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DISCLAIMER

Hydrogen Storage Development for Utility Vehicles

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Abstract: Hydrogen storage for mobile applications is still a challenge. Savannah River Technology Center (SRTC) and its partners have identified industrial utility vehicles and mining vehicles as potential early niche markets for the use of metal hydride to store hydrogen. The weight of metal hydride is not a problem for these vehicles. The low pressure of metal hydride gives a safety advantage. SRTC has developed onboard hydrogen storage containers using metal hydrides for the demonstration of two generations of fuel cell powered utility vehicles. Another storage container is being developed for a mining vehicle. This paper provides a brief overview of the utility vehicle project and a detail discussion of the hydrogen storage system.

1. Introduction

A 3-phase project to study and demonstrate the viability of industrial fuel cell vehicles was completed between 1997 and 2001 by a team of industrial, academic and U.S. Department of Energy contractor organizations. The team included Westinghouse Savannah River Company, Southeastern Technology Center, Energy Partners, Deere and Company, Teledyne Brown Engineering Energy Systems, University of South Carolina, and York Technical College. The U.S. Department of Energy provided the funding. The study in phase 1 concluded that industrial fuel cell vehicles are a commercially viable product in a well-understood niche market. In phase 2 and 3, the team developed and demonstrated two John Deere Gator™ vehicles using a fuel cell power system and onboard metal hydride hydrogen storage. This paper briefly reviews the technical aspects of the project and discusses the hydrogen storage system in detail.

2. Vehicle and power system

The vehicles employed in this project were modifications of a commercial John Deere Gator™ model. They are light duty industrial vehicles originally powered by a gasoline internal combustion engine. Their common uses are in farming, ground-keeping and golf course maintenance. For this project, the combustion engine, the transmission, the drives and other related supporting equipment were replaced with a fuel cell stack, a series wound electric motor, and metal hydride hydrogen storage vessels. Figure 1 is a picture of Gator™ 2 after the modification. A 60-cell fuel cell stack by Energy

Figure 1. Picture of the Gator 2 industrial fuel cell vehicle.

Partners [1] is installed under the cargo box. Two assemblies of metal hydride hydrogen storage vessels are mounted on both sides of the vehicle between the front and rear wheels. Gator™ 1 and 2 looks identical. The differences are in the fuel cell stack design, the metal hydride material, and the heat and water management.

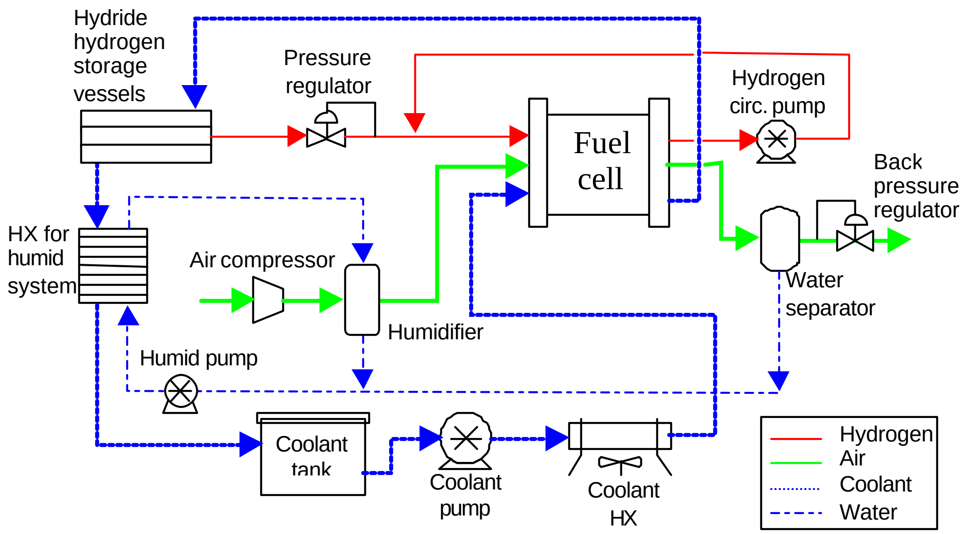


Figure 2. The power system of Gator 2.

