On-Board Hydrogen Storage for a City Transit Bus

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ON-BOARD HYDROGEN STORAGE FOR A CITY TRANSIT BUS

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Abstract. An electric bus was modified to use hydrogen fuel for demonstration in the city of Augusta, Georgia, USA. The hydrogen fuel is stored in a solid form using an on-board metal hydride storage system. The storage system performs better than expected.

1. Introduction

Hydrogen is widely considered to be the fuel of the future, mainly because it is renewable and burns cleanly. As part of the technology transfer effort of the US Department of Energy (DOE), a team named H2Fuel was formed to utilize the hydrogen technology developed at the Savannah River Site. The team involved DOE, its site contractor, industry, academia and local government. The task of the team is to convert a battery powered, 10-meter transit bus into a hydrogen-powered hybrid bus. The bus would be used by the city of Augusta, Georgia, in its transit system. The objectives of the project include: 1) Apply the existing metal hydride technology at the DOE Savannah River Site to develop an on-board hydrogen storage system; 2) Develop a near-zero emission internal combustion engine; 3) Enhance public awareness and acceptance of hydrogen as a fuel for transportation. The emphasis of this paper is on the on-board hydrogen storage system.

2. The Power Train

The original electric bus was powered by four 28-battery packs and had a driving range of about 130 km. Two of the four battery packs (approximately 1,000 kg per pack) were replaced with metal hydride hydrogen storage vessels. An internal combustion (IC) engine and an electric generator were added. The hydride storage system stores and feeds hydrogen to the combustion engine. The engine-generator set produces electricity to power the electric drive motor and to charge the batteries. The batteries serve as a reservoir for the excess energy of the generator, to be charged when the power demand is low and to be drawn down when the power demand is high. This arrangement allows the use of a small generator (70 kW) and a large electric drive motor (170 kW). This hybrid power system permits the IC engine to run most efficiently and is expected to extend the driving range of the original electric bus from 130 km to 200 km. A photo of the bus and a schematic of the hybrid power system are shown in Figures 1 and 2, respectively.
The hydrogen is stored in metal hydride vessels. The metal hydride stores hydrogen in a solid state, and will not release the hydrogen until heat is provided. It is therefore has a safety advantage over compressed gas or liquid hydrogen. Metal hydrides have been studied for onboard hydrogen storage before\(^1\),\(^2\), but not for a large bus like the one in this project.

![Schematic of the hydrogen-powered hybrid power system](image)

**Advantages**
- IC engine at high efficiency
- Ultra low emission

Figure 2. Schematic of the hydrogen-powered hybrid power system

3. **On-Board Hydrogen Storage System Design Requirements**

When serving in the Augusta city transit system, the bus is expected to be started up in the morning and run for the day. At the end of the day it will be refueled and charged. To fulfill this operation plan, the hydride storage system must meet the following design requirements:

- Hydrogen storage capacity is for a full day's scheduled operation of the bus.
- The storage system does not add more weight to the original electric bus.
- Hydrogen pressure and flow rate meet the fuel requirements of the engine.
- Refueling time to be compatible with the operation schedule.
- Engine coolant is used to provide heat for hydrogen desorption.
- Water is used for cooling during refueling via an external heat exchanger.
- Refueling hydrogen is from a tube trailer or an electrolyzer.

To meet the above requirements, different metal hydrides and hydride vessel designs were considered. The chosen metal hydride and vessel design are described below.

4. **Metal Hydride Selection**

Lanthanum-nickel-aluminum type material has been used at the Savannah River Site for more than 15 years in various applications\(^3\),\(^4\). This type of material has been shown to have excellent chemical stability and was chosen to be the starting material for the bus project. To reduce the cost of the material, lanthanum was replaced with "lanthanum rich mischmetal" (designated symbol Lm). The general formula was Lm\(_x\)Ni\(_{5+y}\)Al\(_y\). A value of \(x\) slightly larger than 1 was used to improve the material's performance\(^5\). The value of \(y\) is adjusted for the required hydrogen
pressure, since the hydrogen pressure increases with the decrease of the y value. Three specific formulations were tried before the selection criteria were met. The final material has the following properties:

