

Hydrogen Storage – Gaps and Priorities

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Abstract

The objective of this paper is to provide a brief overview of the possible hydrogen storage options available today and in the foreseeable future. Hydrogen storage can be considered for onboard vehicular, portable, stationary, bulk, and transport applications, but the main focus of this paper is on vehicular storage, namely fuel cell or ICE/electric hybrid vehicles. The technical issues related to this application are weight, volume, discharge rates, heat requirements, and recharging time. Another important merit factor is cost. The paper discusses in detail the advantages and disadvantages of the various hydrogen storage options for vehicular storage, identifies the main technological gaps, and presents a set of concrete recommendations and priorities for future research and development. The main conclusions can be used as input to future policy documents on hydrogen storage.

1. INTRODUCTION

The main objective of this paper is to provide an overview of the three principal forms of hydrogen storage (gas, liquid, and solid), with focus on technology gaps and R&D priorities. Figure 1 compares the volumetric and gravimetric H₂ density of some of the most common storage options, and clearly shows the theoretical potential for low volumetric density for solid-state storage systems. However, there are more system requirements that need to be fulfilled. Table 1 shows the practical H₂-storage system and media targets for fuel cell determined by USA, Japan, and the IEA, while Table 2 shows the most probable (state of the art) H₂-storage methods today. This paper provides the key technical details for these, and other and more novel H₂ storage technologies.

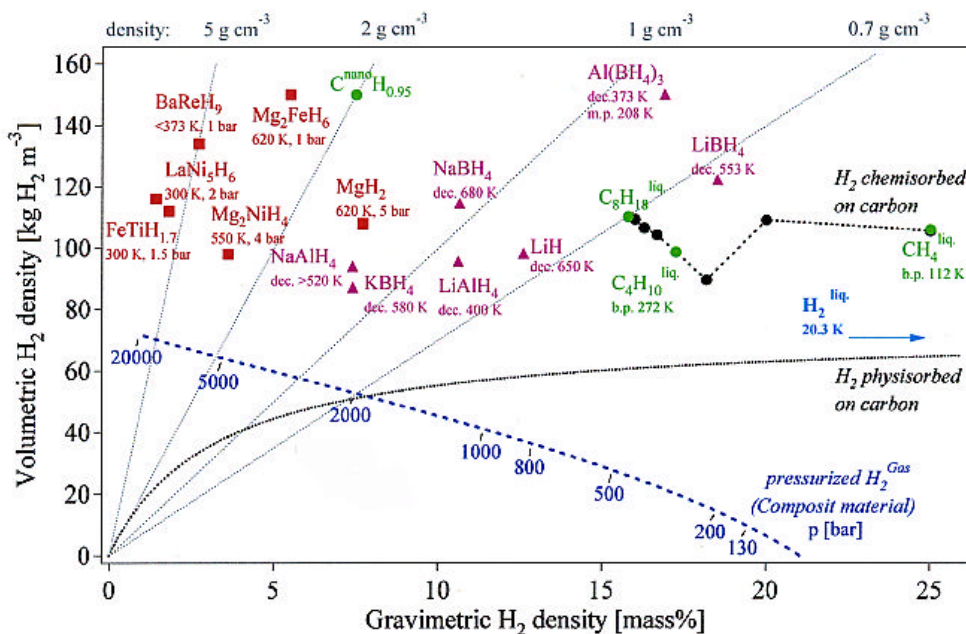


Figure 1 Storage density for various H₂ storage forms (Source: Schlapbach and Züttel, Nature, 2001 [1]).

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Table 1 Selected H₂-storage system and media targets for fuel cell vehicles[†].

Property	Units	2010 USA	2007 Japan	2006 IEA*
System density (by weight)	wt.% H ₂	6	3	–
System density (by volume)	kg H ₂ /m ³	45	–	–
System cost	US\$/kg H ₂	133	–	–
Refuelling time	minutes	3	–	–
Medium density (by weight)	wt.% H ₂	–	5.5	5.0
H ₂ liberation temperature	C	–	150	80

[†] 500 km range = ca. 5-13 kg stored H₂

*IEA HIA Task 17

Table 2 State of the art technology and estimates for system volumes and weights for vehicular compressed gas, cryogenic liquid, and hydride storage of 3 kg H₂[†]

Technology	Volume [liters]	Weight [kg]	Density [Wt. % H ₂]
35 MPa (350 bar) compressed H ₂	145	45	6.7
70 MPa (700 bar) compressed H ₂	100	50	6.0
Cryogenic liquid H ₂	90	40	7.5
Low-temperature metal hydride	55	215	1.4

[†]Source: A. Niedzwiecki (QuantumTechnologies), US DOE Hydrogen Vision Meeting, November 2001 [2].

