Using Metal Hydride H₂ Storage in Mobile Fuel Cell Equipment: Design and Predicted Performance of a Metal Hydride Fuel Cell Mobile Light

C. Song¹, L.E. Klebanoff^{1*}, T.A. Johnson¹, B.S. Chao²,
A. F. Socha¹, J.M. Oros³, C.J. Radley³, S. Wingert⁴, and J.S. Breit⁵

¹Sandia National Laboratories, Livermore, CA 94551 USA

²Ovonic Battery Company, 2983 Waterview Dr., Rochester Hills MI, 48309 USA

³Altergy Systems, 140 Blue Ravine Road, Folsom, CA 95630, USA

⁴Multiquip Inc., 18910 Wilmington Ave., Carson CA 90746 USA

⁵Boeing Commercial Airplanes, System Concept Center, Everett, WA 98203 USA

*Author to whom correspondence should be addressed

Abstract

This study examines the practical prospects and benefits for using interstitial metal hydride hydrogen storage in “unsupported” fuel cell mobile construction equipment and aviation GSE applications. An engineering design and performance study is reported of a fuel cell mobile light tower that incorporates a 5 kW Altergy Systems fuel cell, Grote Trilliant LED lighting and storage of hydrogen in the Ovonic interstitial metal hydride alloy OV679. The metal hydride hydrogen light tower (*mhH₂LT*) system is compared directly to its analogue employing high-pressure hydrogen storage (*H₂LT*) and to a comparable diesel-fueled light tower with regard to size, performance, delivered energy density and emissions. Our analysis indicates that the 5 kW proton-exchange-membrane (PEM) fuel cell provides sufficient waste heat to supply the desorption enthalpy needed for the hydride material to release the required hydrogen. Hydrogen refueling of the *mhH₂LT* is possible even without external sources of cooling water by making use of thermal management hardware already installed on the PEM fuel cell. In such “unsupported” cases, refueling times of ~ 3 – 8 hours can be achieved, depending on the temperature of the ambient air. Shorter refueling times (~ 20 minutes) are possible if an external source of chilled water is available for metal hydride bed cooling during rapid hydrogen refueling. Overall, the analysis shows that it is technically feasible and in some aspects beneficial to use metal hydride hydrogen storage in portable fuel cell mobile lighting equipment deployed in remote areas. The cost of the metal hydride storage technology needs to be reduced if it is to be commercially viable in the replacement of common construction equipment or mobile generators with fuel cells.

Introduction

There is increasing interest in using quiet, efficient and non-polluting hydrogen fuel cell technology in non-motive equipment such as construction equipment and aviation ground support equipment (GSE). Keller et al. have reviewed the attributes of hydrogen-based power for zero-emissions transportation technology [1], while also describing the history and worrisome magnitudes of the greenhouse gas (GHG) emission and global climate change problems. Proton exchange membrane (PEM) fuel cell systems and their potential use in automotive and portable power technology were recently reviewed by Klebanoff and co-workers [2]. While high-pressure hydrogen storage can be used for such fuel-cell-based equipment, metal hydrides offer potential advantages for hydrogen storage, including a higher volumetric storage density, filling from lower pressure hydrogen sources, and added safety stemming from a lower overall system pressure. The U.S. Department of Energy (DOE) has historically sponsored research in solid-state hydrogen storage materials, including complex metal hydrides [3], with a focus on hydrogen storage for light-duty vehicles. However, more recently that interest has broadened to include solid-state hydrogen storage for non-vehicular but still mobile applications [4]. Unlike metal hydride (MH) use in fuel-cell electric vehicles (FCEVs) which will be refueling at hydrogen stations, or in fuel-cell material handling equipment (which will be used in a facility), fuel-cell-based portable construction equipment may not have access to supporting facilities in the field such as chilled water for dissipating heat released by the MH material during hydrogen refueling. One purpose of the present work is to assess the practical prospects for using MH hydrogen storage in the demanding and “unsupported” mobile construction equipment and aviation GSE applications.

This work originates from Boeing’s interest in bringing fuel-cell technology to aviation. Breit et al. [5] have reviewed Boeing’s interests in fuel cells, both for on-board power applications and for aviation GSE. Fuel cells provide an efficient and flexible way of providing power for aircraft needs that were formerly provided by hydraulic or pneumatic sources, such as engine start, de-ice, environmental control, pressurization, brakes and flight controls. Fuel cells can also find application as Auxiliary Power Units (APUs) [6], or as an emergency power system to replace a Ram Air Turbine (RAT) [7]. The applicability of PEM fuel cells for use on-board commercial aircraft was recently examined by Pratt et al. [8].

