HYDRIDES ALLOYS FOR HYDROGEN STORAGE

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4/3/2021

INTRODUCTION

Hydrogen is the most abundant element in the universe. It possesses the highest energy per unit weight of any chemical fuel and is non-polluting as it burns into water vapor:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1}$$

As a compressed gas or cryogenic liquid, it is quite volatile, and poses an explosion hazard, and hence requires special handling.

Table 1. Comparison of hydrogen to other hydrocarbon fuels.

	Hydrogen H_2	Methane CH_4	Octane C_8H_{18}	H_2:C_8H_{18}
Heat of combustion, MJ/kg	120	50	45	2.7:1
Heat of combustion at ambient, MJ/liter	0.011	0.036	31.4	0.00035:1
Heat of combustion at liquid state, MJ/liter	8.5 -253 ^{o}C	20.7 -161 ^{o}C	31.4	0.00035:1
Density at ambient, gm/liter	0.09	0.072	703	1:10,000
Density at liquid, kg/liter	0.071	0.415	0.703	0.1:1

Three hydrogen storage options are currently available:

1. Compressed hydrogen gas at 5,000-10,000 psi.
2. Liquid cryogenic hydrogen at -253 ^{o}C.
3. Adsorbed hydrogen in Metal Hydrides, MH and other materials.

Hydrogen offers promise as an energy carrier or energy storage medium for other sources of energy such as wind, solar and nuclear energy. Hydrogen can be used in a fuel cell to produce electricity.

Another possibility is its use as a working fluid in a variety of devices such as pumps, air compressors and air conditioners. Stored as a metal hydride, application of heat, such as from solar energy or automobile exhaust allows its use as a working fluid moving a piston of a heat engine.

Humanity is reaching an era when we must seek alternatives to the depleting supplies of fossil fuels. The most promising alternative is a hydrogen based economy based on renewable sources such as wind and solar and conventional systems such as geothermal and nuclear energy. Metal hydrides are a promising way to safely and efficiently storing and transporting hydrogen.

HYDROGEN STORAGE

The output of net energy E_{net} from hydrogen involves a substantial amount of energy input E_{in} in the production, on-site storage, transportation, distribution station storage, as well as on-board storage.

One can define the hydrogen energy storage efficiency as:

$$\begin{aligned}\text{Hydrogen Storage Efficiency} &= \frac{\text{Net energy output}}{\text{Energy input}} \\ &= \frac{\text{Energy output - Energy Consumption}}{\text{Energy input}}\end{aligned} \tag{1}$$

This can be written as:

$$\eta_H = \frac{E_{net}}{E_{in}} = \frac{E_{out} - E_{in}}{E_{in}} > 0 \tag{2}$$

From Eqn. 2, one can deduce a simple energy breakeven condition for a sustainable viable energy storage system as:

$$\begin{aligned} E_{out} - E_{in} > 0 \\ E_{out} > E_{in} \end{aligned} \tag{3}$$

A substantial amount of energy is expended in compressing and liquefying cryogenic hydrogen.

COMPRESSION AND REFRIGERATION ENERGIES

Compressed Hydrogen

For the adiabatic compression of hydrogen the compression energy in MJ/kg (1 MJ = 1,055 BTU) is:

47 MJ/kg, for 10,000 psi
36 MJ/kg, for 5,000 psi

Liquefied hydrogen

For cryogenic liquid hydrogen, the theoretical cooling energy expenditure is:

2.94 MJ/kg, for gas from 25 ^{o}C to 20 K

0.45 MJ/kg, for gas to liquid at 20 K
Total: 3.40 MJ/kg

However, liquefaction involves a reverse Carnot Cycle efficiency of:

$$\eta_{\text{Reverse Carnot}} = \frac{Q_{extraction}}{Q_{rejection} - Q_{extraction}} = \frac{T_2 \Delta S}{T_1 \Delta S - T_2 \Delta S} = \frac{T_2}{T_1 - T_2} \qquad (4)$$

For liquefaction from $T_1 = 25\ {}^{o}C = 25 + 273\ K = 298\ K$ to $T_2 = 20\ K$,

$$\eta_{\text{Reverse Carnot}} = \frac{20}{(25+273)-20} = \frac{20}{298-20} = \frac{20}{278} = 0.0719 = 7.19\ percent$$

This lead to actual liquefaction energies for a refrigeration efficiency of 7.19 percent of:

Refrigeration energy = 3.4 / 0.0719 = 47.3 MJ/kg, for gas to liquid at 20 K
Vaporization and warmup = 3.4 MJ/kg
Total = 50.7 MJ/kg

Metallic Hydrogen

1. Compressing hydrogen to 20 atm =	12.0 MJ/kg
2. Unextractable heat of absorption = 7 kcal / kg =14.6 MJ/kg	
3. Energy for refrigeration to 10 ^{o}C = 14.6 MJ/kg	
Coefficient of performance, COP = 5	
Cooling Energy = 14.6 / 5 =	3.0 MJ/kg
4. Energy for desorption, using waste heat =	0.0 MJ/kg
Total energy expenditure:	15.0 MJ/kg

A comparison between the energy needs of the three processes for hydrogen storage is shown in Table 1.

Table 2. Comparison of hydrogen storage options.

	Compressed H_2 gas 340 atm	Cryogenic liquid hydrogen	Metal Hydride
Energy input, MJ/kg	36.0	50.7	15.0
Conditions	Very high pressure	Very low temperature	Moderate pressure and temperature
Hydrogen density, kg/liter	0.03	0.07	0.06
Hydrogen weight, percent	100	100	1.5
Volatility, percent	30	42	13

METAL HYDRIDES STORAGE OF HYDROGEN

The field of metal-hydrogen systems has been active for a century, especially since the middle of the 20th century. Discoveries of easily rechargeable metal hydrides based on alloys and inter-metallic compounds started around 1970 and led to a hydride renaissance and several proposed and commercial applications.

