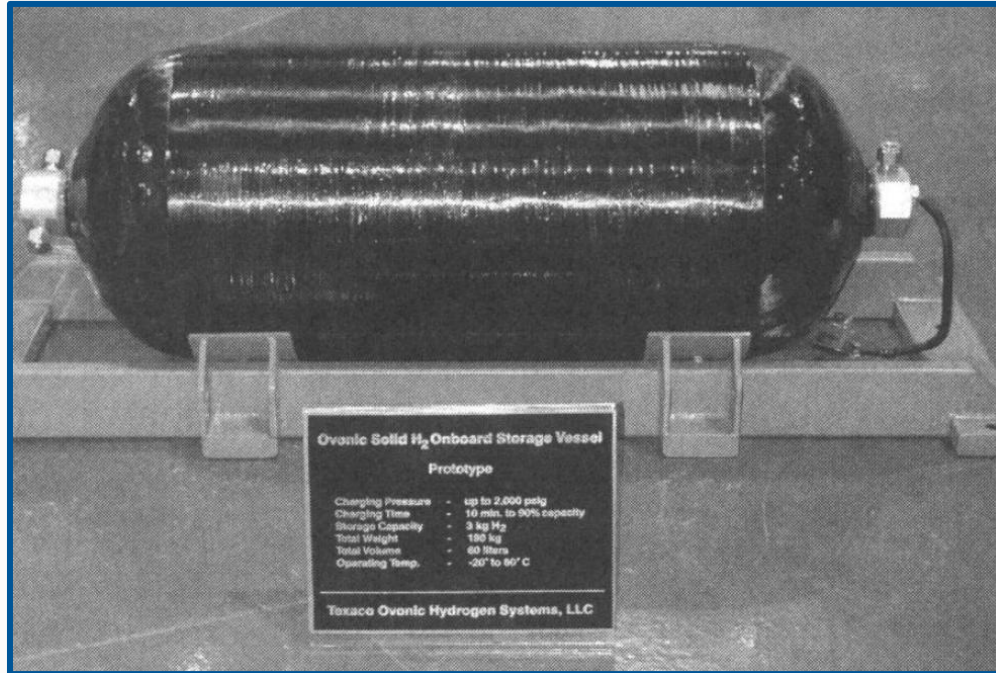
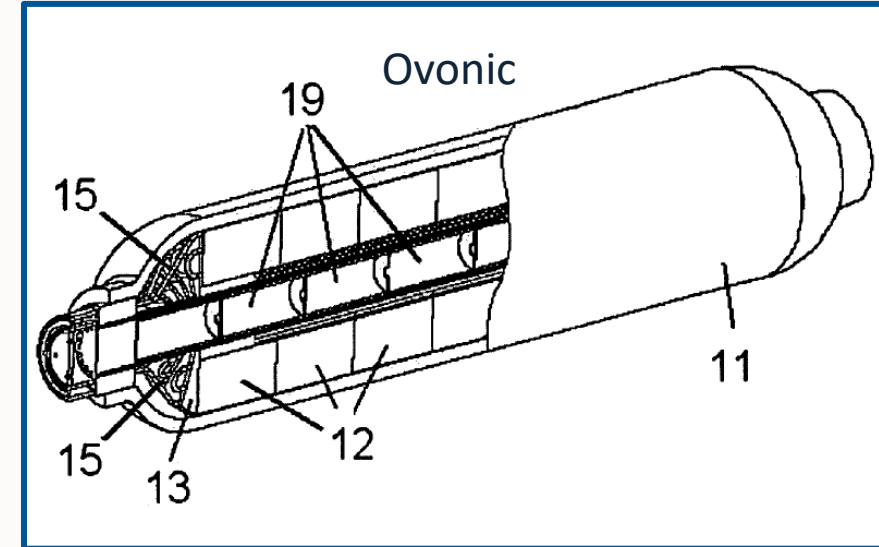
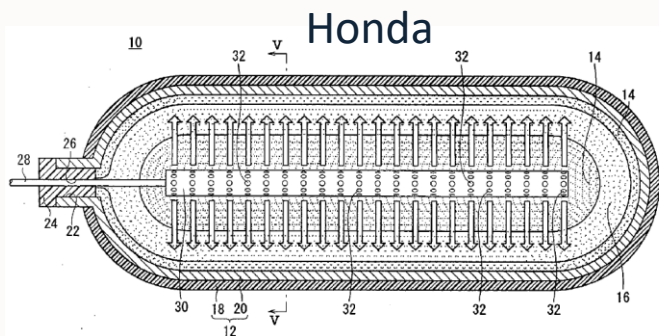
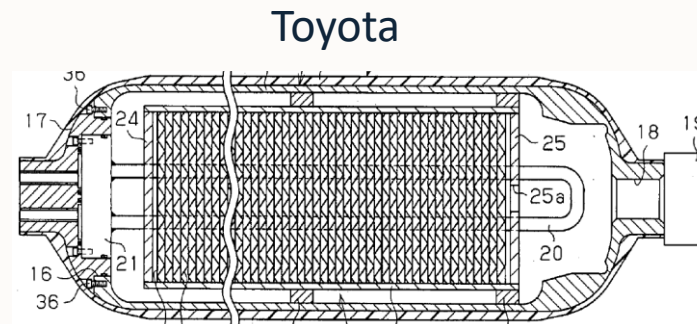


Ranong, C., Höhne, M., Franzen, J., Hapke, J., Fieg, G., Dornheim, M., Eigen, N., & Metz, O. (2009). Concept, Design and Manufacture of a Prototype Hydrogen Storage Tank Based on Sodium Alanate. *Chemical Engineering & Technology*, 32, 1154-1163.  
<https://doi.org/10.1002/ceat.200900095>