In advance of installing a new power technology on-board commercial aircraft, Boeing’s strategy has been to gain operational experience with PEM fuel cells in a situation just off the aircraft, in a piece of aviation GSE on the tarmac. That way, Boeing could assess the technology for performance, reliability, safety and ease of fueling in an aviation environment not as challenging as the “on-board” aircraft application. Klebanoff et al. [9] have recently reported the results of a project funded by Boeing and the U.S. DOE to design, build, field-test and then commercialize fuel-cell GSE equipment in the form of a hydrogen fuel cell mobile light tower (H₂LT), two of

which are currently in use at the San Francisco International Airport (SFO), with another two H₂LT units deployed in the Los Angeles entertainment industry by Saunders Electric Inc. The deployed H₂LT systems combine a 5 kW PEM fuel cell with hydrogen stored as a high-pressure gas at 5,000 psig (~ 350 bar) pressure in Type III, carbon fiber overwrapped pressure vessels (COPV) (i.e., “composite tanks”) to power advanced lighting. Real-world experience has now been gained with these units to provide a context in which to assess and compare the use of MH storage of hydrogen in the H₂LT application.

Sandia National Laboratories recently conducted a market analysis [10] indicating that the portable construction equipment and aviation GSE realms represent good early markets to introduce fuel cells, thereby supporting the DOE goals of fuel cell market growth. The current diesel-based mobile light tower market is approximately 100,000 units in the United States [11], thus representing a niche market within the portable equipment realm, but a good starting point for introducing fuel cells into construction equipment and aviation GSE.

The possibility was considered [12] early in the Fuel Cell Mobile Light Project that one day metal-hydride tanks could be used to store hydrogen for the fuel cell mobile light application, perhaps offering operational advantages. This study investigates how an interstitial MH hydrogen storage system would function in the PEM fuel cell mobile light, and what the attendant benefits and challenges would be compared to using 350 bar storage of hydrogen. We call the metal-hydride hydrogen light tower the *mh*H₂LT, and examine questions of feasibility, design, performance and safety that include:

1. Is it possible to design a *mh*H₂LT system that satisfies the demands of the end-user?
2. What are the volumetric energy density improvements offered by MH hydrogen storage?
3. What are the essential engineering issues to be managed in designing a *mh*H₂LT?
4. At what hydrogen pressure would the system operate?
5. How much would the *mh*H₂LT weigh?
6. How long would it take to refuel it?
7. Is it possible to refuel the *mh*H₂LT using commercial hydrogen cylinders at 150 bar?
8. Does the fuel cell provide sufficient waste heat to desorb H₂ from the metal hydride?
9. Can heat be dissipated from the MH tank during refueling without external cooling equipment?
10. What safety aspects are different with a *mh*H₂LT compared to the H₂LT?

The questions of feasibility rest largely on answers to the questions 6 – 9. Questions 6 and 9 in particular ask if a self-contained *mh*H₂LT unit without access to supporting infrastructure (cooling water, 350 bar hydrogen) could be used and refilled by traditional ~ 150 bar hydrogen cylinders typically available from local gas companies, or perhaps from mobile refueling

services such as that provided by IGX/GTM and demonstrated for the H₂LT [9]. Our analysis examines the feasibility of using the *mh*H₂LT in the mobile lighting application and sheds light on how advanced hydrogen storage approaches may find application in non-vehicular uses of fuel cells.

The remainder of this paper is organized as follows. The “Beta” H₂LT system that has recently been field tested is described, along with its operational capabilities. Then we briefly review how hydrogen can be stored in interstitial metal hydrides, focusing on the OV679 alloy developed by Ovonic and its properties most important for *mh*H₂LT performance. Results are then presented for heat transfer in the *mh*H₂LT system during fuel cell use and metal hydride recharging. An engineering 3D model is presented of the *mh*H₂LT that allows a detailed comparison with the Beta H₂LT with regard to size, mass, hydrogen storage capacity, duration, gravimetric and volumetric storage densities for hydrogen and deliverable energy, ease of system refueling and overall light tower safety. We also compare the *mh*H₂LT to the existing diesel-fueled mobile light tower technology, describing the environmental benefits, and discuss how this work relates to prior studies in this area.

Fuel Cell Mobile Light Tower (H₂LT):

The basic concept of the H₂LT is shown in Figure 1 [9]:

Figure 1: General concept of the H₂LT. The H₂LT replaces a traditional diesel-powered light tower with a system that combines gaseous hydrogen (stored on the system), a PEM fuel cell, and an energy efficiency lighting (lamp) technology. In the H₂LT, hydrogen is stored in 350 bar composite tanks; in the *mh*H₂LT hydrogen is stored in an interstitial metal hydride packed into a storage vessel. Figure reproduced with permission from Reference 9.