Figure 2 shows an example of a vehicular hydrogen fuel cell system with some kind of hydride storage. It is important to note that all H₂ storage systems, except gaseous systems, require a heat exchanger. In general, heat must be added during discharging and removed during recharging. In practical system waste heat from the fuel cell or combustion engine (ICE) should be utilized. Hence, the propulsion technology dictates the required discharge temperature of the hydrogen storage medium (e.g., ca.80 °C for PEMFCs). One of the main challenges is to be able to recharge the system in 3 minutes (one of the targets in Table 1). A typical 5 kg H₂hydride bed, for instance, would require 500 kW of heat removal. That means that off board recharging may be required.

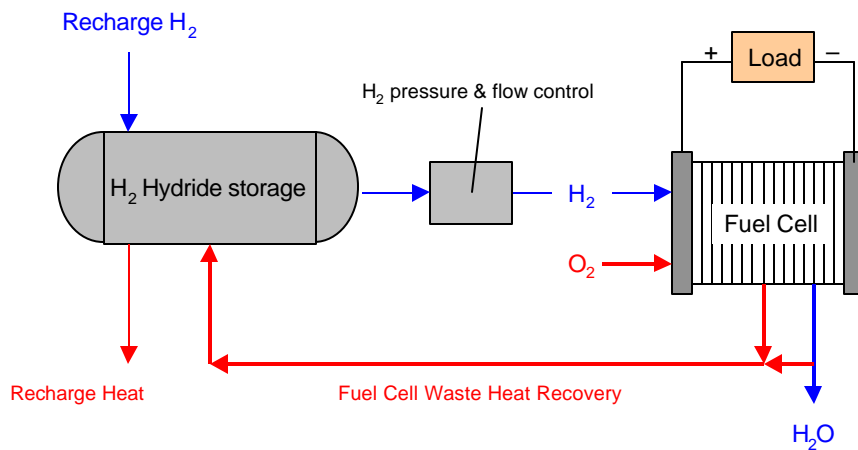


Figure 2 Example of a typical vehicular hydrogen fuel cell system

2. GASEOUS HYDROGEN

The most common method to store hydrogen in gaseous form is in steel tanks, although lightweight composite tanks designed to endure higher pressures are also becoming more and more common. Cryogas, gaseous hydrogen cooled to near cryogenic temperatures, is another alternative that can be used to increase the volumetric energy density of gaseous hydrogen. A more novel method to store hydrogen gas at high pressures is to use glass micro spheres. The next two sections provide some more details on two of the most promising methods to store hydrogen gas under high pressure: composite tanks and glass micro spheres.

2.1. Composite Tanks

A schematic of a typical high-pressure H_2 -storage C-fiber-wrapped composite tank is shown in Figure 3. The main advantages with such composite tanks are their low weight (meets targets), and that they are commercially available, well-engineered and safety tested (extensive prototype experience exists), and have codes that are accepted in several countries for pressures in the range 350-700 bars. Composite tanks require no internal heat exchange and may be usable for cryogas. The main disadvantages are the large physical volume required (does not meet targets), the ideal cylindrical shape makes it difficult to conform storage to available space, the high cost (500-600 USD/kg H_2), and energy penalties associated with compressing the gas to very high pressures. There are also some safety issues that still have not been resolved, such as the problem of rapid loss of H_2 in an accident. The long-term effect of hydrogen on the materials under cyclic or cold conditions is not fully understood either. Hence, there is still need for more R&D, specifically:

1. Research on material embrittlement, using new *ad hoc* fracture mechanics techniques.
2. Development of stronger and lower cost construction materials, especially carbon fibers.
3. Development of an efficient and clean (without oils) 1000 bar compressor.
(Practical hydride-type compressors utilizing waste heat or solar energy could be considered).
4. Development of techniques that recover the compression energy during vehicle operation.

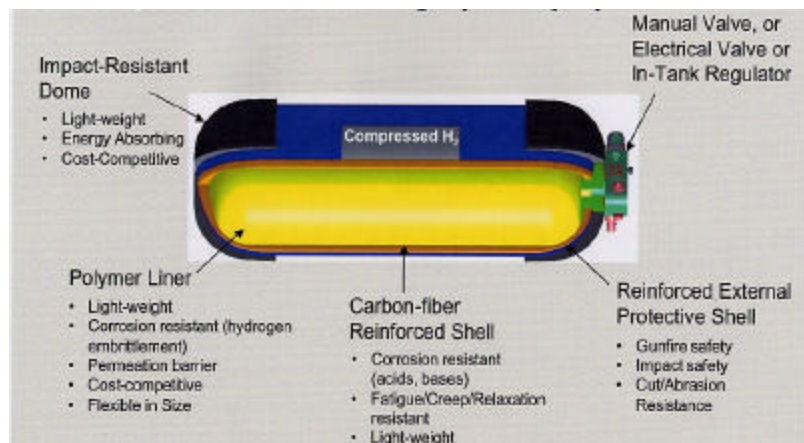


Figure 3 Schematic of a typical compressed H_2 gas composite tank (Source: Quantum Technologies) [2].