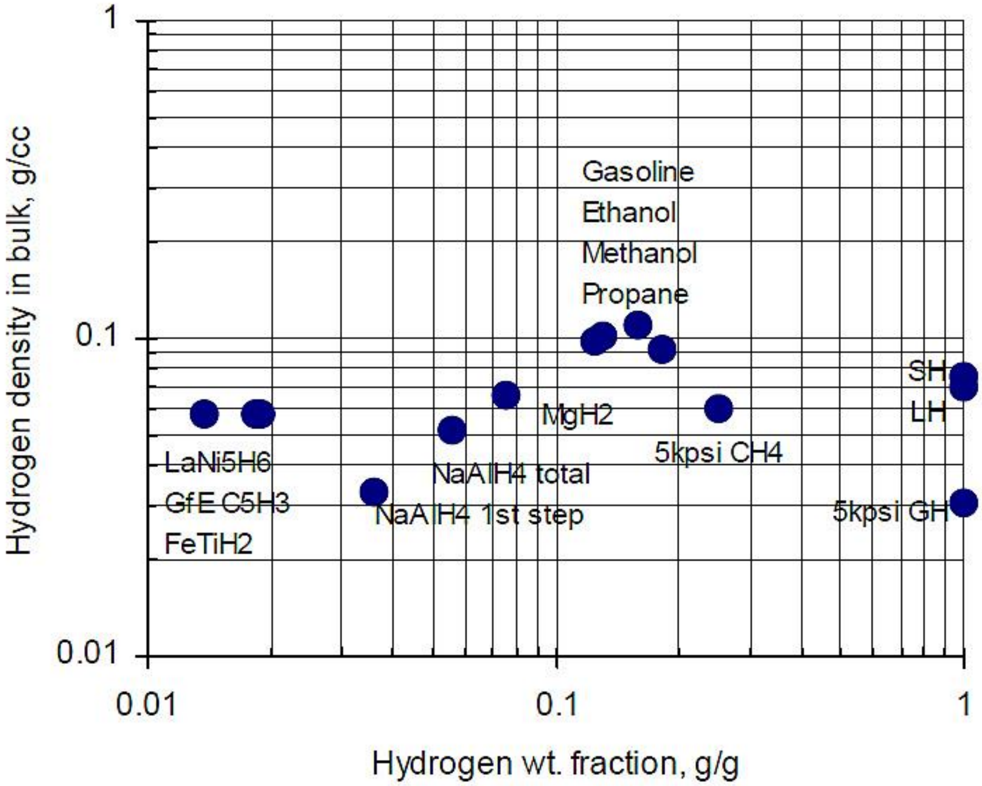

Figure 1. Hydrogen content in different materials. SH = solid hydrides, LH = liquid hydrides, GH = gaseous hydrides [2].

A commonly used applications example is the nickel metal hydride NiMH battery that uses a metal hydride for the negative energy storage electrode.

Another potentially important application area is the storage of hydrogen fuel for vehicular propulsion and stationary power generation; in both cases fuel cells.

The Metal-Hydrogen Systems are based largely on hydride forming alloys, although some M-H systems form H solid solutions. Most of the alloys are nominally single phase, although many exceptions probably exist as well as amorphous, nanocrystalline and multiphase alloys.

Palladium is notorious for its ability to store hydrogen. When it is saturated, the ratio of hydrogen to palladium can be as high 0.6, which is why the metal is used to filter and even store hydrogen.

Figure 2. Metal hydrides.

Many metals such as nickel, titanium, uranium and thorium can form metal hydrides. The key to practical use of metal hydrides is their ability to both absorb and release the same quantity of hydrogen many times without deterioration. A typical reaction can be expressed as:

$$M + H_2 \rightleftarrows MH_2 \qquad (2)$$

where M represents the metal and H is hydrogen.

The reaction is reversible and its direction is determined by the pressure of the hydrogen gas. If the pressure is above a certain level (the equilibrium pressure), the reaction proceeds to the right to form a metal hydride. If the pressure is below the equilibrium pressure, hydrogen is liberated and the metal returns to its original state.

The equilibrium pressure depends upon temperature. It increases with increasing temperature and vice versa.

High purity titanium sponge is ideal for trapping hydrogen and its isotopes. The material can be thermally cycled and has excellent properties for retention of He^3.

The metal hydrides provide a safe and efficient solid state approach to hydrogen energy storage. In addition, the energy implications of this continuously repeatable phenomenon are the basis for a wide range of commercial products.

METALLIC ALLOYS

In addition to random Solid Solution Alloys, there are five classes of Intermetallic Compounds of the form AB_x, where A represents one or more strongly hydride-forming elements and B represents one or more weakly hydride-forming elements. There also exist Mg-alloys and Complex Hydrides which are hydrides that form mixed ionic-covalent structures with a charged MH_x complex incorporated.

Some metallic alloys have the ability to absorb and store large quantities of hydrogen. The hydrogen can be released or desorbed as a gas and the alloy is returned to its original state.

In addition to binary alloys there exist multi-component systems such as the $LaNi_{5-y}Al_y$ (y=0.1-1.0) system.

An example is the $LaNi_{4.7}Al_{0.3}$ hydride alloy. When filled with H to capacity, the alloy holds 1 H atom for each metal atom to become $LaNi_{4.7}Al_{0.3}H_6$ when fully hydrided.

$$LaNi_{4.7}Al_{0.3} + 3H_2 \rightarrow LaNi_{4.7}Al_{0.3}H_6 \tag{3}$$

Solid-State Hydrogen Storage based on reversible metal hydrides offers several benefits over other means of storing hydrogen. Reversible metal hydrides operate at low pressure, especially when compared to compressed hydrogen, and do not need to be kept at the cryogenic temperatures required for liquid hydrogen storage.

Reversible hydride storage typically requires less energy on a system basis, is compact, and can be conformable to fit space available on the application.