The right side of Figure 1 shows a diesel-powered mobile lighting system. These diesel-based light stands typically provide ~ 180,000 lumens of lighting from metal halide lights, weigh

~1730 lbs (mass of 786 kg), possess a 30 gallon diesel fuel tank and employ a 12 HP diesel engine to drive a generator. The light duration is typically ~ 48 hours. The H₂LT hydrogen fuel cell lighting system meets or exceeds the performance of the diesel light tower technology while producing zero emissions at the point of use and low operational noise. As shown in the left side of Figure 1, the fuel cell mobile light system is conceptually composed of three subsystems: fuel cell, hydrogen storage and lighting.

The PEM fuel cell used for all of the H₂LT prototype units in the Fuel Cell Mobile Light Project was the Altery Systems FPS-5 (5 kW) fuel cell, shown in Figure 2. This fuel cell was chosen because of its appropriate power output, rugged design, its successful use as a backup power system in hundreds of telecom installations, and the fact that it could be mass manufactured by a robotic assembly line for installation in commercial H₂LT units. The same PEM fuel cell will be assumed for the *mh*H₂LT system analysis presented here.

Figure 2: Altery Systems FPS-5 PEM Fuel Cell. The fuel cell has a maximal (nameplate) output power of 5 kW. Figure reproduced with permission from Reference 2.

The prototype “Beta” H₂LT units were designed by Steve Wingert of Multiquip Inc. [9]. The H₂LT hydrogen storage system used during the field tests consisted of four Type III, 350 bar COPV composite tanks with a capacity of 2.1 kg of hydrogen per tank, giving a total system hydrogen capacity of 8.4 kg. The brand of tank chosen was the ALT 836U model from Structural Composites Industries (SCI). The hydrogen tanks are mounted with steel mounting brackets for firm seating, and are protected from impact threats by steel stabilizer bars. These tanks require a 350 bar source of hydrogen for filling. Pictures of the H₂LT are shown in Figure 3. The overall dimensions of the H₂LT enclosure are 86.4 cm tall x 116.8 cm wide x 181.4 cm long. The mass of the H₂LT unit is 1132 kg, which is light enough to be towed behind a pick-up truck using standard hitch hardware (e.g. pintle or ball hitch). This H₂LT system will be directly compared with the *mh*H₂LT system to be designed and characterized in this study.

Figure 3: H₂LT enclosure, with fueling panel and electronics control panel. Figure reproduced with permission from Reference 9.

LED lighting will be assumed for the *mh*H₂LT analysis presented here. There are many choices and manufacturers for LED lights, and they have varying energy efficiencies which determine H₂LT duration. We will assume LED lighting comprised of Grote Trilliant 24V lamps. Testing of these lights [9], performed by U.C. Davis with funding from the California Department of Transportation (Caltrans), demonstrated a lighting energy efficiency of 54.3 lumens/W. A light tower can be configured based on the Grote Trilliant LEDs such that the total light output will be 177,600 lumens, consuming 3264 W of fuel cell input power. For this power consumption, the H₂LT unit (storing 8.4 kg of hydrogen) would have a duration of 40.6 hours. This light output would be about the same as a 4 lamp metal halide diesel light tower. This is a considerable light output; with 177,600 lumens output, one could read a book in otherwise pitch darkness at 150 yards distance from the H₂LT.

Design Considerations of the *mh*H₂LT

Overall System Requirements:

We consider the *mh*H₂LT to meet or exceed the operational performance of the H₂LT. Recall that with LED lighting, the duration of the H₂LT unit is 40.6 hours for a power consumption of 3264 W, giving a light output of 177,600 lumens. Our experience with the field-testing of the H₂LT indicates that this lighting performance is at the high end of the needs of various applications. This illumination was required for wide-area construction lighting at the Q-bridge

construction project in New Haven, CT [9]. However, H₂LT units with half of this light output have found satisfactory use in ground service operations at SFO, for entertainment lighting and for lighting used by road construction crews from Caltrans. Thus, the power requirements for mobile lighting can vary considerably. For this analysis, we will adopt the 177,600 lumens illumination, 3264 W power consumption and 40 hour lighting duration as the baseline (minimal) performance required.

The hydrogen storage, fuel cell and balance of plant (B.O.P.) must also fit within designated weight and geometric limitations as specified by Multiquip, Inc., the commercialization partner in the Fuel Cell Mobile Light Project. We will assume that the maximal size of the *mh*H₂LT enclosure can be the same as the overall dimensions of the H₂LT enclosure which is 86.4 cm tall x 116.8 cm wide x 181.4 cm long. Of course a smaller overall enclosure size for the *mh*H₂LT would be desirable. The total mass of the system should be 1590 kg or less if it is to be towed using pick-up trucks. If the system were heavier, there would need to be an upgrade to the axle of the mobile light trailer platform, which is an undesirable additional system cost.