The power system includes the fuel cell stack, the hydrogen storage system, the coolant loop, the water loop and the air loop. The arrangement of these components for Gator™ 2 is shown in Figure 2. Hydrogen from the metal hydride storage vessels goes through a pressure regulator to the fuel cell stack. A hydrogen circulation pump recycles the hydrogen from the outlet of the fuel cell stack back to the inlet to maximize the use of the hydrogen. A periodic purge of the recycle hydrogen limits the accumulation of impurities including water vapor. An air compressor delivers air through a humidifier to the fuel cell stack. The outlet air stream passes through a water separator then exhausts to ambient through a backpressure regulator. The separated water joins the humidifier water that loops through a heat exchanger then the humidifier by a circulation pump. The coolant loop includes a coolant pump, 3 fan-cooled heat exchangers, the fuel cell stack, hydrogen storage vessels, the humidifier heat exchanger and a coolant tank. Heat removed from the fuel cell stack is first used to release the hydrogen from the storage metal

Table 1. Specifications of Gatorä 2

Vehicle chassis mfr./type	Deere & Co. / Gator™ 6x4
Fuel cell stack manufacturer	Energy Partners
Fuel cell type	NG2000™ 60 cells
Fuel cell operating pressure	150 kPa (122 to 308 kPa)
Fuel cell operation temperature	60 ^{o}C
Hydrogen / air flow rates	1.5x / 2.5x stoichiometric
Coolant	De-ionized water
Fuel cell power @ 163 kPa	8.3 kW at 38 V
Metal hydride hydrogen storage designer	Westinghouse Savannah River Co.
Metal hydride hydrogen storage fabrication	Hydrogen Components Inc.
Hydride material	$Fe_{0.9}Mn_{0.1}Ti$
Hydrogen discharge temp./ pressure @ 50% loading	50 ^{o}C / 756 kPa
Total hydrogen storage	2 kg
Maximum refueling time @ 2170 kPa	60 minutes
Operating range	7 hours, or 80 km @ 11.5 km/hr avg.
Maximum cruising speed	19 km/hr
Vehicle weight	~ 900 kg

hydride, then to warm up the humidifier water, before it is cooled by the fan-cooled heat exchanger. Some key specifications of Gator™ 2 are given in Table 1. The power system arrangement for Gator™ 1 is different and is less efficient. It will not be discussed here.

3. Metal hydride hydrogen storage

Hydrogen storage for mobile application is still a challenge. The storage methods being developed include compressed gas, cryogenic liquid and solid metal hydride. Each of these storage methods has its advantages and disadvantages. The main issues are safety, volume, weight, and energy efficiency. There is still no clear winner at this point. We had chosen metal hydride for this project for several reasons. It stores hydrogen at low pressures that is a safety advantage. Hydrogen is absorbed and released by the metal hydride using low quality cooling and waste heat therefore it is energy efficient. Hydrogen volumetric density in metal hydride is as high as liquid hydrogen and 600-bar compressed gas, so that the container is compact. The main disadvantage of metal hydride hydrogen storage is its weight. The weight content of hydrogen in practical metal hydrides is still low at the present, less than 1.8 wt%. We had chosen applications that weight is not critical. The thinking is that, in the near future, lighter metal hydrides or other solids will be available. When that happens, the design of the metal hydride vessel developed in this project will be directly applicable. And the weight reduction will be a great improvement.

3.1 Hydrogen storage system design targets

The storage system for the Gator™ vehicle was designed to support the vehicle to run for 7 hours per refuel. Based on a fuel cell stack average power of 5 kW, and a fuel cell efficiency of 60%, the target hydrogen storage capacity was set to be 2 kg. The hydrogen pressure and delivery rate was targeted to meet the full power requirements of the fuel cell stack, targeted for 10 kW. Other parameters were set based on acceptability and capability of the system. Table 2 summarizes the target performance of the storage system for the Gator™ vehicle.

Table 2. Storage system target performance for the Gatorä vehicle

Parameters	**Target**
Hydrogen capacity	2 kg
Desorption temperature	50 ^{o}C
Desorption pressure (min.)	5 atm
H_2 delivery rate (max.)	100 STP L/min
Refueling temperature	35 ^{o}C
Refueling pressure	20 atm
Refueling time	< 60 minutes
System volume	<100 liters
System weight	< 350 kg

3.2 Metal hydride selection

The first parameters for the selection of a metal hydride for the application is the desorption pressure and temperature. The heat source is the coolant for the fuel cell stack. The fuel cell stack target operating temperature is 60 ^{o}C. This will be the maximum desorption temperature for the metal hydride. The selected metal hydride must be able to provide a desorption hydrogen pressure of 5 bars or more at a temperature somewhat lower than 60 ^{o}C. A target temperature of 50 ^{o}C was selected. Next to the desorption temperature and pressure, stability and cost of the material are important. The material must be able to repeat the hydrogen absorption and desorption cycles without loosing its capacity. It needs to be produced at a practical cost.