Formula: $Lm_{1.06}Ni_{4.96}Al_{0.04}$  
(Lm = La 55.7% Ce 2.5% Pr 7.7% Nd 34.1%)

Absorption pressure at 60°C and 0.5 H/M: 18.5 atm  
Desorption pressure at 60°C and 0.5 H/M: 13.5 atm  
H$_2$ capacity at 40°C and 20 atm: 0.92 HIM; 1.27 wt%  
van't Hoff equation at 0.5 H/M: $\ln P = \Delta H/(R*T) + \Delta S/R$

(P=pressure, atm; $\Delta H$=enthalpy, 6580 cal/mol for absorption, 6577 cal/mol for desorption; $\Delta S$=entropy, 25.56 cal/mol/°K for absorption, 24.91 cal/mol/°K for desorption; R=gas constant, 1.987 cal/mol/°K)

5. **Hydride Vessel Design**

The technical issues in the design of metal hydride vessels for on-board hydrogen storage include the following:

- Hydride particles expand upon hydrogen absorption and contract on desorption, which can cause compaction, swelling and consequent damage to the vessel.
- Metal hydride powder is a poor heat transfer medium causing slow hydrogen absorption and desorption.
- Filters used to confine the hydride powder can impede the flow of hydrogen due to clogging.
- Metal hydrides are heavy and require light weight vessels.

With the above issues in consideration, the final design of the on-board hydrogen storage system consists of two "boxes" of metal hydride vessels. Each "box" contains 24 horizontally installed cylindrical vessels. The vessels are 9-cm in diameter and 152-cm long. They are assembled inside an aluminum box to form a stack of 6 vessels wide and 5 layers high. The aluminum boxes are 66-cm wide, 53-cm high, and 173-cm deep. All 24 vessels in a box are connected in parallel. The photo of a partly assembled box is shown in Figure 3. The boxes are installed below the bus floor on both sides of the chassis. The total weight of the two boxes of hydride vessels is 1900 kg, about the same as the two packs of batteries which they replaced. The weight of metal hydride is 1250 kg, or 66% of the total weight. The hydrogen capacity is 15 kg compared to the bus gross weight of 15,000 kg.

The cylindrical hydride vessels are made from thin wall, stainless steel tubes. The components inside each vessel include a porous stainless steel filter, aluminum divider plates, cylindrical
aluminum foam pieces, and a U-shaped water tube. The filter permits hydrogen to flow freely in and out of the vessel but confines the metal hydride powders in the vessel. The divider plates separate the vessel into short sections to prevent the metal hydride powders from shifting among the sections. The aluminum foam pieces with metal hydride particles in their pores improve the heat transfer between the hydride and the water tube. The engine coolant flows through the water tube to provide heat during desorption and to remove heat during absorption of hydrogen. A schematic of the hydride vessel is shown in Figure 4.

![Schematic of the hydride hydrogen storage vessel](image)

**Figure 4. Schematic of the hydride hydrogen storage vessel**

6. Heat Transfer

The desorption of hydrogen from the storage system depends on the transfer of heat from the engine coolant to the hydride vessels. When running at full power, the hydrogen combustion engine requires a hydrogen feed rate of 6 kg/hr at 10 atm pressure. At this rate the heat required for hydrogen desorption is calculated to be 19800 kcal/hr. The hydride storage system must be able to transfer this much heat from the coolant to the metal hydride when needed during operation. It can be shown by calculation that the main resistance to heat transfer is in the metal hydride powder. Based on previous work, the heat transfer coefficient of a metal hydride bed is solely dependent on the hydrogen pressure and is approximately 70 cal/hr/m²/°C at 10 atm hydrogen pressure. With this heat transfer coefficient, the coolant can only transfer about 8,000 kcal/hr to the metal hydride, which is only 0.4 of what is required. The heat transfer coefficient must be increased to 180 kcal/hr/m²/°C to meet the required heat transfer rate.