Hydrogen Storage in Interstitial Metal Hydrides:

We consider the use of interstitial metal hydrides, since hydrogen storage systems based on these materials have been commercially available, for example by Ovonic Hydrogen Solutions, currently Vodik Labs. Chao and Klebanoff have reviewed hydrogen storage in interstitial metal hydrides [13]. Here we briefly summarize the most important aspects of hydrogen storage in interstitial metal hydrides for the *mh*H₂LT design and performance analysis.

Metal hydrides are a broad class of materials that undergo a reversible reaction with hydrogen. The reaction is written as:

where M_{solid} is the metallic element or alloy to be hydrogenated, $MH_{x \text{ solid}}$ is the metal hydride and ΔH is the enthalpy of formation (or hydrogenation enthalpy) associated with the metal hydride. The forward hydrogen charging reaction is exothermic ($\Delta H < 0$) where heat is liberated, whereas the reverse hydrogen discharge reaction is endothermic ($\Delta H > 0$) requiring the supply of heat to release hydrogen. Without adding heat to metal hydride MH_x during hydrogen release, the temperature of the metal hydride bed would drop as heat was scavenged from the hydride bed and its surroundings. This cooling would self-limit how much hydrogen could be released from the metal-hydride tank. Thus external heat (ideally fuel cell waste heat) needs to be supplied. Analogously, during refueling, heat is released as the spent material M_{solid} is hydrogenated. If the MH bed is not under temperature control, this heat release would produce higher bed temperatures. Eventually, the temperature would become high enough such that no further

hydrogen could be adsorbed by M_{solid} at the prevailing pressure, self-limiting how much hydrogen could be refueled. Providing for a heat supply during hydrogen consumption and providing for heat removal during hydrogen refueling, are important engineering concerns that any MH hydrogen storage system must manage [14].

Hydrogenating the metal M_{solid} produces a growing metal hydride phase $MH_x \text{ solid}$ resulting in expansion of the lattice. Depending on the absorbed hydrogen content, the volume expansion can be up to 30 - 40 %. When the metal hydride MH_x starts to release atomic hydrogen, which diffuses onto the surface of the metal alloy to form molecular hydrogen, the lattice starts to contract back towards its original state. Any well-functioning metal hydride tank must be designed to accommodate the 30 – 40% MH expansions and contractions as the system is used and refueled. Accommodating the strains associated with MH expansion largely determines the pressure rating of an interstitial MH hydrogen storage vessel.

The heat of formation ΔH and the entropy of formation ΔS of a metal hydride can be derived from pressure-composition data collected at different temperatures by means of the van't Hoff equation written for the hydrogenation reaction [13]:

$$\ln P = \Delta H/RT - \Delta S/R \quad (2)$$

where P is the equilibrium hydrogen pressure above the MH at a particular temperature T . Plotting $\ln P$ versus $1/T$ yields a line with slope $\Delta H/R$ and y-axis intercept of $-\Delta S/R$. For the interstitial metal hydrides, the entropy of formation ΔS is determined largely by the change in entropy of the hydrogen itself as it transforms from molecular H_2 in the gas phase into dissolved atomic hydrogen in the solid metal hydride phase. A ΔS value of $-110 \text{ J/K mol } H_2$ for the hydrogenation reaction (1) is typical for many of the interstitial alloys. The enthalpy term characterizes the stability or bond strength of the M-H bond. From Eq. (2), to reach an equilibrium pressure of 5 bar (72.5 psig) at 298 °K, ΔH needs to be $-28.8 \text{ kJ/mol } H_2$ assuming a ΔS value of $-110 \text{ J/K mol } H_2$. For context, the bond dissociation energy of molecular hydrogen is $436 \text{ kJ/mol } H_2$, and the H-O bond strength is $\sim 426 \text{ kJ/mol}$ [13]. Thus, it takes about an order of magnitude less energy to release molecular hydrogen from a typical interstitial metal hydride than it does to produce molecular H_2 by rupturing covalent chemical bonds involving hydrogen.

We designed our *mhH₂LT* system using the Model 2.7FW1104 metal hydride tanks commercially available originally from Ovonic Hydrogen Systems. Since the intent of the Fuel Cell Mobile Light Project was to develop a commercial H_2 LT, only commercially available sub-components were considered. This tank has an Al liner with carbon fiber overwrap to provide a maximal allowable working pressure of 310 bar, with a typical use pressure of 69 – 103 bar. The maximal temperature limit for the 2.7FW1104 tank is 85 °C, as determined by the 110 °C glass transition temperature of the organic resin in the carbon fiber overwrap reinforcing the Al liner.