Based on these parameters, two metal hydrides were selected for the project. A lanthanum-rich-mischmetal (Lm) alloyed with nickel and aluminum, $Lm_{1.06}Ni_{4.96}Al_{0.04}$, was used in Gator™ 1. An iron-manganese-titanium alloy, $Fe_{0.9}Mn_{0.1}Ti$, was used in Gator™ 2. The first alloy was procured from Japan Metals and Chemicals, the second was from Hydrogen Components Inc. and Galt Alloys Inc. USA. Both alloys have similar pressure-temperature properties. The first alloy has a flatter and slightly wider plateau, and is expected to be more stable toward temperature and gas impurities. But the second alloy is lighter and is much lower in cost. The hydrogen capacity by weight is 1.2% and 1.6% for alloy 1 and 2, respectively. The cost is $34/kg versus $14/kg. This translates to hydrogen storage costs of $2.83/g and $0.88/g of hydrogen stored, a reduction by a factor of 3. A third alloy, the Hydralloy C15 by GfE was considered but not chosen, for it was several times more expansive than the $Fe_{0.9}Mn_{0.1}Ti$. Figure 3 compares the desorption van't Hoff plots of these three alloys. All three meet the desorption pressure and temperature requirements of the application. Figure 4 shows typical desorption isotherms of the $Lm_{1.06}Ni_{4.96}Al_{0.04}$ and the $Fe_{0.9}Mn_{0.1}Ti$. The first material has a wider and flatter plateau. The second material has two plateaus. Producer data indicated that the second plateau has the tendency to drift up in pressure after repeated cycles. Stability improvement of this material is under study by the producer and user.

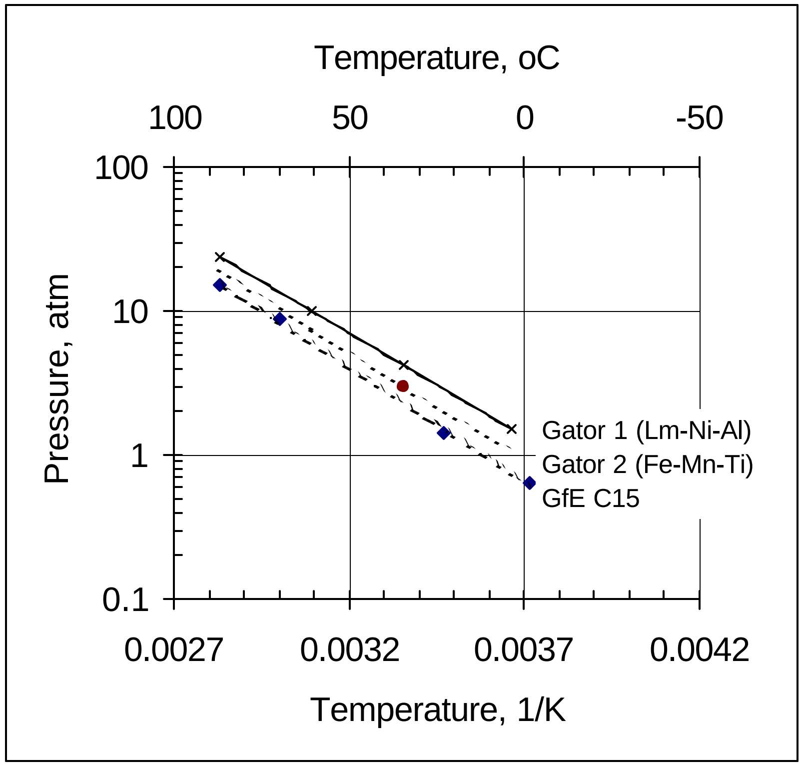


Figure 3. Desorption van't Hoff plots of $Lm_{1.06}Ni_{4.96}Al_{0.04}$, $Fe_{0.9}Mn_{0.1}Ti$, and GfE C-15 (data from producers)