2.2. Glass Micro Spheres

The basic concept for how glass micro spheres can be used to store hydrogen gas onboard a vehicle can be described by a three step process (charging, filling, and discharging): First, the hollow glass spheres are filled with H_2 at high pressure (350-700 bars) and high temperature (ca. 300 °C) by permeation in a high-pressure vessel.

Next, the micro spheres are cooled down to room temperature and transferred to the low-pressure vehicle tank. Finally, the micro spheres are heated to ca. 200-300 °C for controlled release of H₂ to run the vehicle.

The main problem with glass micro spheres is the inherently low volumetric densities that can be achieved and the high pressures required for filling. The glass micro spheres slowly leak hydrogen at ambient temperatures. Another practical challenge is that there is too much breakage during cycling. The main operational challenge is the need to supply heat at temperatures higher than available from the PEM fuel cell (ca. 70-80°C). The high temperature (ca. 300°C) required also makes rapid response control difficult. However, there do exist some clear advantages also. Glass micro spheres have the potential to be inherently safe as they store H₂ at a relatively low pressure onboard and are also suitable for conformable tanks. This allows for low container cost. The significant technical advantage is the demonstrated storage density of 5.4 wt.% H₂. R&D on glass micro spheres that leads to a reduction in the H₂ liberation temperatures to less than 100 °C needs to be performed. General studies on infrastructure and cost are also needed, in addition to more specific R&D tasks:

1. Development of stronger glasses.
2. Development of specific low-cost production techniques.
3. Development of coating techniques for optimization of H₂ permeability.
4. Development a technique to control permeability by other than thermal methods (e.g., magnetic, electric, and microwave fields)

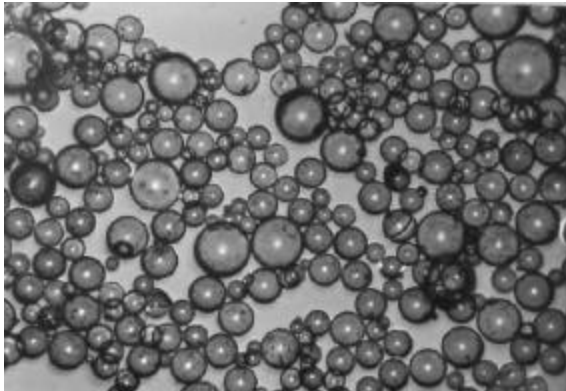


Figure 4 Photo of glass micro spheres for H₂ gas storage (Source: Teitel, BNL 51439, 1981 [3]).

Table 3 compares the main merit factors for two promising gaseous H₂ storage options for the future, namely composite tanks and glass micro spheres. In general it can be concluded that it is possible to build safe systems, but costs need to be reduced. The main overall system drawback with composite tanks is the high-pressure requirements, while glass micro spheres suffer from their high temperature requirement.

Table 3 Merit factors for gaseous H₂ storage – comparison of composite tanks and glass micro spheres.

Parameter	Composite Tanks		Glass Micro Spheres	
	Value	Comment	Value	Comment
Temperature, <i>T</i>	+	No heat exchanger needed	–	High <i>T</i> needed
Pressure, <i>p</i>	–	High <i>p</i> compressors needed	+	Low onboard <i>p</i> possible
Energy density	–	Only partially -conformable	+	Up to 5 wt.% H ₂ , conformable
Robustness	+	Extensively tested	–	Breakable spheres
Safety	+	Existing codes & standards	+	Inherently safe
Cost	–	500-600 USD/kg H ₂	?	Needs to be determined

3. LIQUID HYDROGEN

The most common way to store hydrogen in a liquid form is to cool it down to cryogenic temperatures (-253°C). Other options include storing hydrogen as a constituent in other liquids such as NaBH₄ solutions, rechargeable organic liquids, or anhydrous ammonia NH₃. This section discusses the three most promising methods: cryogenic H₂, NaBH₄ solutions, and rechargeable organic liquids.

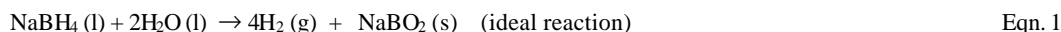
3.1. Cryogenic Liquid Hydrogen (LH₂)

Cryogenic hydrogen, usually simply referred to as liquid hydrogen (LH₂), has a density of 70.8 kg/m³ at normal boiling point (-253 °C). (Critical pressure is 13 bar and critical temperature is -240°C). The theoretical gravimetric density of LH₂ is 100%, but only 20 wt. % H₂ of this can be achieved in practical hydrogen systems today. On a volumetric basis the same respective values are 80 kg/m³ and 30 kg/m³. This means that liquid hydrogen has a much better energy density than the pressurized gas solutions mentioned above. However, it is important to recall that about a 30-40% of the energy is lost when LH₂ is produced. The other main disadvantage with LH₂ is the boil off losses during dormancy, and the fact that a super insulated cryogenic container is needed. The general public's perception of LH₂ as an unsafe and very high tech system should not be underestimated. The main advantage with LH₂ is the high storage density that can be reached at relatively low pressures. Liquid hydrogen has been demonstrated in commercial vehicles (particularly by BMW), and in the future it could also be co-utilized as aircraft fuel, as it provides the best weight advantage of any H₂-storage. The main R&D tasks are to:

1. Develop more efficient liquefaction processes (hydride compressors, magnetic and acoustic cooling, etc.)
2. Lower costs and improve the insulated containers.
3. Develop systems that automatically capture the boiloff (e.g., via hydrides) and re-liquefy the fuel.