Eight categories exist for metal hydrides. Their designation is according to the elemental composition before the incorporation of hydrogen:

Table 3. Metal hydrides categories

Material Category	Examples	Reference
AB_5 (naturally reversible)	$LaNi_5$ NiMH	
AB_2 (naturally reversible)	A=Ti+Zr B=Cr+Mn+Ni+Fe+V	https://doi.org/10.1016/j.matpr.2017.12.378
AB (naturally reversible)	TiFe	https://www.slideserve.com/Mercy/hydrogen-storage
A_2B (naturally reversible)	Mg_2NiH_4	
AB_3 (naturally reversible)	$LaY_3Ni_{8.2}Mn_{0.5}Al_{0.3}$	https://doi.org/10.1016/j.ijhydene.2016.09.049
A_2B_7 (naturally reversible)	$LaY_3Ni_{9.7}Mn_{0.5}Al_{0.3}$	
A_5B_{19}	$LaY_3Ni_{10.6}Mn_{0.5}Al_{0.3}$	
Complex Compounds	$LaNi_{4.7}Al_{0.3}$	
Mg Alloys		
Miscellaneous other Intermetallic Compounds	$Fe_{0.9}Mn_{0.1}Ti$	
Solid Solution Alloys		https://www.slideserve.com/Mercy/hydrogen-storage
Transition Metals (naturally irreversible)	Mg_2FeH_6	
Non-transition Metals (naturally irreversible)	$Be(BH_4)_2$ $NaAlH_3$	

Hydrogen storage systems range in size from small to large. The potential applications are small storage units that provide fuel for hydrogen fuel cell-powered cell phones, and pure hydrogen for the Cassini spacecraft's exploration of Saturn's moon, Titan.

VAN’T HOFF EQUATION

The PCT, Pressure-Composition-Temperature or PCI, Pressure-Composition Isotherm thermodynamic properties of metal hydrides are presented in direct relationship to the van't Hoff equation:

$$\ln P = \frac{\Delta H}{RT} - \frac{\Delta S}{R} \tag{4}$$

$\ln P$ = natural logarithm of pressure in absolute atmospheres

T = temperature in Kelvins, K= ^{o}C+273

ΔH = enthalpy change of hydriding, $\frac{kJ}{mol\, H_2}$

ΔS = entropy change of hydriding, $\frac{kJ}{K.mol\, H_2}$

R = gas constant =0.0083145 $\frac{kJ}{K.mol}$

where:

HYDROGEN CAPACITY

The hydrogen capacity of a metal hydride is presented in both an atomic ratio, H/M, and weight percent where:

$$wt\,\% = 100\frac{H}{H+M} \tag{5}$$

The capacity is given as the fully hydrided value, that is, the highest hydrogen concentration measured in the hydride phase limit. It does not necessarily represent the reversible capacity for engineering purposes.

METAL HYDRIDES

Metal hydrides begin as inter-metallic compounds produced in much the same way as any other metallic alloy. They exhibit one crucial difference. When exposed to hydrogen gas at certain pressures and temperatures, they absorb large quantities of the gas and form metal hydride compounds. In this case, hydrogen is distributed compactly throughout the metallic lattice.

Metal hydrides represent a promising method for storing hydrogen. They are inherently safer than compressed gas or liquid cryogenic hydrogen and have a higher volumetric hydrogen storage capacity.

Some hydrides can actually store twice the amount of hydrogen than can be stored in the same volume of liquid hydrogen.

The hydrogen sorbing behavior of metal hydride alloys is characterized using equilibrium pressure-temperature-composition (PTC) data. This data is determined by keeping an alloy sample at constant temperature while precisely measuring the quantity of hydrogen sorbed and the pressure at which sorption occurs.

The quantity of hydrogen sorbed is expressed in terms of alloy composition, either as an atomic ratio of hydrogen atoms to the number of atoms in the base metal alloy, or as the capacity of hydrogen in the alloy on a weight percent basis.

Figure 3 shows that most of the hydrogen is absorbed in a region where there is little pressure change. This region of near-constant pressure is known as the plateau pressure. Metal hydride formation is also accompanied by hysteresis, which appears as the difference between the upper absorption curve and the lower desorption curve.

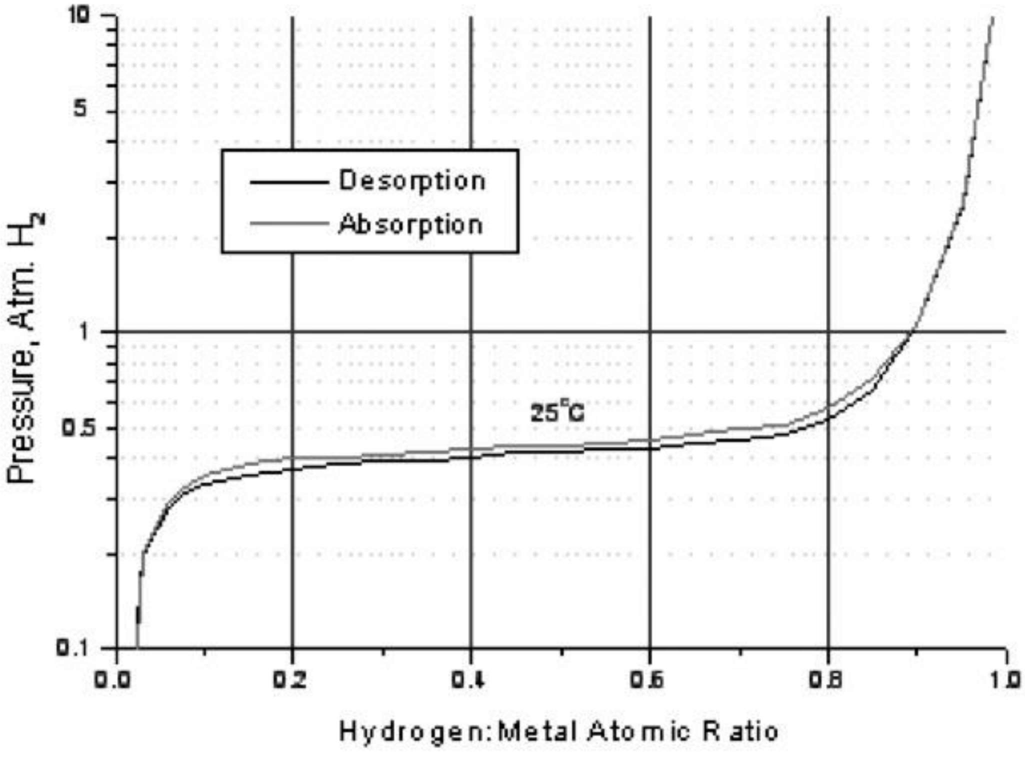

Figure 3. Pressure-Temperature-Composition , PTC Absorption and Desorption Isotherms for the $LaNi_{4.7}Al_{0.3}$ alloy at 25°C. When filled to capacity, the alloy holds 1 H atom for each metal atom to become $LaNi_{4.7}Al_{0.3}H_6$ when fully hydrided.