Ovonic was purchased in 2012 by Vodik Labs who is now the commercial supplier of the Ovonic alloys.

There exist a number of different MH alloy compositions with different properties. We chose to base our system on the Ovonic 679 alloy (OV679) for reasons explained below. The exact composition of the material is proprietary, but it is a transition-metals-based AB₂ type alloy with A = Ti, Zr and B = V, Cr, Mn, Fe, Al. With the OV679 alloy, one Model 2.7FW1104 tank holds 3 kg of hydrogen with a fully-fueled mass of 190 kg (weight = 417 lbs) [15].

Figure 4 shows the general strategy for using hydrogen storage in interstitial metal hydrides to provide H₂ to the Alteryg 5 kW fuel cell providing electrical power to the LED lighting system. The 5kW PEM fuel cell is air-cooled to dissipate its waste heat. In the *mh*H₂LT, that waste heat is captured by a heat exchanger and used to heat a recirculating water supply in order to drive hydrogen off of the MH bed. The air-to-liquid heat exchanger that will be used is a Lytron 4310 Stainless Steel Tube-Fin Heat Exchanger [16]. The rationale for this choice is provided below. Due to water pressure losses in the heat exchanger, in the manifolding and in the MH tank itself, a pump is used to circulate water through the MH storage tanks. The water pump chosen is a Sealless Centrifugal Pump [17] from McMaster-Carr. The MH tanks contain an internal heat exchanger system that will transfer heat from the flowing water to the OV679 metal hydride. This added heat will allow the metal hydride to continue to desorb hydrogen as hydrogen is removed from the MH tank, flowing to the fuel cell.

Figure 4: Schematic of the process flow during operation (i.e. lights are on) of the fuel cell on the *mh*H₂LT. Red arrows signify warmer recirculating water; blue arrows signify cooler water. The orange arrow shows hot air from the operating fuel cell. The purple arrow shows hydrogen gas.

Design and Analysis Results

Heat Transfer Analysis from Fuel Cell to Heat Exchanger:

Part of the design for the mhH_2LT system involves analysis of the heat transfer through the system and selection of the appropriate heat exchanger and pump that will meet the design requirements. This section describes in greater detail the heat transfer process during operation of the mhH_2LT and selection of a heat exchanger that will fit the requirements. Before selecting a heat exchanger, the amount of heat needed to desorb hydrogen from the metal hydride must be determined, which requires selecting the interstitial MH material.

An equilibrium plot of pressure and temperature is typically used to assess the operational character of the MH storage system. Figure 5 shows equilibrium plots for three candidate metal alloys developed by Ovonic using the experimentally determined values of ΔH and ΔS .

Figure 5: Equilibrium plot of hydrogen pressure versus temperature for Ovonic-developed metal alloys. The OV 679 alloy was used in this work. The values of ΔH and ΔS are given for the hydrogenation reactions (see Equation 1 in the text). Figure reproduced with permission from Reference 13.

Figure 5 shows the equilibrium hydrogen pressure of the OV679 alloy at various temperatures. If the hydrogen pressure above the metal hydride is increased above the equilibrium pressure at a given temperature, say during refueling, the metal hydride will begin to absorb hydrogen. Since heat is released when the metal hydride absorbs hydrogen, the temperature of the metal hydride increases. The prevailing (initially elevated) hydrogen pressure eventually coincides with the

equilibrium pressure at the increased bed temperature, and net hydrogen adsorption stops. Therefore, it is important that during the absorption (refueling) process, the metal hydride is cooled while the hydrogen pressure is kept above equilibrium.

When the fuel cell consumes hydrogen, the hydrogen pressure falls below the equilibrium value at the existing temperature. The MH material responds by desorbing more hydrogen. If heat is not externally supplied, the MH material itself provides the heat of desorption, and the material cools. The prevailing (initially decreased) hydrogen pressure eventually coincides with the equilibrium pressure of the now cooled material, and further net hydrogen release from the alloy stops. To maintain hydrogen pressure, the metal hydride must be prevented from cooling down as it desorbs hydrogen. For the *mhH₂LT* system, the metal hydride is kept at a constant temperature through the heat exchanger system that maintains warm water flow through the MH tanks.

Figure 5 suggests that the OV679 alloy is best suited for the *mhH₂LT*. At the operating MH temperature of 50 °C, OV679's equilibrium pressure is ~300 psig (~ 20.7 bar). This is higher than the ~50 psig (~ 3.4 bar) needed for the fuel cell to operate, which is ideal for the hydride to successfully desorb hydrogen. The OV679 alloy also provides a good range of operating temperatures. Even at low temperatures, such as 0 °C, the equilibrium hydrogen pressure is high enough to operate the fuel cell. This will give the system the ability to start even in cold environments.