3.2. NaBH₄ Solutions

Borohydride (NaBH₄) solutions can be used as a liquid storage medium for hydrogen. The catalytic hydrolysis reaction is:



The theoretical maximum hydrogen energy storage density for this reaction is 10.9 wt.% H₂ (ideal reaction: 4H₂/(NaBH₄+2H₂O)). The specific cost (USD/kg) of hydrogen storage using NaBH₄ solutions is quite simple to calculate:

$$\text{Cost H}_2 = 4.69 \times \text{Cost NaBH}_4 \quad (\text{ideal reaction}) \quad \text{Eqn. 2}$$

The main advantage with using NaBH₄ solutions is that it allows for safe and controllable onboard generation of H₂. The main disadvantage is that the reaction product NaBO₂ must be regenerated back to NaBH₄ off board. Although use of NaBH₄ solutions in vehicles may be prohibitively high (the cost of NaBH₄ regeneration must be reduced from present 50 USD/kg to < 1 USD/kg), there do exist a few commercial companies that promote the technology (Millennium Cell, USA and MERIT, Japan). The required cost reduction is unlikely because of the unfavourable thermodynamics. However, NaBH₄ solutions may be useable in high-value portable and stationary applications. The following R&D tasks have been identified:

1. Research how close one can approach the ideal energy density (10.9 wt.% H₂) by optimizing the H₂O needed in the reaction (Eqn. 1) and develop methods to obtain H₂O from the fuel cell.
2. Develop practical NaBO₂ removal, regeneration, and replacement methods.
3. Develop a direct borohydride fuel cell.

3.3. Rechargeable Organic Liquids

Some organic liquids can also be used to indirectly store hydrogen in liquid form. The following three steps summarize the basic concept. First, an organic liquid is dehydrogenated (catalytic process) to produce H₂ gas onboard. The next step is to transport the dehydrogenated product from the vehicle tank to a central processing plant, while simultaneously refilling tank with fresh H₂-rich liquid. Finally, the H₂-depleted liquid need to be re-hydrogenated and brought back to the starting compound and returned to the filling station.

One example of a rechargeable organic liquid process is the dehydrogenation and hydrogenation of methylcyclohexane (C₇H₁₄) and toluene (C₇H₈):



The ideal reaction in Eqn. 3 yields a gravimetric and volumetric H₂ energy storage density of 6.1 wt.% H₂ and 43 kg H₂/m³, respectively. It should also be noted that the organic liquids involved in this reaction (Eqn. 3) must be handled with great care (e.g., methylcyclohexane is a clear colorless liquid that reacts violently with strong oxidants, causing fire and explosion hazards). This means that it is necessary to perform detailed safety and toxicity studies. General studies on possible infrastructure scenarios and corresponding cost calculations should also be performed. The more specific R&D tasks are to:

1. Develop organic systems that can be dehydrogenated at low temperatures and produce useable H₂ pressures
2. Develop optimal metal dehydrogenation catalysts and onboard systems.
3. Develop the re-hydrogenation process.

A comparison of the merit factors for liquid hydrogen (LH₂), borohydride (NaBH₄) solutions and the organic liquids discussed above is presented in Table 4. In general it can be concluded that the handling and transport of liquid hydrogen, which may involve highly toxic chemical substances or extreme temperatures, requires a safe and well-organized industrial infrastructure. The H₂-liquid production (or regeneration) infrastructure would have to be distributed in order to minimize the transport cost to the distributed refueling stations. The build-up of such infrastructure could be quite costly and should be combined with non-vehicular applications, both stationary power production and aviation transport. LH₂ could meet the fuel demands for aviation, while the other two options (borohydride solutions and organic liquids) could be suitable for refueling of terrestrial transport (e.g., private cars and fleet vehicles).