The plateau pressure moves up with an increase in temperature and down with a temperature decrease. Figure 4 shows several PTC plots for the same alloy at several different temperatures.

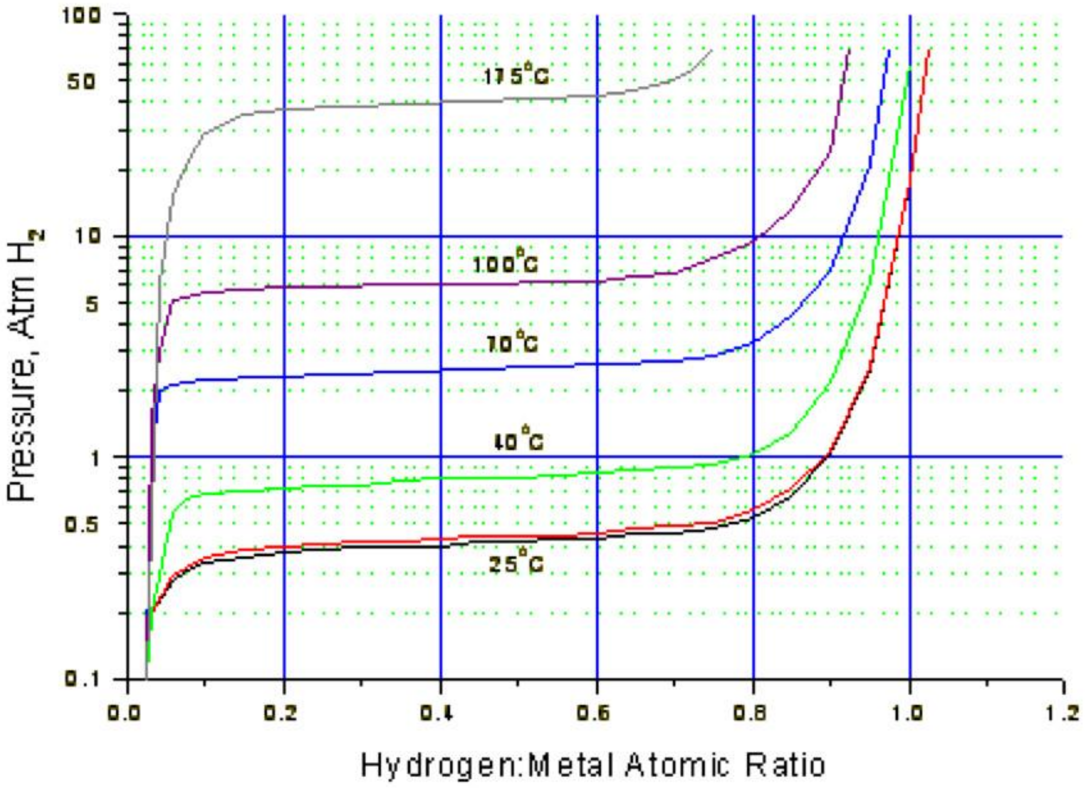

Figure 4. Equilibrium Pressure increases with increasing temperature, as shown in these Pressure-Temperature-Concentration, PTC Isotherms for the $LaNi_{4.7}Al_{0.3}$ hydride alloy.

Hydride alloys can be engineered to operate at different temperatures and pressures by modifying the alloy composition and the production techniques.

Before hydriding, an alloy is usually crushed to coarse particles and activated. The activation step eliminates surface barriers for hydrogen penetration. Activation prepares the alloy for repeated use to rapidly take up and release hydrogen. Should the hydrides be exposed to critical levels of contaminants such as CO_2, CO, O_2, or H_2O during H_2 cycling, they can be restored by reactivation with pure hydrogen.

Hydride absorption is accompanied by a heat of formation which is exothermic. In order to continuously absorb hydrogen to an alloy's maximum capacity, heat must be removed from the alloy bed. The rate at which a hydride alloy can absorb or release hydrogen is dependent upon the rate at which heat can be transferred into or out of the alloy. Increasing the heat transfer rate allows the processing of higher flow rates.

HYDROGEN AS A WORKING FLUID

Hydriding alloys absorb hydrogen when they are cold and then release that hydrogen at higher pressure when they are warm. This allows their use in thermal hydrogen compressors that are driven solely by thermal energy, as well as in temperature sensors and sensor-actuators.

When releasing hydrogen, the alloys cool off and vice versa. Using the cooling and heating properties of hydrides, air conditioners that are powered by waste heat and rapid heating devices, such as a Cold Start Heater for catalytic converters have been built.

APPLICATIONS

Hydrides applications are numerous, including low energy nuclear reactions or cold fusion, and involve both the gas phase as well as the electrochemical applications.

Table 4. Categories of metal hydrides applications.

Category	Application
Electrochemical hydrogen storage	Stationary Mobile Batteries, e. g. NiMH secondary batteries Catalysis
Thermal Applications	Heat storage Heat pumping Refrigeration Heat engine / Actuator
Hydrogen processing	Separation Purification Gettering Isotope separation Compression
Materials processing	Magnet powder processing
Gettering	Vacuum maintenance and inert gas purification

SEGMENTED BATTERY APPLICATION

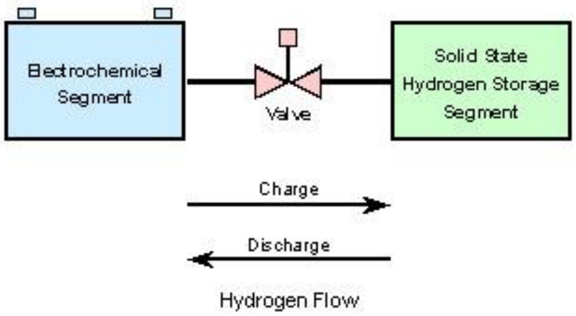

Figure 5. Electrochemical and solid state hydrogen storage segment of bipolar battery. Source: Ergenics.

A Segmented Battery is a rechargeable battery developed for hybrid electric vehicle energy storage. It combines the energy storage capability of metal hydride alloys with the cycle life and discharge rate capabilities of nickel-hydrogen fuel cells.

The battery offers performance, economic and safety advantages that are competitive to other battery technologies.