Ahluwalia, R. (2007). Sodium alanate hydrogen storage system for automotive fuel cells. *International Journal of Hydrogen Energy*, 32, 1251-1261. <https://doi.org/10.1016/j.ijhydene.2006.07.027>



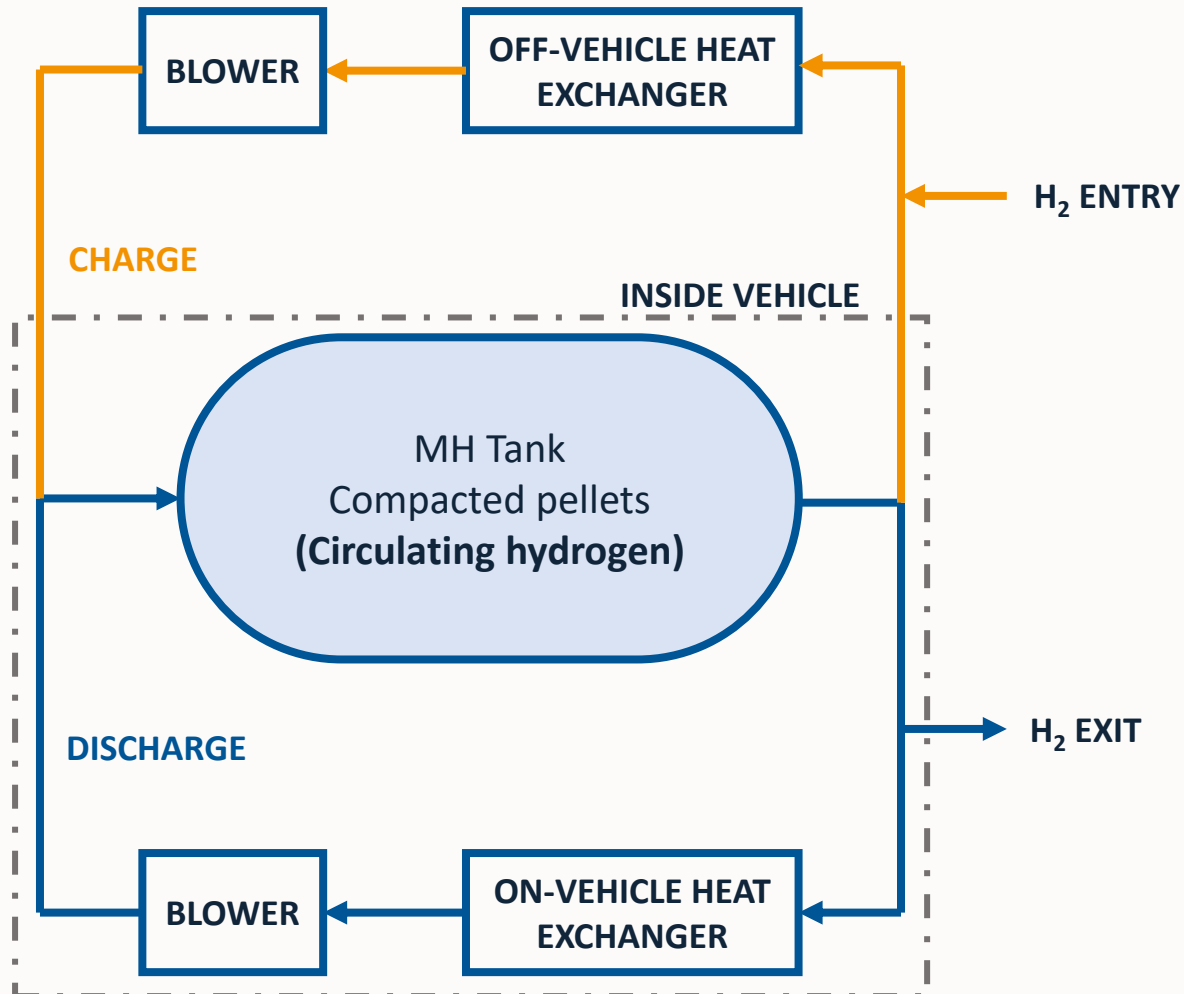
# Heat transfer vs Engineering Cost



All designs are complicated  
→ expensive but how expensive?



# System Design (example)



- Tank ID = 55 cm
- Total tank length = 124 cm
- Blower/compressor a key challenge.

## CHARGE (15 mins)

- Circulation flow = 1180 kg/h
- 143 kW heat exchanger (off board)