Table 4 Merit factors for liquid H₂ storage – comparison of LH₂, NaBH₄ solutions and organic liquids

Parameter	LH ₂		NaBH ₄ Solutions		Organic Liquids	
	Value	Comment	Value	Comment	Value	Comment
Temperature, <i>T</i>	–	30-40% losses	+		–	<i>T</i> _{dehyd} = 300-400°C
Pressure, <i>p</i>	+	Low <i>p</i>	+		+	
Energy density*	+	100 wt.% H ₂ †	+	10.9 wt.% H ₂	+	6.1 wt.% H ₂
Safety	–	Public perception	?		–	Toxicity
Cost	–	Infrastructure	–	Regeneration costs	–	Infrastructure

* Theoretical maximum

† 20 wt.% H₂ in practical LH₂ systems

4. SOLID HYDROGEN

Storage of hydrogen in solid materials has the potential to become a safe and efficient way to store energy, both for stationary and mobile applications. The four main groups of suitable materials are carbon and other high surface area materials, H₂O-reactive chemical hydrides, thermal chemical hydrides, rechargeable hydrides. Table 5 summarizes the potential materials within each of these groups, while more details are provided below.

Table 5 Overview of solid hydrogen storage options

Carbon & other HSA* materials <ul style="list-style-type: none"> • Activated charcoals • Nanotubes • Graphite nanofibers • MOFs, Zeolites, etc. • Clathrate hydrates 	Chemical hydrides (H₂O-reactive) <ul style="list-style-type: none"> • Encapsulated NaH • LiH & MgH₂ slurries • CaH₂, LiAlH₄, etc
Rechargeable hydrides <ul style="list-style-type: none"> • Alloys & intermetallics • Nanocrystalline • Complex 	Chemical hydrides (thermal) <ul style="list-style-type: none"> • Ammonia borozane • Aluminum hydride

* HSA = high surface area

4.1. Carbon and other high surface area materials

4.1.1. Carbon-based Materials (Nanotubes and Graphite Nanofibers)

Carbon-based materials, such as nanotubes (Figure 5a-c) and graphite nanofibers (Figure 5d) have over the last decade received a lot of attention in the research community and in the public press. The general consensus today is that the high H₂-storage capacities (30-60 wt%) reported a few years ago are impossible and were the result of measurement errors. Pure H₂ molecular physisorption has been clearly demonstrated, but is useful only at cryogenic temperatures (up to ca. 6 wt.% H₂) and extremely high surface area carbons is required. Pure atomic H-chemisorption has been demonstrated to ca. 8 wt.% H₂, but the covalent-bound H is liberated only at impractically high temperatures (above ca. 400 C). Room temperature adsorption up to a few wt.% H₂ is occasionally reported, but has not been reproducible. This requires a new bonding mechanism with energies between physisorption and strong covalent chemisorption. The surface and bulk properties needed to achieve practical room temperature storage are not clearly understood and it is far from certain that useful carbon can be economically and consistently synthesized. Hence, the potential for H₂ storage in carbon-based materials is questionable, and some even suggest cessation of all research work in the area. A more moderate approach would be to continue carbon work for a limited additional time, say two years. In this timeframe the most reasonable specific R&D tasks seem to be to:

1. Perform fundamental surface and electronic studies.
2. Continue theoretical modeling studies of H on carbon surfaces and in bulk. Determine if there is some new C-H bonding mechanism possible and, if theoretically so, how to achieve it in practice.
3. Study carbon-metal composites capable of catalyzing H₂ dissociation and so-called “spillover”.
4. Calculate the high volume production costs for promising carbons (e.g., graphite nanofibers and nanotubes).
5. Develop standard testing techniques for measuring H₂ uptake and release from small carbon samples.
6. Develop a carbon sample and activation procedure that can be used as an international standard for researchers in the field. (This sample should have a reversible room temperature capacity > 2 wt.% H₂).