The amount of energy needed to release one gram of hydrogen from the hydrogenated OV679 material ($\Delta H = - 25.8 \text{ kJ/moleH}_2$) can be calculated as follows:

$$\Delta H = 25.8 \frac{\text{kJ}}{\text{molH}_2} * \frac{1\text{molH}_2}{2.016\text{gH}_2} = 12.8\text{kJ} / \text{gH}_2 \quad (3)$$

As shown in Figure 4, this energy is supplied by the fuel cell waste heat, whose availability is determined by the fuel cell thermal efficiency. The Altergy Systems FPS-5 fuel cell was measured to have a thermal efficiency of 47%. If the fuel cell is operating at its maximum power, providing 5 kW of electrical energy, then the rate of hydrogen fuel energy (LHV) being supplied to the fuel cell must be 10.64 kW, with 5.64 kW of waste heating power discharged into the cooling air. The LHV of hydrogen is 119.7 kJ/gram [18]. Thus, the mass flow of hydrogen into the fuel cell needs to be 0.089 grams/second for the fuel cell to provide 5 kW of electrical power. The power required to release the hydrogen from the metal hydride at the prescribed rate is:

$$Q = \Delta H * \dot{m} = .089\text{gH}_2 / \text{s} * 12.8\text{kJ} / \text{gH}_2 = 1.14\text{kW} \quad (4)$$

Thus, we see that the maximum rate of heat transfer needed by the metal hydride tankage, 1.14 kW, is significantly less than the 5.64 kW being discharged as fuel cell waste heat. Therefore, the air-to-liquid heat exchanger need only transfer ~20% of the waste heat from the fuel cell. For all mhH_2LT powers of operation, there is always enough waste heat to release the required hydrogen from the OV679 alloy bed.

Another factor to consider in selecting a heat exchanger for the mhH_2LT is the operating environment the heat exchanger produces. The fan within the fuel cell blows hot air at 800 cfm with an output air temperature of 55 °C when the fuel cell is operating at 5 kW and the ambient air temperature is 22 °C. The air-to-liquid heat exchanger must be able to transfer sufficient heat under these conditions. In addition, the heat exchanger should preferably fit within the framework of the fuel cell unit. An off-the-shelf heat exchanger is preferred for the mhH_2LT to minimize cost.

The air-to-liquid heat exchanger that was selected for the final conceptual design is a Lytron 4310 stainless steel tube-fin heat exchanger [16]. Its dimensions allow the heat exchanger to be attached directly in front of the fuel cell waste heat exhaust fan. A 3D model of the Lytron heat exchanger installed on the Altergy PEM fuel cell is shown in Figure 6. The Lytron heat exchanger is connected to the fuel cell fan via an intervening duct, and transfers 170 W/°C with air flow at 800 cfm and water flow at 4 gallons per minute (gpm). Thus, the heat exchanger can transfer 1.7 kW of power given a 10 °C difference between the exhaust air and the recirculating water. This is more than enough heat to desorb hydrogen from the MH bed for fuel cell operation. The pressure drop of the water flowing inside the heat exchanger is 7 psi, while the pressure drop of the air flowing through the heat exchanger is 0.8 inches H_2O at 800 cfm. This air side pressure drop is not significant enough to disrupt the discharge of fuel cell waste heat which is the fan's primary function. Likewise the pressure drop of the water is compensated by the addition of a water pump indicated in Figure 4.

Figure 6: 3D model of the *Lytron* 4310 Heat Exchanger installed near the PEM fuel cell fan situated on the back of the Altergy FPS-5 PEM fuel cell stack. The Lytron heat exchanger is connected to the fuel cell fan via an intervening duct that channels hot air to the heat exchanger without loss.

Given the operating environment and the heat transfer capability of the selected heat exchanger, the nominal operating conditions can be calculated. The temperature difference between the hot air and the water is found to be:

$$\Delta T = \frac{Q}{UA_{\text{heatexchanger}}} = \frac{1.14 \text{ kW}}{0.170 \text{ kW}/^{\circ} \text{C}} = 6.7^{\circ} \text{C} \quad (5)$$

Where $UA_{\text{heatexchanger}}$ is the overall heat transfer coefficient of the heat exchanger. If the temperature of the fuel cell exhaust air is at 55°C , the temperature of the water flowing out of the heat exchanger to the metal hydride tank will be 48.3°C .