In a bipolar cell battery configuration, individual cells are placed next to one another in a "stack" assembly with a conductive plate located between each cell. Electrical current passes from one cell to the next across the entire electrode area, enabling operation at high rates of power.

Such a battery makes use of the low pressure nickel-hydrogen battery electrochemistry. During charge, hydrogen is produced in the Electrochemical Segment and flows to the Solid State Hydrogen Storage Segment where it is safely stored in a metal hydride alloy at low pressure and in solid form.

Hydrogen can be stored in this situation at two to three times higher energy density in an ambient temperature hydride alloy than as compressed gas.

Upon discharge, hydrogen is released from the alloy in the Storage Segment and flows to the Electrochemical Segment to produce electrical power.

A valve, located between the segments, eliminates self-discharge, isolating the reactants from one another when the battery is in the charged state.

For electric vehicles, the valve can automatically close in the event of an accident to immediately turn the battery off, enhancing safety.

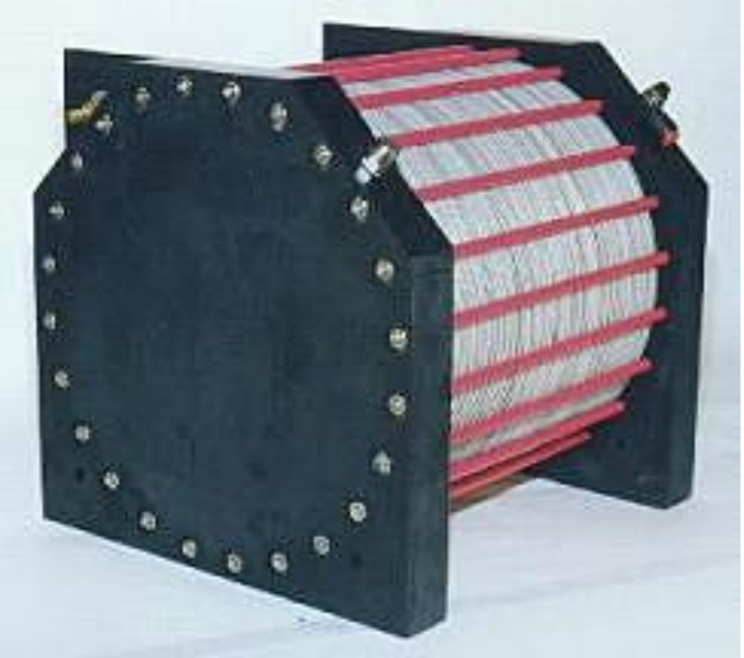

Figure 6. Bipolar 75 volts, 1.2 kWhr battery module. Source: Ergenics.

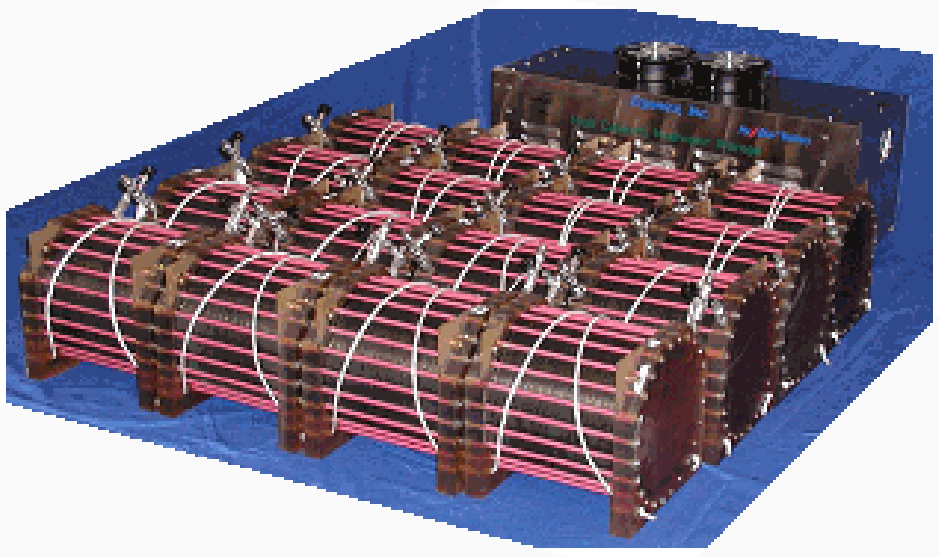

Figure 7. Sixteen modules in association of a solid state hydrogen storage unit for a 20 kWhr bipolar battery. Photo: Ergenics.

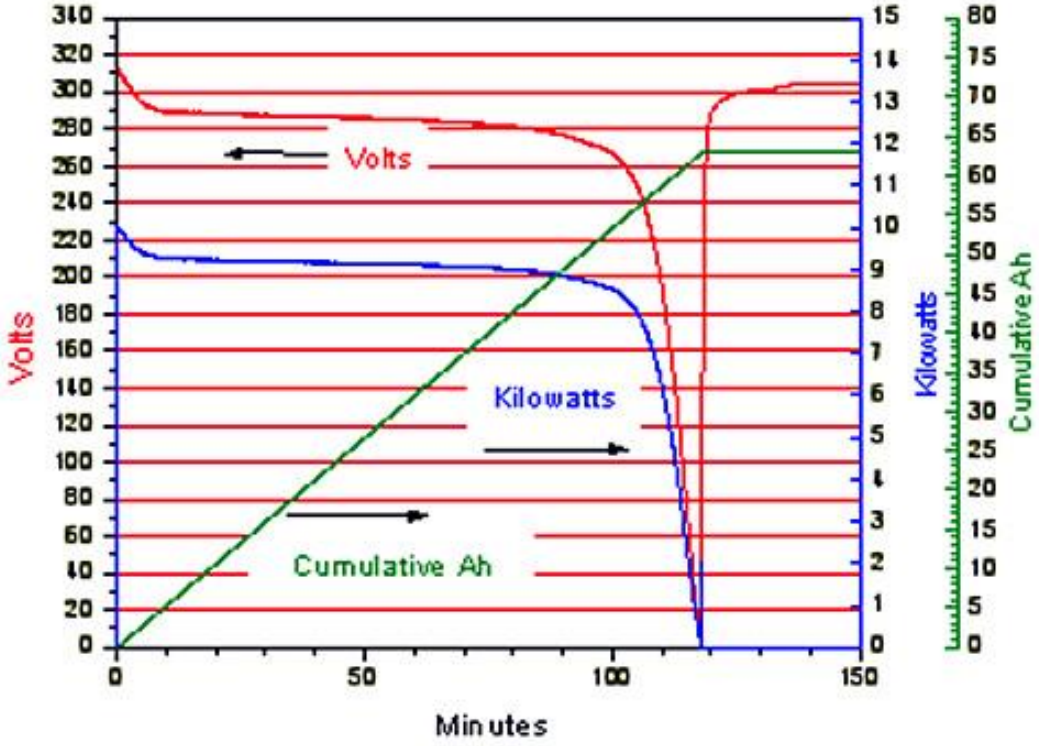

Figure 8. Discharge voltage of a bipolar 20 kWhr battery composed of 4 parallel strings of four series connected 75 volts modules. Source: Ergenics.