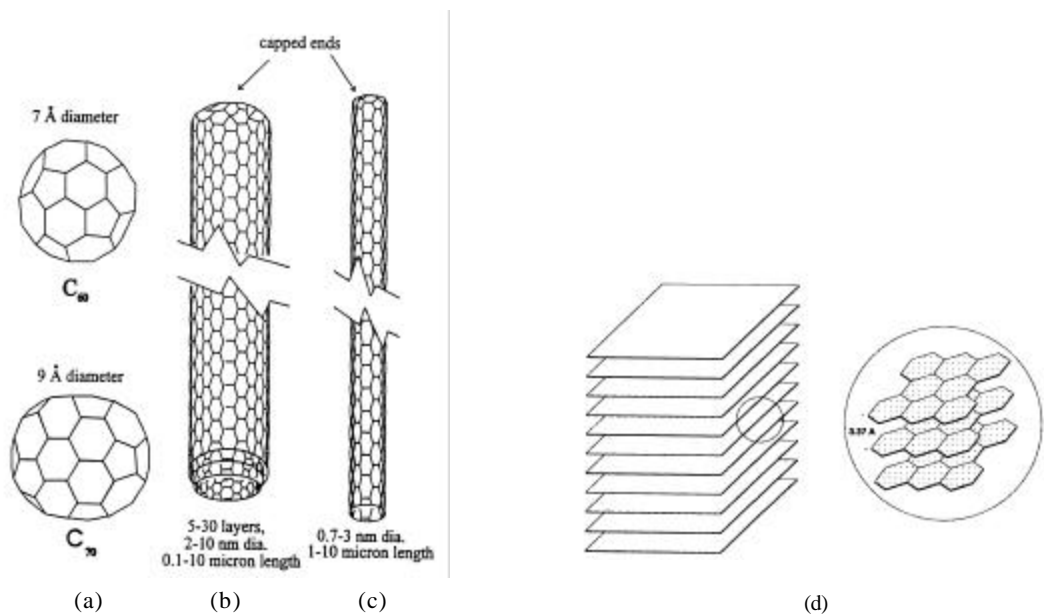


Figure 5 Schematic of (a) Fullerene carbon buckyballs, (b) multi-wall nanotubes (MWNT), (c) single-wall nanotubes (SWNT) (Source: Withers, Fullerene S&T, 1997 [4]) and graphite nanofibers (Source: Chambers et al, J. Phys. Chem. B, 1998 [5]).

4.1.2. Other High Surface Area Materials

The most predominant examples of other high surface area materials are zeolites, metal oxide frameworks (MOFs), and clathrate hydrates. The definitions and main features for these materials are as follows:

- *Zeolites*: Complex aluminosilicates with engineered pore sizes and high surface areas. Well known as “molecular sieves”. The science for capturing non-H₂ gases is well known.
- *Metal Oxide Frameworks (MOFs)*: Typically ZnO structures bridged with benzene rings. These materials have an extremely high surface area, are highly versatile, and allow for many structural modifications.
- *Clathrate hydrates*: H₂O (ice) cage structures, often containing “guest” molecules such as CH₄ and CO₂. The cage size and structure can often be controlled by organic molecules (e.g., THF).

The materials are all characterized by extremely high surface areas that can physisorb molecular H₂. They have been shown to store a few wt.% H₂ at cryogenic temperatures. However, the R&D question is if they can be engineered to reversibly store high levels of H₂ near room temperature. These materials, particularly metal oxide frameworks and clathrate hydrates, represent new storage ideas and should be studied to determine the potential for the near future.

4.2. Rechargeable Hydrides

The two main reversible hydriding reactions in rechargeable metal hydride batteries are illustrated in Figure 6. R&D on rechargeable hydrides has been going on for decades, and a large database with information about their properties exists today within the IEA HIA Annex 17 (<http://hydpark.ca.sandia.gov>). A summary of this database (the metal hydride “family tree”) is provided in Figure 7 and Table 6. From this it becomes clear that it is the complex hydrides that provide the hope for the future, particularly the non-transition metal types such as borohydrides, alanates, and amides. These are discussed in some more detail below.

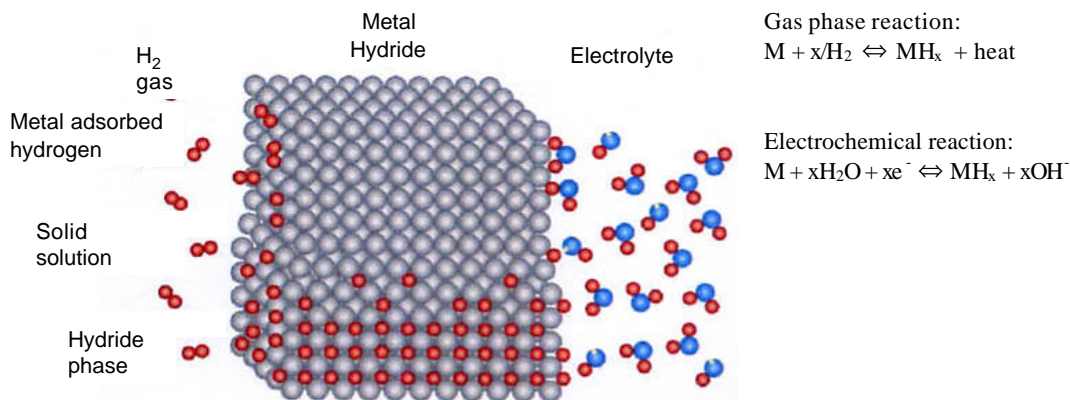


Figure 6 Schematic of a rechargeable metal hydride battery (Source: Schlappbach, Nature, 2001 [1])