Knowing the temperature of the water that enters the metal hydride storage system, the temperature of the water flowing out of the MH tank can be calculated using Equation 6:

$$Q = \dot{m} c_p (T_{\text{outlet}} - T_{\text{inlet}}) \quad (6)$$

In this case, Q is the 1.14 kW of heat that was calculated previously as being needed to liberate hydrogen from the metal hydride material for 5 kW operation, $\dot{m}$ is the mass flow rate of water and c_p is the heat capacity of water (4.18 kJ/kg-K). The water flow is at 4 gpm, since that gives the heat transfer capabilities desired from the heat exchanger. The temperature at the hydride tank inlet is 48.3°C , as calculated from Equation 5. Equation 6 gives an outlet temperature of 47.2°C as the water returns back to the heat exchanger from the MH storage system. The average temperature of the water in the metal hydride tankage is 47.8°C .

Heat Transfer in the Metal Hydride Storage System:

For releasing hydrogen from the MH bed to the fuel cell, the hot water exiting the Lytron heat exchanger is circulated through the MH tankage heat exchanger. At this point, we make a design choice and consider a mhH_2LT consisting of four Ovonic Model 2.7FW1104 metal hydride tanks, with each tank storing 3 kg of hydrogen for a total system hydrogen storage of 12 kg. Thus, the 1.14 kW required for the proper hydrogen mass release is divided between the four tanks. We next need to calculate the internal temperature of the metal hydride tanks, given the heat required to release the needed hydrogen, and the input water cooling temperature. This next step in the calculation requires quantitative knowledge of the thermal properties of the metal hydride tank materials and the performance of the internal heat exchange hardware. The internal heat exchange design of the OV679 MH tank is proprietary, but Ovonic supplied sufficient

information to allow a calculation of the heat transfer capabilities UA_{tank} of the internal heat exchanger and as a result, a calculation of metal hydride tank temperature using equation 7:

$$\frac{Q/4}{UA_{\text{tank}}} = (T_{\text{metalhydride}} - T_{\text{water}}) \quad (7)$$

Where T_{water} is the average temperature of the coolant water in the tank (47.8 °C) and Q is the total thermal power needed to release the hydrogen (1.14 kW), divided equally among the 4 storage tanks in the system. UA_{tank} is the heat transfer coefficient (at 1 gpm flow rate) inferred from tank refueling data provided by Ovonic. By substituting those values in Eq. 7, the temperature of the MH bed during operation is calculated to be 50.5 °C.

Water Pressure Drop Calculations and Pump Selection:

Pressure drops are inevitable as the water flows through the recirculation thermal management system. The highest pressure drop occurs inside the Lytron heat exchanger, for which the water pressure drop is 7 psi for a 4 gpm fluid flow. For the Ovonic MH tanks, the ensemble pressure drop is only 1 psi. The water pressure for the remaining manifold was estimated through standard fluid engineering calculations [19]. The calculations showed that the pressure drop is 0.14 psi in the 1.5" diameter coolant manifold tubing, giving a total system coolant pressure drop of 8.14 psi. A 3D model of the *mhH₂LT* heat exchange manifold is shown in Figure 7.

Figure 7: 3D model of the *mhH₂LT* tubing manifold for coolant flow into the metal hydride tanks during operation of the PEM fuel cell. Red pipes signify warmer water entering the metal hydride tanks; Green pipes indicate cooler water exiting the metal hydride tanks. The water flow rate through each tank is 1 gpm, giving a total water flow rate through other parts of the cooling loop of 4 gpm.

The coolant recirculation pump that was selected for the system is a McMaster-Carr Sealless Bronze Centrifugal Pump [17] as indicated in Figures 4 and 7. Without a mechanical seal, these pumps have longer pump life and are appropriate for hot water circulation. This pump will fit within the system and provides 8.66 psi of pressure at 4 gpm flow rate. This is greater than the water pressure drop within the system itself. Therefore, the pump selected will work with the *mhH₂LT* system design and can be readily purchased off the shelf.

Process Flow for Refueling:

The greatest engineering challenge to using metal hydrides is to manage the heat released when the spent metal hydride material (M_{solid} in Equation 1) is rehydrogenated. Although the *mhH₂LT* will use its 12 kg of hydrogen over the course of ~ 60 hours or more, typically the customer would want to refuel the unit as fast as possible, and certainly within a 8-hour work shift. Although the *mhH₂LT* could be refueled using external cooling equipment such as that potentially provided by hydrogen stations for FCEVs, in a construction equipment application the *mhH₂LT* may not have access to external chilled water for dissipating heat generated by

rehydrogenating the spent MH material. Thus the mhH_2LT needs to be able to be refueled in the field using only thermal management equipment on the unit, as described in Figure 8.

Figure 8: Process flow for refueling of mhH_2LT with hydrogen. Red arrows signify warmer recirculating water; blue arrows signify cooler water. Purple indicates hydrogen gas and the aqua blue arrow indicates cool air. The fuel cell powers only the system cooling fan and water pump during refueling.