3.3 Heat transfer considerations

Hydrogen absorption and desorption of metal hydride is a heat driving reaction. The heat of reaction varies from one material to another, but for the practical materials it ranges approximately from 5 to 10 Kcal/mole of hydrogen reacted. That is, for every mole of hydrogen absorbed approximately 7 kcal of heat must be removed from the material. Similar amount of heat must be supplied to the material

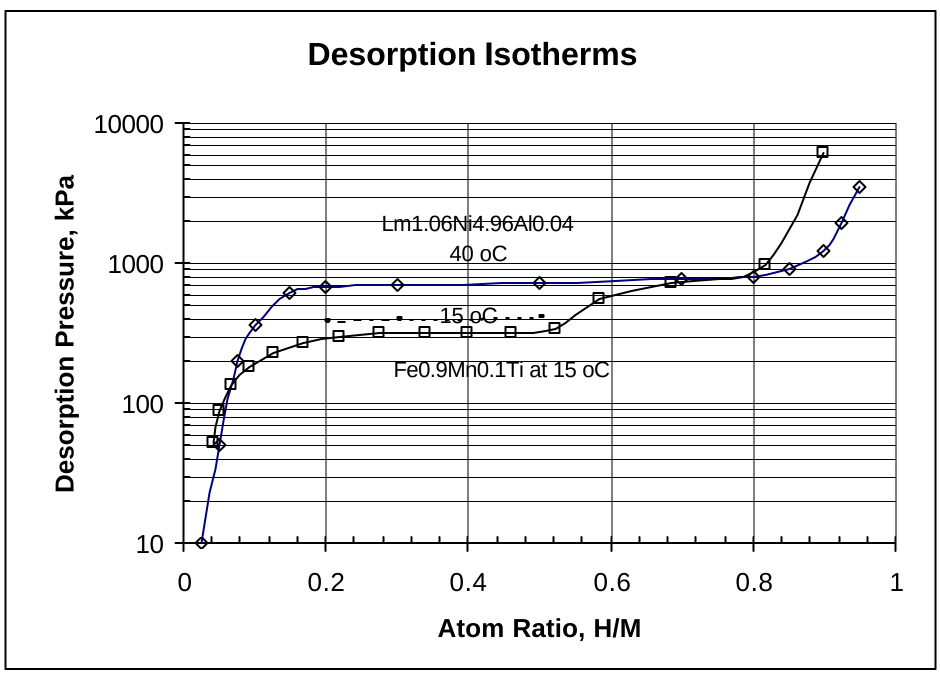


Figure 4. Typical desorption isotherms of $Lm_{1.06}Ni_{4.96}Al_{0.04}$ and $Fe_{0.9}Mn_{0.1}Ti$ (data from producers)

for hydrogen desorption. The rate at which this heat can be removed from or supplied to the material determines the refueling time, or the maximum hydrogen delivery rate. For all practical applications, the refueling time is desired to be short, much shorter than the operation time. Therefore, the target refueling time dictates the heat transfer requirements.

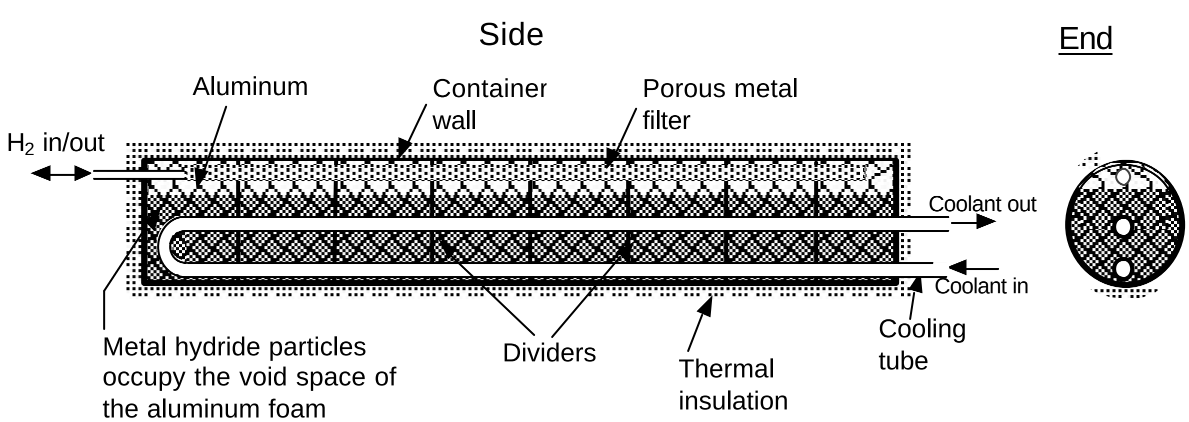
Let us consider a metal hydride vessel as having a vessel wall and a vessel volume. The vessel wall defines the volume, and the volume contains the metal hydride. The vessel wall has a surface, and through this surface the needed heat is transferred. Therefore, the term ”surface per unit volume” can be used to indicate relatively how quickly a given metal hydride vessel can be refueled. The simplest vessel is a cylindrical container of radius R and length L. The volume is then pR^2L, the surface is 2pRL (end surface neglected), and the surface to volume ratio is 2/R. From this last term it is obvious that the smaller the radius the quicker the vessel can be refueled. But the volume is also small that many vessels will be needed for a given storage capacity. That will be impractical. Therefore, the trick is how to design a large radius vessel with a large surface for heat transfer at the same time. Two options are available. One may use fins or foams to increase the effective heat transfer area in a metal hydride vessel.