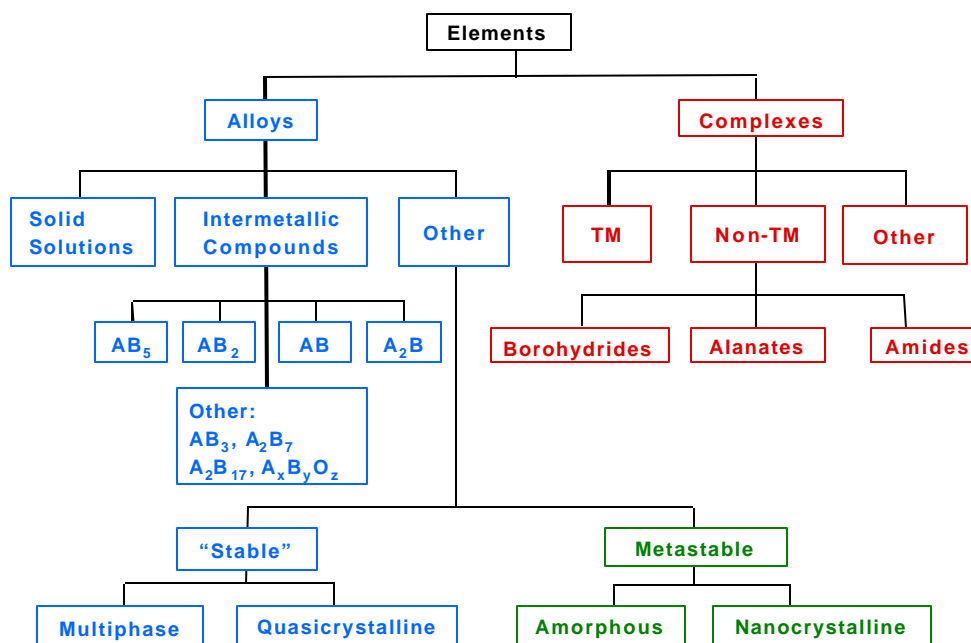


Figure 7 Metal hydride family tree (Source: Sandrock, after JALCOM, 1999 [6]).

Table 6 Status and potential for metal hydrides listed in Figure 7.

Hydrides	Status & Potential
Elements	Well characterized but thermodynamics unfavorable. Too stable or too unstable to use at temperatures around 0-100 C.
Alloys & Intermetallic Compounds	Very well studied. Many work well at temperatures less than 100 C, but too low gravimetric capacities for vehicles (< 2.5 wt% H ₂). Technically suitable for stationary storage, but rather expensive.
Nanocrystalline & Amorphous:	Good kinetics, but H-capacities and desorption temperatures are unfavorable.
Complex	Main hope for the future.

4.2.1. Alanates

The key properties of the most known alanates are provided in Table 7, where particularly NaAlH₄ is being intensely studied on many fronts. The low-temperature kinetics and reversibility of these alanates are improved by adding a catalyst (e.g., Ti). These catalyst mechanisms are today nearly understood. However, NaAlH₄ cannot meet weight targets (only ca. 4-5 reversible wt. % H₂) and has potential problems with pyrophoricity and cost. The research on catalyzed Mg(AlH₄) shows that this type of alanate is not nearly as reversible as NaAlH₄. Hence, the near term applicability of Mg(AlH₄) is unlikely. The main R&D task is to extend the catalyst concept to other alanates beyond NaAlH₄. Other R&D questions to be answered are:

- Can the pyrophoricity problem be eliminated?
- Can the catalyzed alanates meet cost restraints?

Table 7 Alanates – Key properties of most common types.

Type	Storage density*, wt.% H ₂	Desorption temperature, C
LiAlH ₄	10.6	190
NaAlH ₄	7.5	100
Mg(AlH ₄)	9.3	140
Ca(AlH ₄)	7.8	> 230

*Theoretical maximum

4.2.2. Borohydrides

The key properties of the most known borohydrides are provided in Table 8, which shows that the borohydrides have much higher capacity potential than the alanates. However, they are also much less studied than alanates. In general borohydrides are too stable, and are not as reversible as alanates, but are at the same time considered more safe than the alanates. Lately there has been some preliminary progress on LiBH₄, particularly on reversibility and destabilization. The main R&D questions to be answered on borohydrides are:

- Can NaAlH₄ catalyst learning be extended to the borohydrides?
- Can borohydrides be destabilized to achieve <100 C desorption?
- Can the price of LiBH₄ be substantially reduced?

Table 8 Borohydrides – Key properties of most common types.

Type	Storage density*, wt.% H ₂	Desorption temperature, C
LiBH ₄	18.5	300
NaBH ₄	10.6	350
KBH ₄	7.4	125
Be(BH ₄) ₂	20.8	125
Mg(BH ₄) ₂	14.9	320
Ca(BH ₄) ₂	11.6	260

*Theoretical maximum

4.3. Chemical Hydrides (H₂O-reactive)

Chemical hydrides can be handled in a semi-liquid form, such as mineral oil slurry. In this form hydrides can be pumped and safely handled. Controlled injection of H₂O during vehicle operation is used to generate H₂ via hydrolysis reactions. The liberation of H₂ is exothermic and does not require waste heat from the vehicle power source. The overview of the hydrolysis reactions for the most common chemical hydrides provided in Table 9 shows that the theoretical potential storage density is around 5-8 wt.% H₂. In practical systems, one approach for NaH is to encapsulate small spheres in polymeric shells. In general, MgH₂ probably offers the best combination of H₂-yield and cost. The key R&D question to be answered is the cost of processing the spent hydroxide back to the starting hydride. In all cases, this is an energy intensive process, and it is doubtful cost can be reduced to vehicle targets.