## DISCHARGE (10 hours)

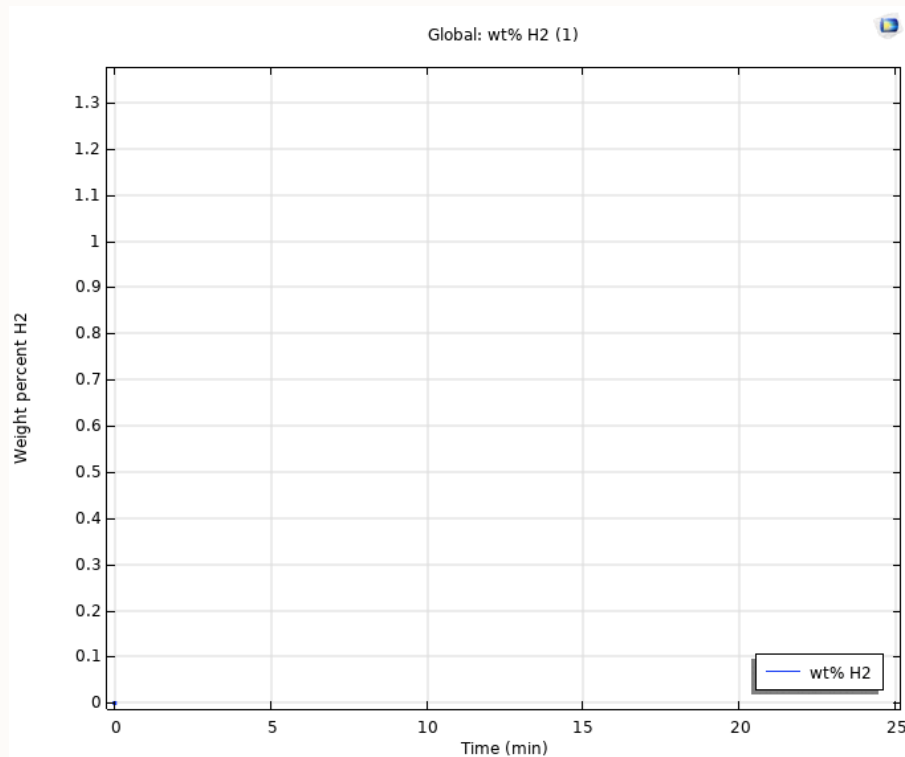
- Circulation flow = 90 kg/h
- Hydrogen flow to engine = 1 kg/h
- 3.6 kW heat exchanger (on board)



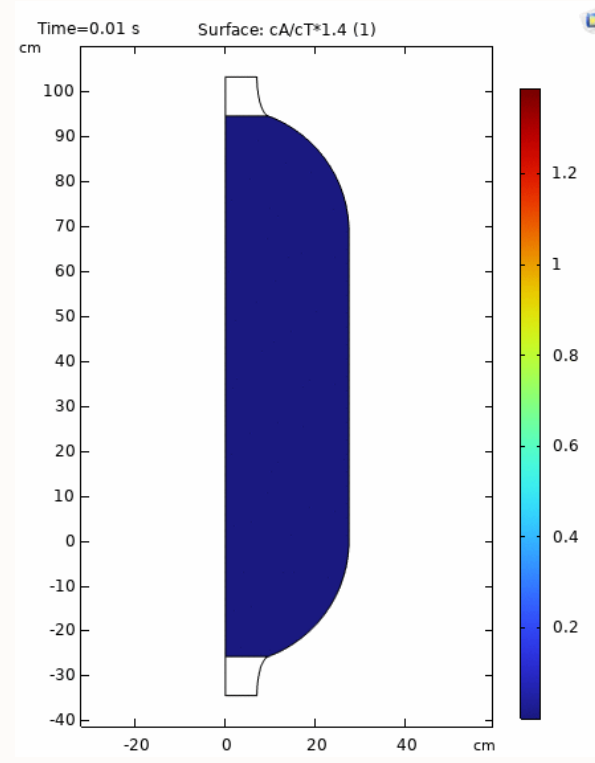
# System Design Simulation (example)