3.4 Weight considerations

Metal hydride is heavy. The weight of the vessel itself should be as light as possible to minimize the total weight. The vessel weight can be minimized by the use of a light construction material and by the design of an efficient heating/cooling channel. On material, aluminum and stainless steel were considered. The analysis showed that on the basis of weight per volume of the vessel, stainless steel gives a lighter vessel. For the heating/cooling channel, one may use a full jacket or internal tubes. Analysis showed that internal tubes are much lighter than a full jacket. The challenge is how to create sufficient surface area for heat transfer without using too many tubes. This again requires the use of extended surfaces in the form of fins or foams.

3.5 Vessel design

Based on the above discussion, a modular design approach was used. Each module is a tubular vessel as shown in Figure 5. Each tubular vessel is constructed from thin wall stainless steel tubes about 9 cm in diameter and 76 cm long. Inside are metal hydride powder, aluminum foams, aluminum divider plates, a U-shape coolant tube and a porous stainless steel filter. The aluminum foam is a network of ligaments forming a three-dimensional open structure. The foam structure occupies essentially the whole space of the vessel, but the aluminum takes up only about 6% of the volume. The metal hydride powder fills about 80% of the open space among the aluminum



U.S. Patent 6,015,041

Figure 5. Schematic of the SRTC metal hydride hydrogen storage vessel.

ligaments. The 20% free space allows the powder to expand and contract so that the expansion stress on the vessel wall is minimized. The aluminum divider plates separate the length of the vessel into compartments so that the metal hydride powder will not shift from one compartment to the others. This prevents any of the compartments from filling up by the metal hydride powder and avoids the expansion stress problem. The U-shape tube is for water circulation, transferring heat away from the metal hydride powder during refueling, and heat to the powder during discharging hydrogen. The aluminum foams help the heat transfer between the coolant tube and the metal hydride powder. The porous filter running through each compartment near the top, permits hydrogen gas to flow in and out each compartment freely, but confines the metal hydride powder within the compartments. This basic design was applied successfully in an earlier project for onboard hydrogen storage for a transit bus [2].