Table 9 Hydrolysis reaction for selected H₂O-reactive chemical hydrides

Hydrolysis Reaction	Storage density*, wt.% H ₂
LiH + H ₂ O ⇒ H ₂ + LiOH	7.8
NaH + H ₂ O ⇒ H ₂ + NaOH	4.8
MgH ₂ + 2H ₂ O ⇒ 2H ₂ + Mg(OH) ₂	6.5
CaH ₂ + 2H ₂ O ⇒ 2H ₂ + Ca(OH) ₂	5.2

*Theoretical maximum

4.4. Chemical Hydrides (thermal)

Ammonia borane is another group of chemical hydrides that potentially could be used to store hydrogen in a solid state. An overview of the decomposition reactions (and corresponding temperatures) and the potential storage density is provided in Table 10. Preliminary results show that NH₄BH₄ can be thermally decomposed in 4 steps with very high H₂ yields. However, the reactions are not reversible, and offboard regeneration is required. Research has shown that nesting in mesoporous “scaffolds” greatly increases the decomposition kinetics. The possibility of gaseous boranes in the evolved H₂ must be carefully studied. They are toxic and would likely contaminate the fuel cell catalysts. In summary, the main R&D tasks are:

- Perform research to find out if the decomposition temperatures can be lowered to < 100 °C.
- Develop safe systems with onboard control of the decomposition reaction.
- Develop cost effective offboard regeneration systems (NH₄BH₄ from BN or NHBN).

Table 10 Decomposition reactions for a thermal chemical hydrides (Source: Autrey et al, DOE EERE Program Review, 2004 [7])

Decomposition reaction	Storage density*, wt.% H ₂	Temperature †, °C
NH ₄ BH ₄ ⇒ NH ₃ BH ₃ + H ₂	6.1	< 25
NH ₃ BH ₃ ⇒ NH ₂ BH ₂ + H ₂	6.5	< 120
NH ₂ BH ₂ ⇒ NHBH + H ₂	6.9	> 120
NHBH ⇒ BN + H ₂	7.3	> 500

*Theoretical maximum

†Decomposition temperature

5. CONCLUSIONS & RECOMMENDATIONS

This paper has discussed the main issues (possibilities and gaps) for storage of H₂ in gaseous, liquid, and solid form. Below is a summary of the main findings with respect to technology status, best option(s), and main R&D issues:

Gaseous H₂ Storage:

Status: Commercially available, but costly.
 Best option: C-fiber composite vessels (6-10 wt% H₂ at 350-700 bar).
 R&D issues: Fracture mechanics, safety, compression energy, and reduction of volume.

Liquid H₂ Storage:

Status: Commercially available, but costly.
 Best option: Cryogenic insulated dewars (ca. 20 wt% H₂ at 1 bar and -253°C).
 R&D issues: High liquefaction energy, dormant boil off, and safety.

Solid H₂ Storage:

Status: Very developmental (many R&D questions).

- Best options: To early to determine. Many options: Rechargeable hydrides, chemical hydrides (H_2O & thermally reactive), carbon, and other high surface area materials. Most developed option: Metal hydrides (potential for >8 wt.% H_2 and >90 kg/m³ H_2 -storage capacities at 10-60 bars).
- R&D issues: Weight, lower desorption temperatures, higher desorption kinetics, recharge time and pressure, heat management, cost, pyrophoricity, cyclic life, container compatibility and optimization.

Comparison:

Comparisons between the three basic storage options shows that the potential advantages of solid H_2 -storage compared to gaseous and liquid hydrogen storage are:

- Lower volume
- Lower pressure (greater energy efficiency)
- Higher purity H_2 output

Compressed gas and liquid storage are the most commercially viable options today, but completely cost-effective storage systems have yet to be developed. The safety aspects with all storage options, particularly the novel hydride storage options, must not be underestimated.

General recommendations :

- Identify the possibilities for integrated and multifunctional systems with several users of H_2 , including power production, transport applications (vehicular, maritime, and/or aviation), and/or specific industrial processes.
- Focus on distributed systems. In the case of refueling stations, identify the infrastructure and system requirements for off board H_2 -production for the most promising storage alternatives:
 - *Near-term*: Gas storage (composite tanks) in small-scale distributed systems
 - *Near to medium term*: LH_2 for large-scale centralized systems
 - *Long-term*: Regenerative complex hydrides in distributed systems
- Focus on end-user and specific application (e.g. for vehicular H_2 /PEMFC-systems)

Specific recommendations :

- Intensify development of practical compressed H_2 gas system (reduce compression energy losses, reduce refueling time, develop 1000 bar pressure vessel)
- Intensify basic research on the complex hydrides
- Encourage truly new and innovative approaches to solid and liquid storage media

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