## Charging profile

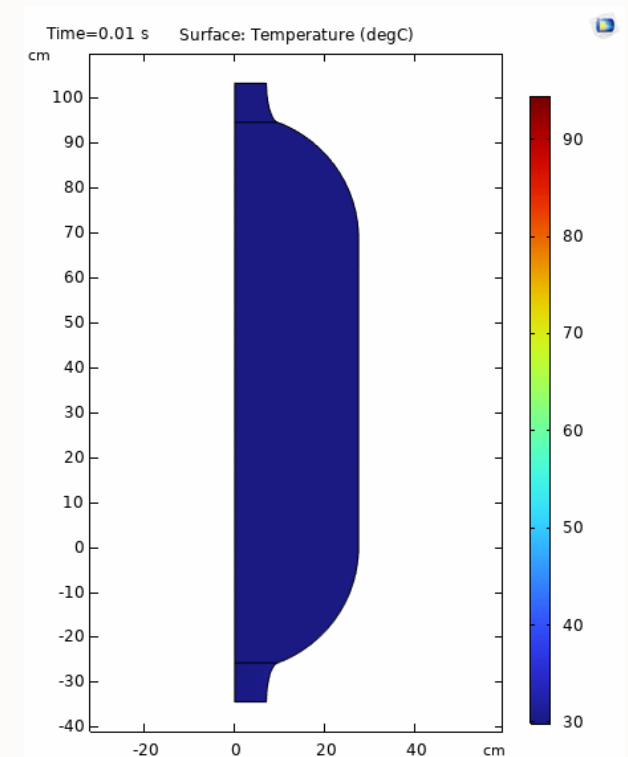
wt% H<sub>2</sub> profile



wt% H<sub>2</sub> profile



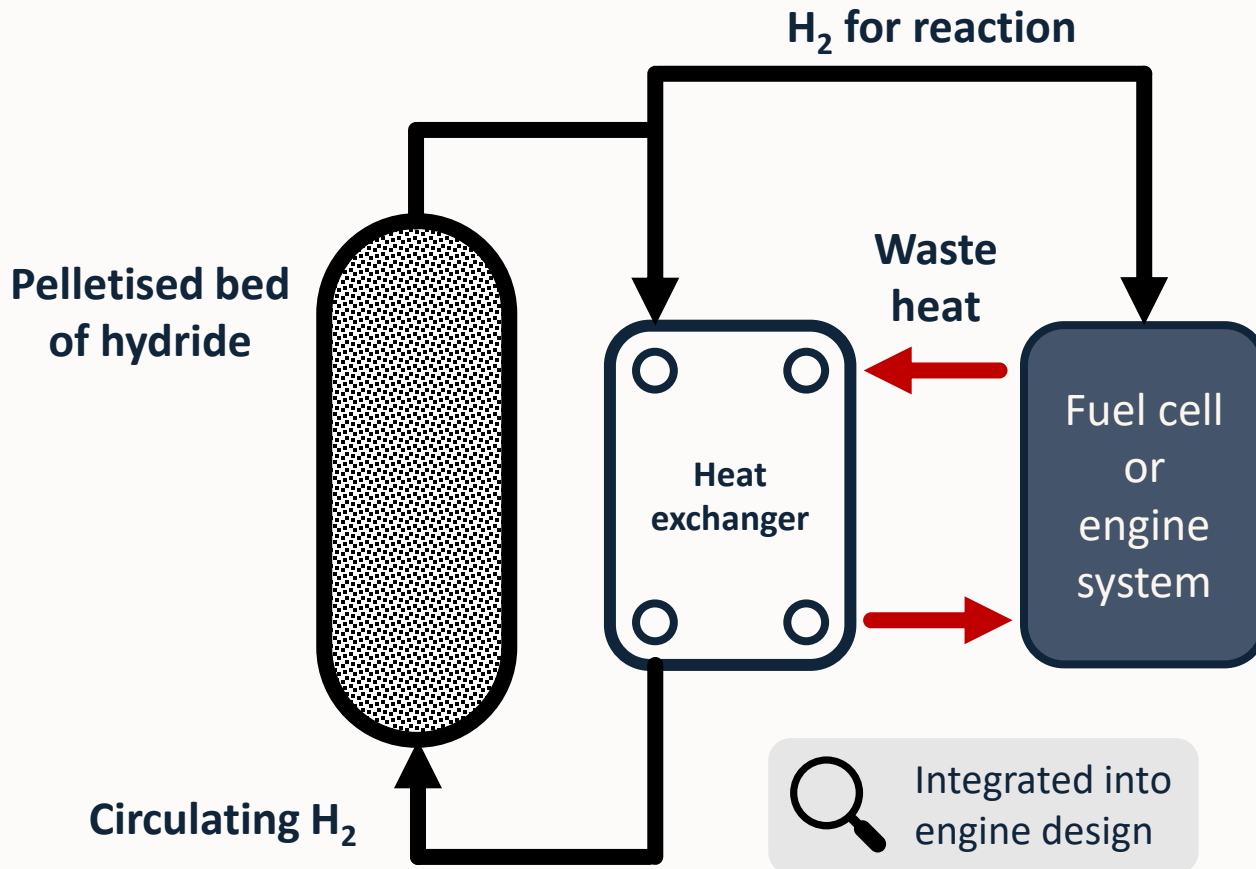
Temperature profile





# System Design (example)

## Dehydrogenation (discharge of tank)



**1** Hydrogenation (charge) has the same layout, but waste heat is released to environment or used

**2** Thermal Power

Discharge

2 h  
10 kW

Charge

10 min  
125 kW

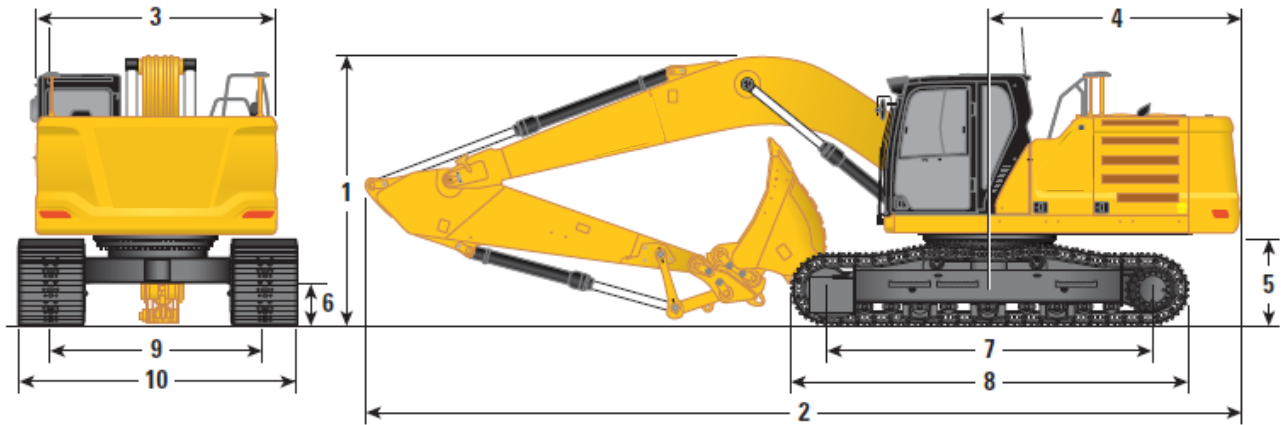
\*Based on 30 kJ/mol H<sub>2</sub> and 5 kg H<sub>2</sub> tank

**3** **A thermodynamic bottleneck**  
Refuelling system needs to dissipate a lot of heat, or a centralised facility to “move fuel” – slurry etc.