3.6 Vessel assembly

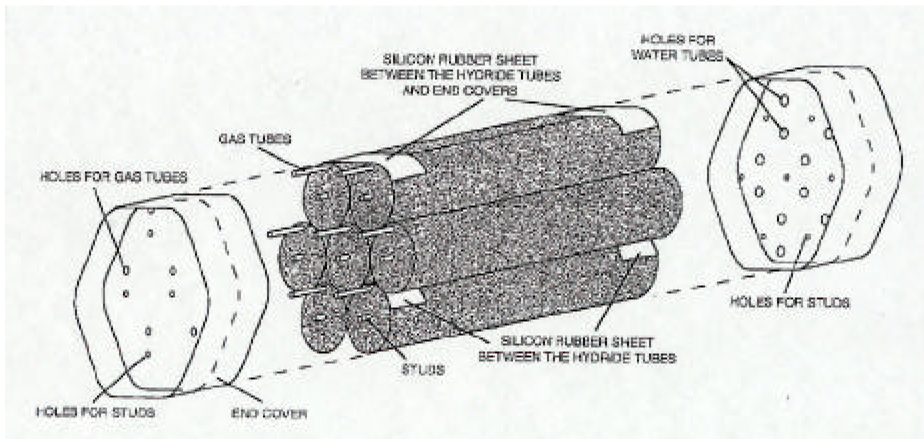


Figure 6. Schematic of metal hydride vessel bundle

The hydrogen storage system for both Gator™ 1 and Gator™ 2 consists of 14 modular vessels, giving a storage capacity of 2 kg hydrogen. The vessels are assembled into two bundles using end covers as shown in Figure 6. One end cover contains the hydrogen header connecting the hydrogen lines from the vessels. The other end cover contains the coolant tubes connecting the inlet and outlet of the water tubes. A metal plate at the bottom running from one end cover to the other protects from road debris. The bundles are mounted onto the sides of the vehicle using two metal straps as shown in the photo of Figure 7. The system is designed to operate at pressures up to 33 bars and is pressure tested at 52 bars. The total weight of the storage system for Gator™ 2 was 244 kg with a total volume of 110 liters.

Figure 7. Metal hydride vessel assembly mounted on vehicle

4. Results

4.1 Activation

Both metal hydrides for Gator™ 1 and 2 required activation before use for vehicle operation. Activation involved two steps. The vessels were first evacuated and purged with hydrogen to eliminate air from the vessels. They were then exposed to hydrogen at a pressure higher than the normal refueling pressure. The Gator™ 1 material, $Lm_{1.06}Ni_{4.96}Al_{0.04}$, was easier to activate than the Gator™ 2 material, $Fe_{0.9}Mn_{0.1}Ti$. It began to absorb hydrogen readily after exposure to 28 bars of hydrogen for approximately 30 minutes. The Gator™ 2 material was activated similarly with a higher pressure of 32 bars. Cooling during activation was provided by water circulation through the water tubes. The hydrogen absorbed during activation was vented to atmosphere. After activation, the metal hydrides could absorb hydrogen easily under the normal refueling hydrogen pressure of 21 bars.

4.2 Refueling

During the driving test period, refueling was achieved by using a band of compressed hydrogen cylinders. The pressure was regulated to 20 bars before the hydrogen was fed to the storage vessels. With the cooling water circulating at 12 L/minute, the vessels were refueled to approximately 50% full in 15 minutes, 70% full in 30 minutes and 90 % full in 60 minutes. The first 15% could be achieved nearly instantly because of the sensible heat of the metal hydride itself. Additional refueling tests under laboratory conditions showed that increase in coolant following rate could further speed up the refueling. For example, 90 % fill could be achieved in 30 minutes with coolant at 17 L/minute.

4.3 Driving tests

The metal hydride storage systems worked well for both Gator™ 1 and Gator™ 2. Shakedown testing of Gator™ 1 revealed a number of problems associated with the fuel cell stack and its operation system. The driving testing on Gator™ 1 was therefore very limited. The limited results showed that the driving range of Gator™ 1 was only 35 km in approximately 2.5 hours. Gator™ 2 was a significant improvement over Gator™ 1. A testing period of about one month was completed before the end of the project. It accumulated 50 hours and travel 340 km. At an average speed of 11.5 km/hr, the operation time was 7 hours covering a range of 80 km. This was more than double that of Gator™ 1. The fuel economy was 22 km/L. The fuel to wheel efficiency was 25% versus 16% for an equivalent vehicle powered by a gasoline fueled internal combustion engine.

5. Conclusions

The hydrogen storage system using metal hydride worked exceptionally well for both Gator™ 1 and Gator™ 2. Gator™ 2 was successfully demonstrate to operate all day on a single refueling and handle tasks compatible with an industrial vehicle of its size. The weight issue of metal hydride was minimized by proper selection of applications. The fuel to wheel efficiency was much better than an equivalent vehicle powered by a gasoline internal combustion engine. The cost of metal hydride is still an issue but is expected to decrease significantly with mass production.

6. References

[1] M. Fuchs, F. Barbir, M. Nadal, Paper presented in the 2001 European PE Fuel Cell Forum, Luzern, Switzerland, July 2-6, 2001

[2] L. K. Heung, in T. O. Saetre (ed.) Hydrogen Power: Theoretical and Engineering Solutions, 251-256, ©1998 Kluwer Academic Publishers