Aluminum foam pieces were added to the vessel to improve the heat transfer in the metal hydride bed. Test results showed that the foam was able to increase the effective heat transfer coefficient of the vessel by a factor of approximately 5, to 360 kcal/hr/m²/°C. This is two times the required value of 180 kcal/m²/°C. With this higher heat transfer coefficient, the required maximum hydrogen rate can be provided by 24 vessels, or one half of the total number of vessels installed.
7. Performance

The H2Fuel bus has undergone driving tests in the streets of Augusta since April 1997, accumulating more than 1000 km of travel distance at the time of this writing. The on-board hydrogen storage vessels have been refueled over 20 times.

7.1 Activation

Activation of the on-board metal hydride was accomplished at ambient temperature using flowing water for cooling. The hydride vessels were evacuated and purged with hydrogen, then exposed to 20 atm hydrogen. The hydride began to absorb hydrogen after an incubation time of about 15 minutes. Once started, the hydrogen was absorbed as fast as it could flow into the vessels. Figure 5 shows the activation data generated in the laboratory with small samples. During activation, when the metal hydride was exposed to hydrogen for the first time, the incubation time and saturation time were pressure dependent. At 27 atm pressure, the hydride reached 90% saturation in about 60 minutes. At 15 atm it took more than 120 minutes. These data are consistent with those of the on-board activation.

![Activation of H2Fuel Metal Hydride](image)

7.2 Hydrogen Feed Rate

Operational data collected to date have shown that the hydrogen storage system can supply hydrogen to the engine at a rate exceeding the design goal. This was demonstrated by a set of data collected during a test operation in which only one box of 24 hydride vessels was used to feed the engine. Using the average values of coolant temperature, hydride temperature and
hydrogen consumption rate, and the water coolant tube surface area, one can calculate the heat transfer coefficient. The calculation yielded a heat transfer coefficient of 426 kcal/hr/m²/°C. See Table 1. This is better than the 360 kcal/hr/m²/°C shown by laboratory tests, and the required value of 178 kcal/hr/m²/°C for 6 kg/hr hydrogen feed. This heat transfer coefficient allows the engine to operate with only one of the two boxes of hydride vessels on line.

<table>
<thead>
<tr>
<th>TABLE 1. Heat transfer and hydrogen feed rate data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant temperature in coolant tube</td>
</tr>
<tr>
<td>inlet=65.5 °C, outlet=54.4 °C</td>
</tr>
<tr>
<td>Average hydrogen feed rate from one box (24) of</td>
</tr>
<tr>
<td>the vessels over a one hour engine operation</td>
</tr>
<tr>
<td>3.4 kg/hr</td>
</tr>
<tr>
<td>Hydride temperature in equilibrium with 10 atm</td>
</tr>
<tr>
<td>hydrogen pressure (average)</td>
</tr>
<tr>
<td>51 °C</td>
</tr>
<tr>
<td>Average heat transfer rate from coolant to hydride</td>
</tr>
<tr>
<td>=3.4 kg/hr × 6.6 kcal/mole*(1000 mole/2 kg)</td>
</tr>
<tr>
<td>12540 kcal/hr</td>
</tr>
<tr>
<td>Overall heat transfer coefficient</td>
</tr>
<tr>
<td>=12540 kcal/hr/(60 °C -51 °C)/2.93 m²</td>
</tr>
<tr>
<td>426 kcal/hr/m²/°C</td>
</tr>
</tbody>
</table>

7.3  REFUELING

Presently, hydrogen from a tube trailer is used to refuel the bus. The connection between the hydrogen supply and the hydride storage system is accomplished by using a Sherex fueling nozzle and receptacle. The heat of absorption during refueling is removed via a water-cooled external heat exchanger. With a supply hydrogen pressure set at 18 atm, the hydride can be charged to 75% full in about 60 minutes; another 60 minutes are needed to charge the remaining 25%. The refueling time meets the original target time of 2 hours.

8. Conclusions

An on-board hydrogen storage system using metal hydride has been successfully developed, fabricated and demonstrated on a city transit bus. Road testing to date has shown that the original design goals have been reached or exceeded. The use of metal hydride for on-board hydrogen storage gives a safety advantage and has a high potential to be successfully used in applications where weight is not a prohibitive factor. The hydrogen storage system in this project was developed for an IC engine, but it can be applied to a fuel cell powered system as well. As the fuel cell technology becomes more economical, the IC engine can be replaced with a fuel cell to further increase the energy efficiency.
Acknowledgments

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References