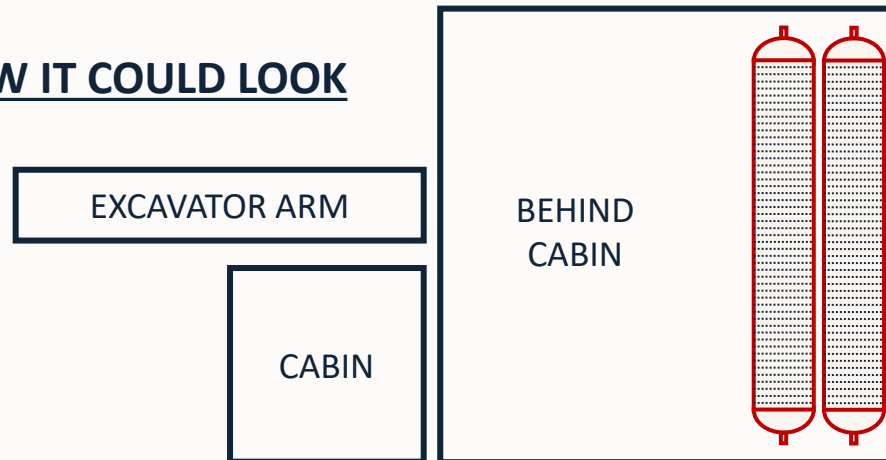
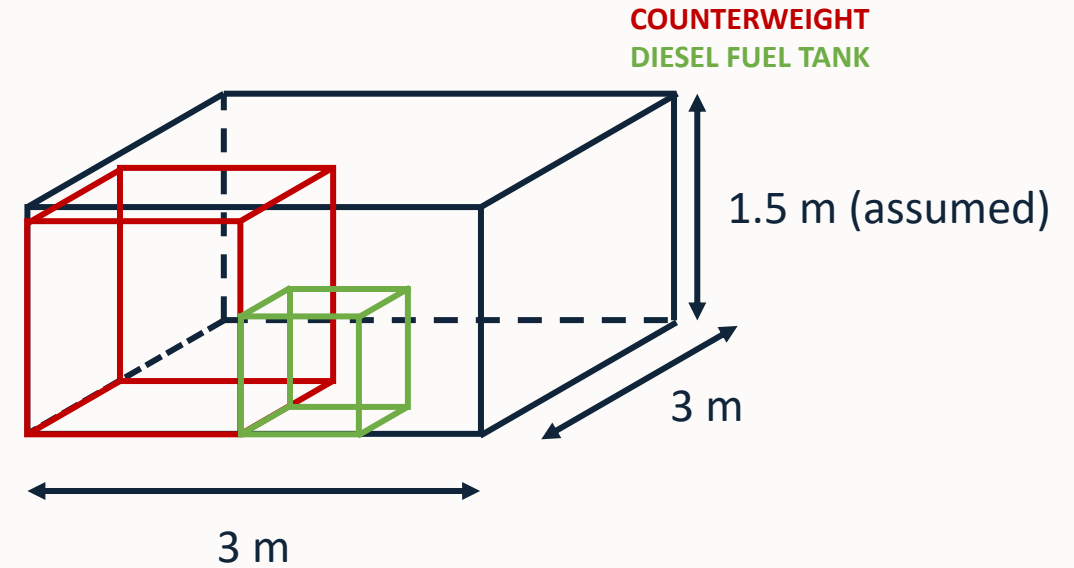
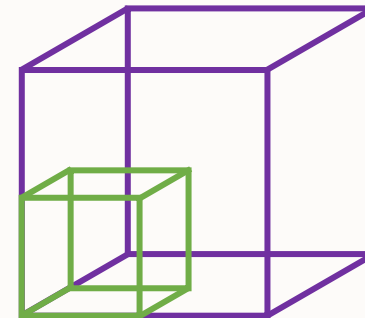


# Off-road Example

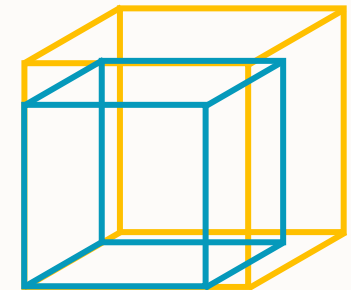
200 kW excavator – vehicles with counterweight can be 100 % MH



## HOW IT COULD LOOK



VOLUME REQUIRED 350 BAR  $H_2$   
DIESEL FUEL TANK

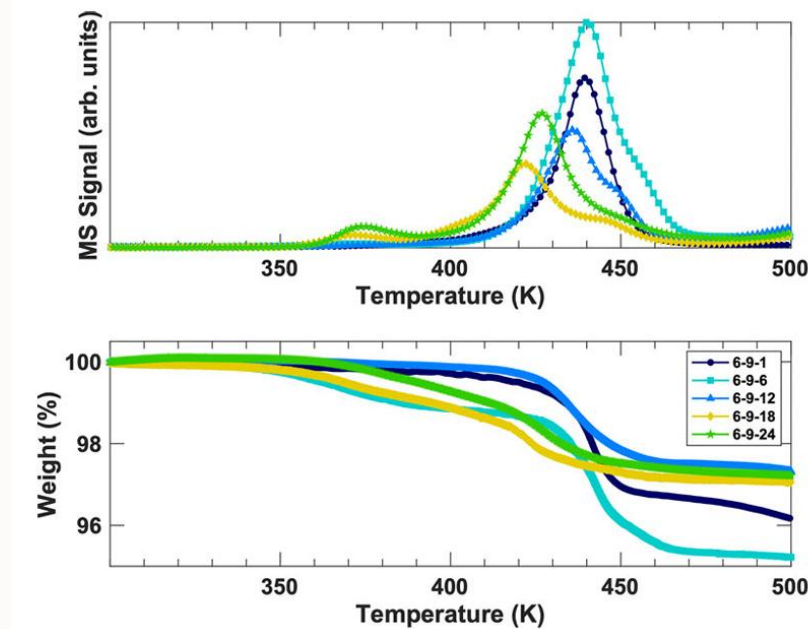
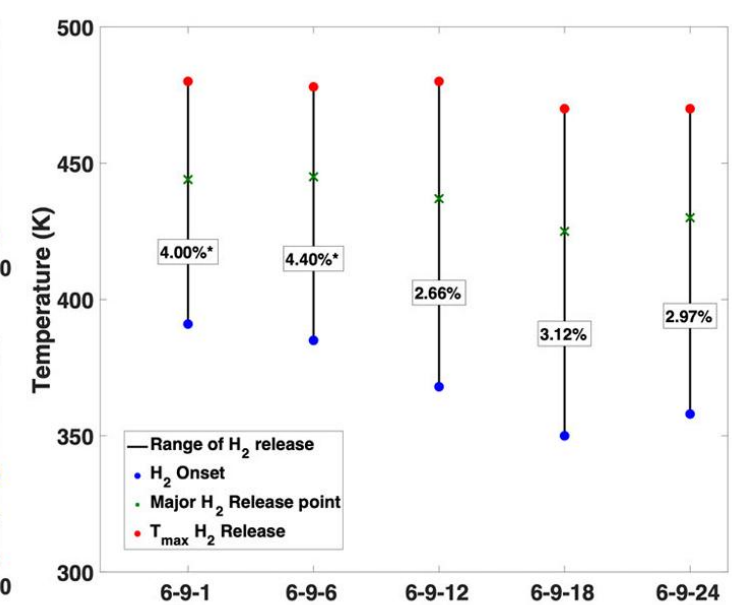