Compared with a conventional nickel-metal hydride battery, the Segmented Battery possesses an advantage in cycle life and rate performance. Increased cycle life comes from the separation of the electrochemical segment from the hydrogen storage segment.

The hydride alloy is not immersed in corrosive electrolyte, resulting in an indefinite alloy life. Also, the alloy does not have to conduct electricity, so there is no need to bond the particles. In a typical nickel-metal hydride battery, the same alloy not only has to store hydrogen, but it also serves as the negative electrode, having to conduct the electrochemical redox reactions. This dual function of the alloy requires a compromise, since its surface cannot be tailored for optimum electrochemical performance.

METAL HYDRIDE HYDROGEN FUEL CELL POWER SYSTEM

A metal hydride and hydrogen fuel cell power system is shown in Fig. 9. It involves four streams of hydrogen, air, water and a coolant system.

E hydride

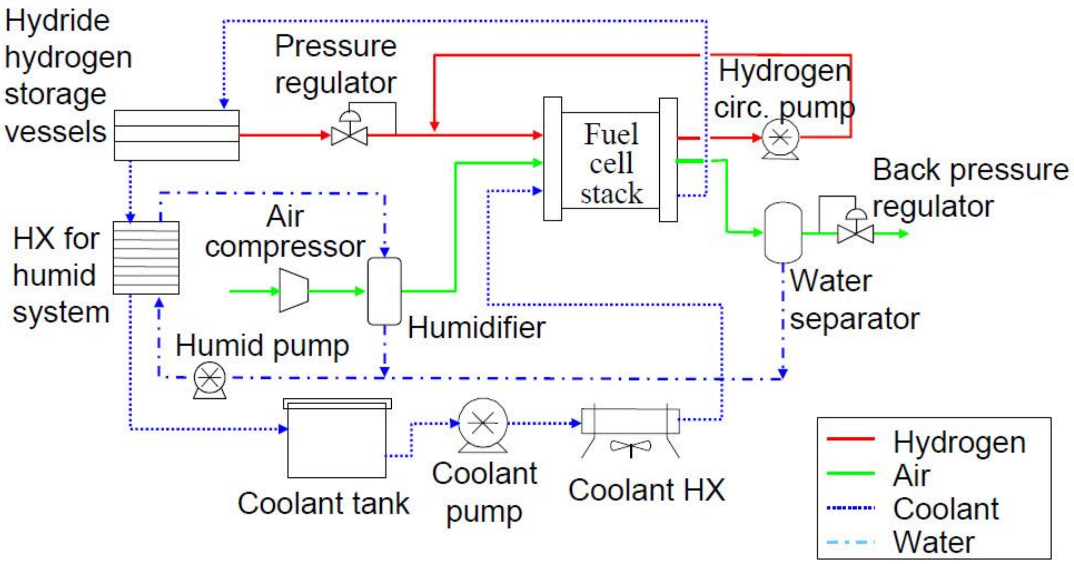

Figure 9. Structure of metal hydride and hydrogen fuel cell power system.

The hydride hydrogen storage container is shown in Fig. 10, including a coolant tube and aluminum foam as a backbone for the metal hydride powder.

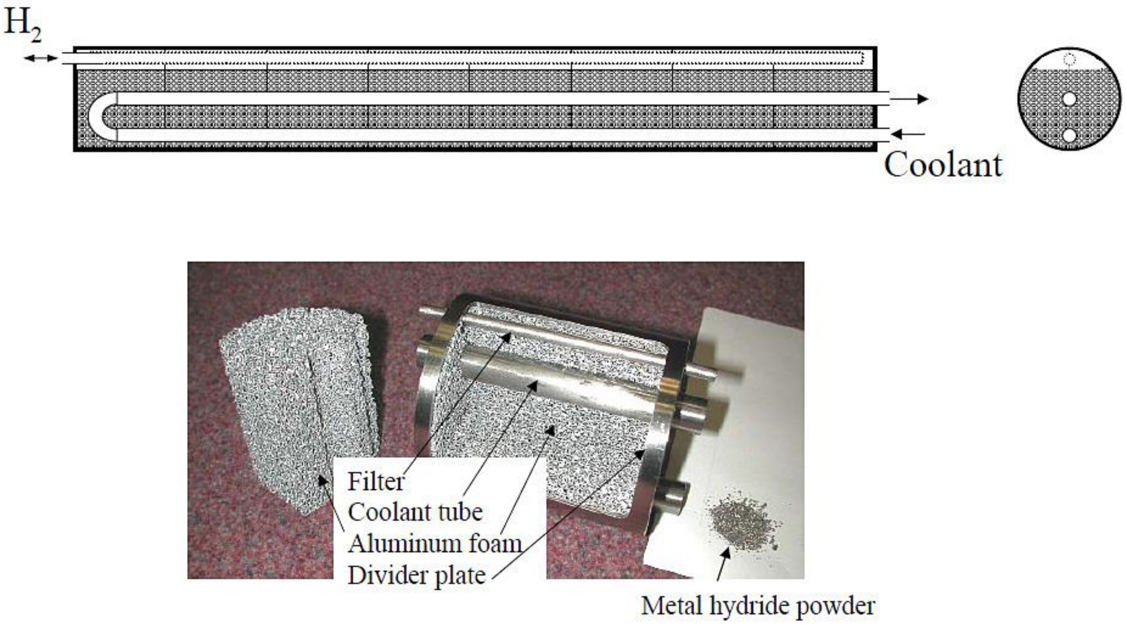

Figure 10. Structure of metal hydride container, showing a coolant channel and aluminum foam backbone for the metal hydride powder.