SOLID-STATE STORE VOLUME  
COUNTERWEIGHT + DIESEL VOLUME  
CW + TANK = 7100 kg  
SS store (system)  $\approx$  7000 – 8000 kg

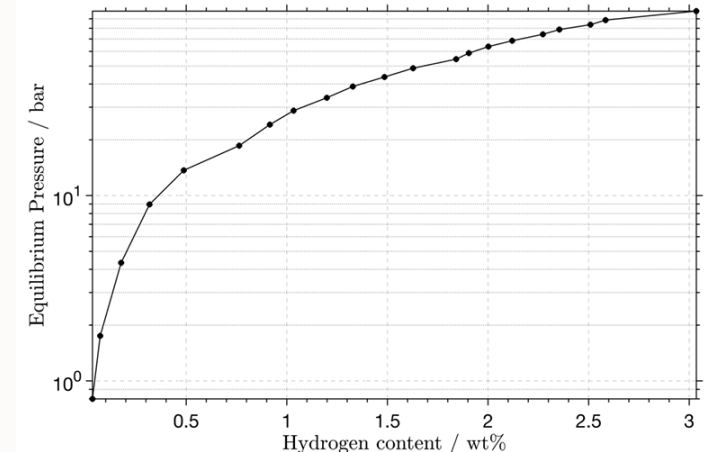


# Reactive Hydride Composites

- The  $x\text{LiH} + y\text{LiBH}_4 + z\text{Mg}(\text{NH}_2)_2$  system exhibits something interesting
- $\text{LiBH}_4$  amine adducts ( $\text{Li}_4(\text{BH}_4)(\text{NH}_2)_3$ ) have low melting points (100 – 180 °C)
  - This increases the reaction rate dramatically ( $\text{Li}^+$ ,  $\text{Mg}^{2+}$ , & H transport)
  - The liquid changes the engineering design in our favour.



Hall, N.J., Grant, D.M., Prosser, J.L. et al. Reversible hydrogen storage in reactive hydride composites under 400 K. Nat Commun 17, 8533 (2026). <https://doi.org/10.1038/s41467-026-75313-0>

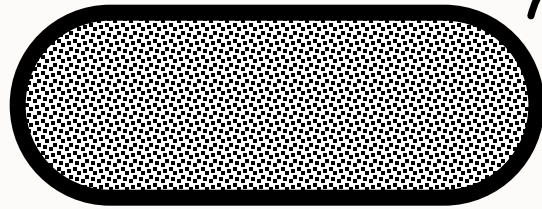


SI Figure 3: Hydrogenation PCI conducted at 433 K



# Reactive Hydride Composites - engineering

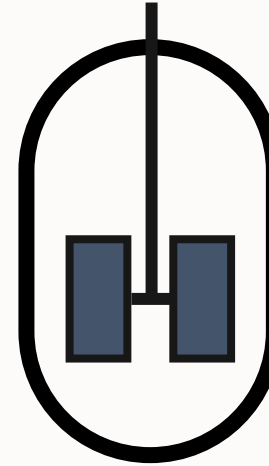
## Pelletised bed



**“Power”** penalty  
Load to circulate  $H_2$

**“Voidage”** penalty  
Hydride  $60 \text{ kg } H_2/\text{m}^3$  crystal  
density can be  $30 \text{ kg } H_2/\text{m}^3$

**“Powder”** penalty  
Poor heat transfer due to  
low thermal conductivity



## Stirred Tank Reactor

- Voidage penalty removed
- Easier thermal design
- Pumpable (at temperature)

$$\frac{P_{stirring}}{P_{thermal}} = \frac{1 \text{ kW m}^{-3}}{75 \text{ kW m}^{-3}} = 1.3\%$$

4 wt%  $H_2$   
 $36 \text{ kg } H_2 \text{ m}^{-3}$   
2 h discharge



# Deployment reality



## **BASELINE TARGET**

**350 bar Compressed H<sub>2</sub> System**

**£300 / kg H<sub>2</sub>**



## **STRUCTURAL SHELL COST**

**Approx. Type I Pressure Vessel Tank**

**£50 / kg H<sub>2</sub>**

## **Hydride Tank Split**

£50

< £250 / kg H<sub>2</sub> (Hydride material + manufacturing)



## **Ballpark Bulk Material Cost @ 5 wt% H<sub>2</sub>**

+ assumed manufacturing overhead

**< £ 10 / kg material**

- The capacity to store hydrogen (wt% H<sub>2</sub>) is an important factor for cost.
- 1 - 2 wt% H<sub>2</sub> is too low, it must be > 5 wt% H<sub>2</sub>.
- Only inexpensive elements can be used (e.g. Mg, Li, Na etc.)
- Transition metals as catalyst only

AB<sub>2</sub> materials arguably too expensive for bulk H<sub>2</sub> storage

# Making hydrides at scale (1)

Two main avenues to make hydrides (depending on type):

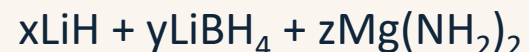
## Examples of hydride costs

Total material cost  $\ll$  £250 /kg H<sub>2</sub>

MgH<sub>2</sub>                      £ 2-5 / kg H<sub>2</sub>

NaBH<sub>4</sub>                     £ 60-80 / kg H<sub>2</sub>

## Example: RHC system



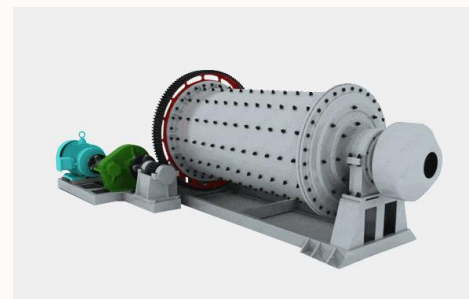
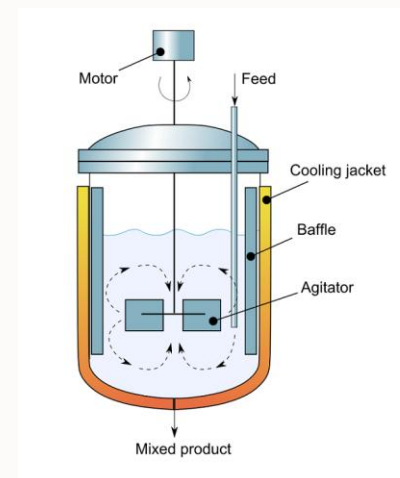
LiH                              £ 15-25 / kg H<sub>2</sub>

Mg(NH<sub>2</sub>)<sub>2</sub>                **Process needed**

LiBH<sub>4</sub>                         **Process needed**

**Dedicated research into large-scale reactor design needed**

- Reactive ball milling
- Stirred tank reactors
- Other avenues – fluidised beds

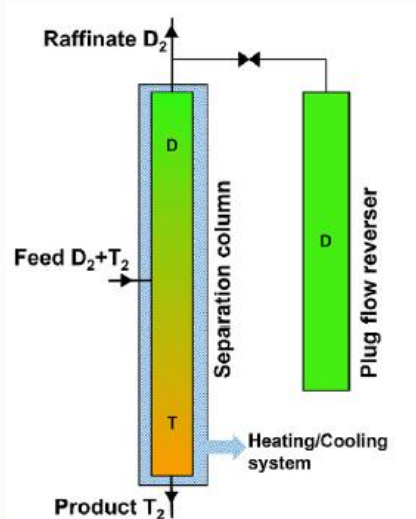


# Pivot towards other applications

To produce cheaper hydrides, we may find other applications as quicker routes to material manufacture scale up rather than a conventional  $H_2$  storage route.

## Isotope Separation

Thermal Cycling Absorption Process (TCAP)



### Thermally Compress $H_2$

Enables solid-state, thermal compression without moving mechanical parts.



### Store Thermal Energy

High-density thermochemical storage for industrial heat recovery.



### Catalysis

Serves as active catalysts, particularly for ammonia synthesis.



### Isotope Separation

Precisely separates deuterium and tritium for advanced processing.



### Purify Gas

Selectively extracts ultra-pure hydrogen gas from mixed streams.