Figure 11. Hydrogen storage vessel.

Table 5. Technical specifications for hydrogen hydride, fuel cell utility vehicle.

Vehicle type	John Deere Cator utility vehicle

Fuel cell type	NG2000, 60 cells
Fuel cell operating pressure	122-308 kPa, 150 kPa average
Fuel cell operation temperature	60 ^{o}C
Hydrogen/air flow rates	1.5x/2.5 stoichometric
Fuel cell power, 163 kPa	8.3 kW at 38 Volts
Hydride material	$Fe_{0.9}Mn_{0.1}Ti$
Storage system weight	244 kg
Hydrogen storage capacity	2 kg
Hydrogen discharge temperature /pressure at 50 percent loading	50 ^{o}C / 756 kPa
Refuelling pressure / time	2,170 kPa / 60 minutes
Operating range	7 hours or 80 km at an average 11.5 km/hr
Maximum cruising speed	19 km/hr

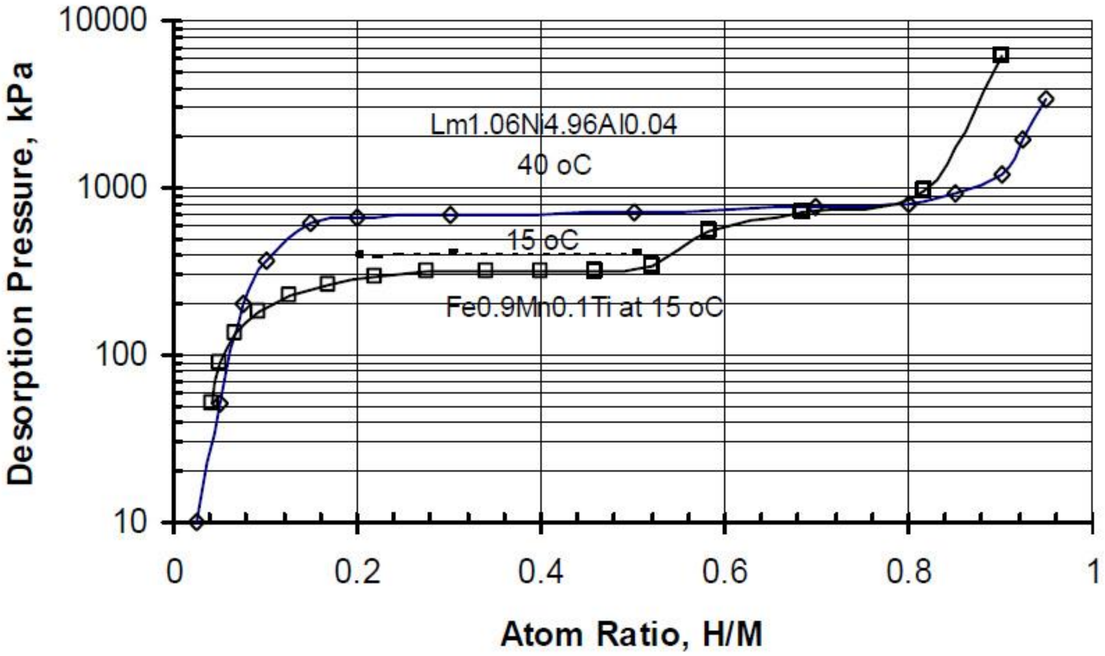

Figure 12. Hydrogen desorption isotherms for $Fe_{0.9}Mn_{0.1}Ti$ at 15 ^{o}C and $La_{1.06}Ni_{4.9}Al_{0.04}$ at 40 ^{o}C.

Figure 13. Utility vehicle with hydrogen storage tanks.

HYDROGEN STORAGE IN PALLADIUM

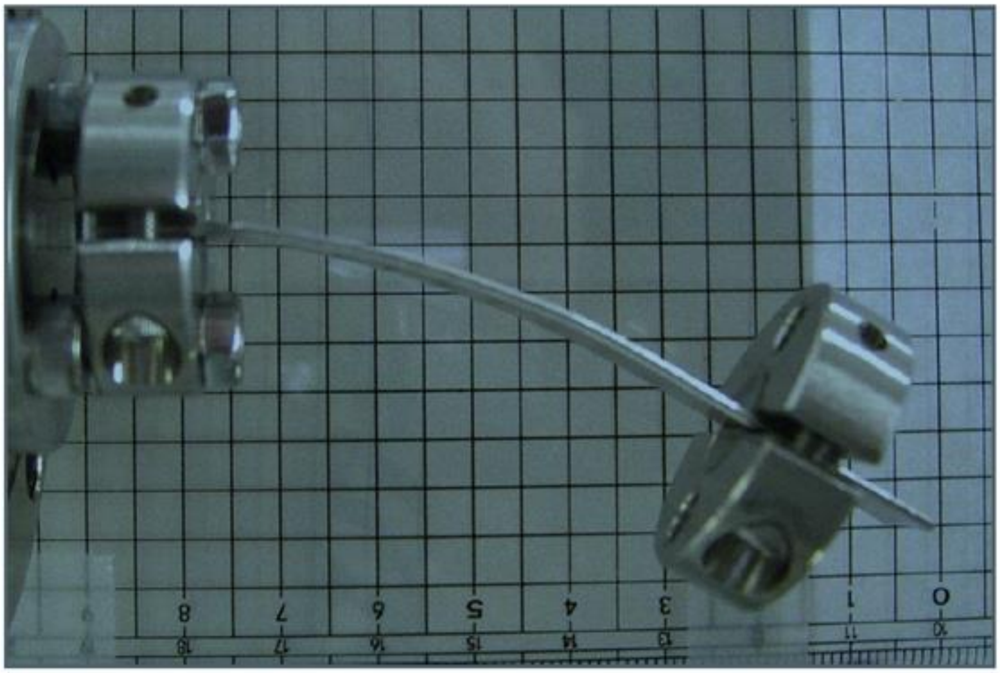

Figure 14. Anomalous deformation of palladium bending with hydrogen absorption [1].