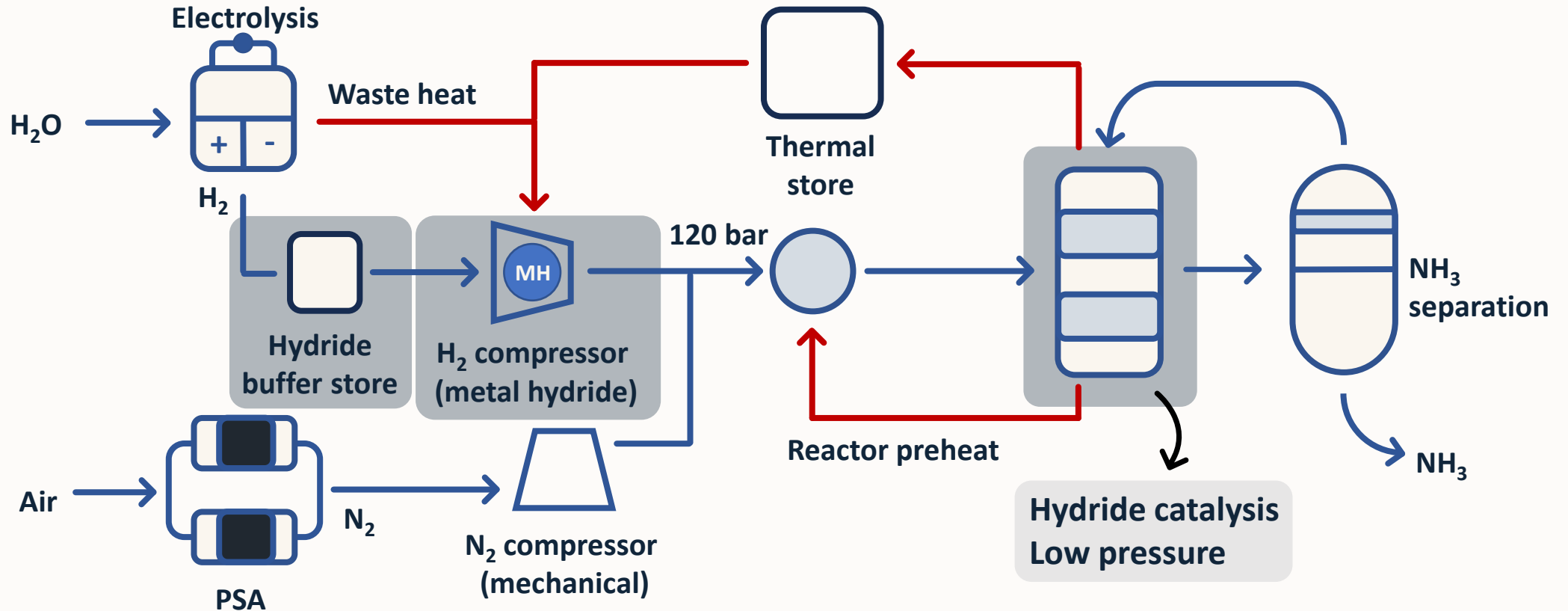
### Enhanced Buffer Storage

Provides stable pressure buffering for dynamic energy demand.

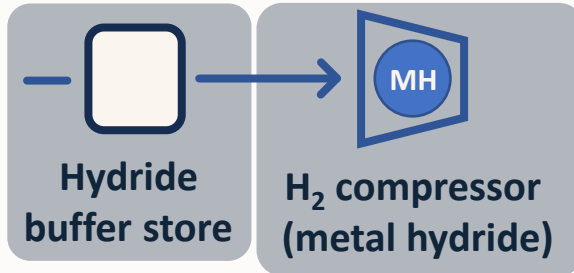


# Industrial application example

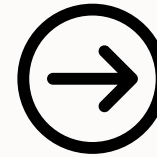
## Agile Ammonia synthesis



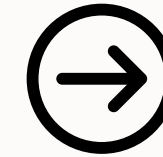
# Making hydrides at scale (2)



Ti-based alloys  
are hard to a  
manufacture:



Processing  
temperatures  
> 1600 °C



Molten Ti is  
chemically  
corrosive  
> 1600 °C



E.g. Based on TiAl

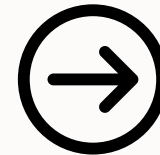
These two types of technology use:

AB<sub>2</sub> intermetallic alloys

Examples:

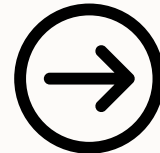


Current techniques  
keep crucible wall  
from molten Ti



Induction Skull  
Melting  
(or levitation)

Vacuum Induction  
Melting is ideal but...



Need to reduce  
oxygen attack.  
Only AlN found  
to be suitable

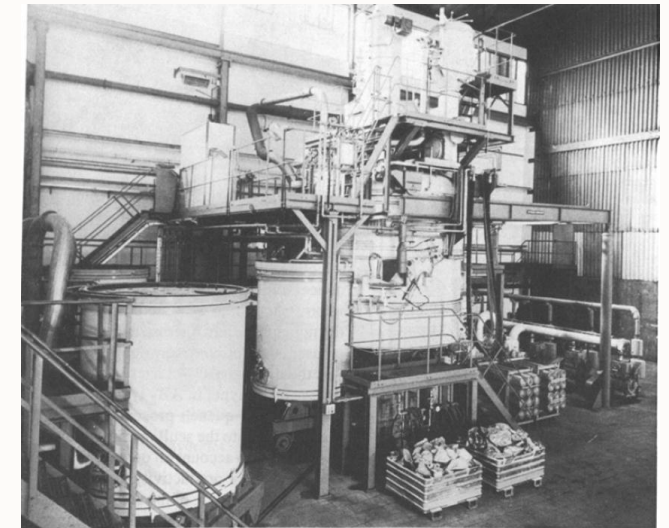


Fig. 5 Typical 1500-kg cover gas induction furnace with mobile cooling chambers.



# Overview

Technology pivots, material bottlenecks, and commercial scale-up pathways

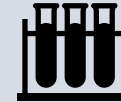
## Key Strategic Shifts

Pivoting away from light vehicles toward industrial applications & heavy off-road vehicles.



## Application Pivot & Thermal Limitations

Shift from passenger vehicles to **off-road & industrial uses**. Historical prototypes were hindered by the “**thermal resistance problem**”.



## Reactive Composites & Liquid phase

**Reactive hydride composites** & liquid-phase systems show potential. R&D must lower liquid temps, improve kinetics (pressure/time), and build engineering prototypes.



## Cost & Density Benchmarks

To compete with compressed  $H_2$ , a material capacity using **low-cost hydrides** is essential to offset raw material expense. With a high-capacity hydride (> 5 wt%)



## Integrated Thermal Power Design

Charge/discharge thermal power design must be co-engineered directly within the **engine architecture**.



## Overlapping Scale-Up Strategies

Manufacturing techniques frequently overlap across sectors. Early commercial adoption and sustainable scale-up are likely to originate in **industrial sectors** rather than passenger automotive.