INTRODUCTION

Palladium is a rare silvery metal notorious in that it can absorb vast quantities of hydrogen in its crystalline lattice. When it is saturated, the ratio of hydrogen to palladium can be as high 0.6, which is why the metal is used to filter and even store hydrogen.

Saturated with hydrogen at room pressure, $PdH_{0.7}$ still contains about 30 percent of the octahedral holes unoccupied, so that under mechanical stress the hydrogen could migrate from place to place, rather than to escape from the lattice. Materials scientists have discovered that this process has an extraordinary effect on the metal.

It is easy to imagine that the movement of hydrogen atoms in and out of the metallic lattice has little effect on the material. But that turns out to be wrong, as Akio Kawasaki et al. at the University of Tokyo discovered when they decided to test the idea [1].

EXPERIMENTAL OBSERVATIONS

In order to investigate the anomalous deformation of palladium metal during hydrogen absorption and desorption cycles Kawasaki et. al. [1] measured the dynamical changes of the bending and extension of a palladium plate at 150 ^{o}C, both spontaneously and under a small gravitational force.

A 7-cm long palladium plate, when held horizontally with a 124 g weight at the free end, was found to be deformed by about 1 cm in 3 minutes after hydrogen absorption, and was further deformed during desorption. The speed of the deformation was largest at around the nominal composition of $PdH_{0.11}$, which is near the point of spinoidal decomposition into the α and β phases. The present observation infers that Pd metal, when it absorbs or desorbs hydrogen, undergoes a transient change to a quasi-liquid, which has a strong correlation with the α to β transitions [1].

Materials scientists have known for some time that palladium expands when it absorbs hydrogen and shrinks during desorption. What they had not known until now is the toll that this process takes on the metal.

Kawasaki et al. attached a rectangular plate of palladium about the size of a stick of gum to the side of a chamber so that it stuck out horizontally. They then heated it to 150 ^{o}C and hung the weight of an apple on the end of plate. They then pumped hydrogen into the chamber and waited while the metal absorbed it.

To their surprise, the palladium immediately drooped under the weight and continued to droop as the hydrogen was pumped out of the chamber and the gas was desorbed.

In contrast, when they hung the plate vertically with the weight hanging beneath, there was almost no stretching at all.

There is no escaping the conclusion that hydrogen somehow robs palladium of its strength but in a very specific way.

INTERPRETATION

That is a somewhat unexpected result; but one that Kawasaki et al. think they can explain. In its pure state, the Pd lattice has a face centered cubic structure but this has to change to allow so much hydrogen on board. Materials scientists know that when this happens, it can adopt two other structures known as the α and β phases as well as a mixture of these phases.

Kawasaki's conclusion is that during this change, the metal atoms are neither held in a rigid solid structure nor able to move in an entirely random way either. This makes it a little like a liquid. In fact, physicists call this type of material a quasi-liquid.

So what they have is a material that they can change into a quasi-liquid at will. That should pique the interest of materials scientists. The next stage will be to study the change using various techniques such as x-ray diffraction and perhaps Nuclear Magnetic Resonance, NMR which should reveal what happens to a substance as it morphs from a solid to a quasi-liquid.

POTENTIAL APPLICATIONS

As for applications, just where such a quasi-liquid could be put to good use is not clear. Suggestions abound.

Water behaves like a quasi-liquid at a low distance scale too due the presence of water clusters, which are held together firmly; but they are still elastic and fluid. One of the applications of this behavior is to insert radio waves into such clusters. If one balances the frequency of the standing waves at the surface and volume of the clusters well, a resonance breaking of water molecules will occur at the energy density, which is a million times lower than the energy density required for splitting of water molecules.

Even more interesting, a metastable mixture of hydrogen and hydrogen peroxide may be formed, which could never appear during splitting of water at high temperatures.

Most interesting; if one creates quasi-liquid deuterium clusters in palladium and insert the proper microwave frequency into it, then the standing waves at the surface of the clusters could resonate with the volume of the atoms in such a way that a beta capture may occur, which could initiate a low energy nuclear reaction at an energy density million-times lower than it is required for production of energy.

Even bettter, during such a reaction the metastable channel of nuclear reaction may occur without formation of neutrons, which is something that does not occur during hot fusion reactions.

The second experiment shows that the palladium did not lose its tensile strength. In the first experiment, the droop shows that it bends easier. Therefore the palladium must have become weaker in compression, i.e., its atoms can be packed closer.

A useful application could be considered for implementation of Pd as a chemical fuse.

ALTERNATE INTERPRETATION

Another explanation of the observations is that when Pd absorbs hydrogen there is a reduction in the bulk modulus but little to no effect on the Young's modulus. It is possible that in the plate the underside has compressed but the top did not lengthen. That would also match the fact that the bar does not stretch under the same conditions.

The strain caused by the absorption of H into the lattice would allow more freedom of movement under compression where H acts like a lubricant, and compression would move the lattice elements relative to each other without reducing the space for the hydrogen. In contrast elongation through stretching would require compression of the hydrogen in the system.

One can measure expansion or compression of a metal strip by bonding it to another metal strip. In this case the effect could be found to be reversed.

DISCUSSION

One of the key challenges of a hydrogen economy is that of hydrogen storage. Without a cost-effective, compact and practical solution to the storage of hydrogen on board moving vehicles, the promise of a clean and reliable energy supply will not significantly materialize in the transportation sector and in other applications.

Worldwide research is underway to solve the storage challenge onboard vehicles with solid-state hydrogen storage based on solid adsorbents, advanced hydrides and combinations thereof.

The challenges include reducing weight, lowering cost and reducing refill time at the service station. There are distinct opportunities for hydride-based hydrogen storage in hydrogen delivery, refueling stations, and portable power in competition for compressed or cryogenic hydrogen.

Metal hydrides offer the advantages of low operation energy, high density without high pressures and low temperatures. The disadvantages are their weight since they hold a low weight percentage of hydrogen, and their sensitivity to impurities. Research is needed in identifying lighter materials with a higher weight percentage in hydrogen, with a resistance to impurities inclusion.

Metal hydride applications can also use hydrogen as a working fluid, not just an energy source in fuel cells. The result is a collection of efficient, cost effective technologies ranging from high power, high cycle life nickel hydrogen batteries to electric automobile air conditioners.

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