Figure 8 shows how the heat generated by refueling can be extracted by circulating water through the tanks and rejected by passing through the system's heat exchanger with cooling air provided by the fuel cell fan. To accomplish this, a small amount of hydrogen must be diverted to the fuel cell to power the fan and pump. The maximum power draw of the fuel cell fan is 300 W. For a 6 hour fueling of 12 kg of hydrogen, the total amount of hydrogen devoted to powering the fuel cell fan would be 0.1 kg, with an additional 0.04 kg devoted to powering the water recirculation pump.

Heat Transfer during Refueling Process:

Heat transfer within the refueling process governs how quickly the unit can be refueled. The refueling time thus depends on the temperature of the ambient air and is also limited by the heat exchanger performance. We can use the fuel cell system fan and Lytron /heat exchanger to cool hot water emanating from the metal hydride tanks, but the heating rate of the water cannot be so high as to boil the water, given the heat exchange limitations. As a result, we have to control the refueling time. In order to determine the ideal refueling time, calculations were made to determine how the temperature difference ΔT between the cooling water and ambient air varies with refueling time. Equation 4 is used to determine the heat rate from refueling, where the mass

flow rate is determined by the total amount of hydrogen (12 kg) needed to fully recharge the mhH_2LT in the desired refueling time. Equation 5 is then used to determine the resulting temperature difference between the ambient air and water based on the refueling time. Figure 9 shows the calculated results for the variation of ΔT as a function of refueling time.

Figure 9: Temperature difference between the recirculating water and the ambient air plotted versus refueling time for the mhH_2LT .

Let's consider the situation where we are trying to refuel the unit on a hot day, with an ambient air temperature of 37.8 °C (100 °F). Our first consideration is to keep the water contained within the mhH_2LT manifold from boiling with some margin, keeping the water temperature below, ~ 80 °C. From Figure 9 we see that we need to refuel for 6 hours or longer to keep within this operational constraint. At 6 hours, ΔT is 42.2 °C, which gives a water temperature of 80.0 °C. This is the temperature of the water entering the metal hydride storage system, T_{inlet} . With a 4 gpm water flow rate and c_p of water of 4.18 kJ/kg-K, Eq. 6 is used to determine the temperature of the water at the outlet of the refueling metal hydride tank system. The temperature at the outlet is 86.7 °C. This gives an average water temperature of 83.3 °C in the MH tankage. Equation 7 can then be used to determine the temperature of the metal hydride. In this case, Q is the heating power released during refueling when the metal hydride absorbs hydrogen, which depends on the refueling time. UA_{tank} is the hydride tank heat exchange value derived earlier from unpublished refueling data for the Model 2.7FW1104 hydride tank from Ovonic. Plugging these values into Equation 7 gives an average metal hydride temperature, $T_{metal\ hydride}$, of 100.3 °C.

Because the glass transition temperature of the organic resin of the fiber wrapped vessel is

110 °C, Dynetek, the manufacturer of the composite tank, recommended to Ovonic to keep the aluminum liner (see Fig. 4) at temperatures below 85 °C during refueling. We adopt a conservative requirement that the average temperature in the entire 2.7FW1104 tank should be kept to 85 °C or below during refueling. This requirement is conservative because in reality the aluminum liner is the coolest part of the tank during refueling so that the average tank temperature could in principle exceed 85 °C and still be within the prescribed liner thermal limits. On a 37.8 °C (100 °F) day, the refueling would need to be performed for longer than 6 hours given the temperature restriction on the tank. The calculations indicate that if the refueling is performed for 8 hours with an ambient air temperature of 37.8 °C (100 °F), then the average MH temperature is kept at 84.7 °C.

If the ambient air temperature is lower, the user can refuel in shorter times. Figure 10 shows the minimum refueling time as a function of outside air temperature, subject to the constraint that the average temperature of the MH bed is maintained at 85 °C. Referring back to the Figure 5, an OV679 alloy temperature of 85 °C results in an equilibrium hydrogen pressure of 800 psig. This means that the refueling hydrogen pressure must be greater than 800 psig in order to successfully charge the metal hydride with hydrogen given the heat exchange capabilities of the *mhH₂LT* system.

Figure 10: Hydrogen refueling times for the *mhH₂LT* considering different ambient air temperature conditions, subject to the constraint that the temperature of the MH bed is maintained at 85 °C.

Figure 10 shows that refueling time can range from 3.0 hours if the ambient air temperature is - 40 °C to 8.3 hours if the air temperature is 40 °C. Since these refueling times are on the order of an 8-hour work shift or less, this refueling rate is acceptable since the *mhH₂LT* would typically only be used at night. In addition, if the temperature in the hydride bed can be kept to 85 °C or less, then the unit can be effectively filled using industrial grade (99.95% pure) hydrogen from commercially available cylinders (pressurized to 150 bar) from most local gas suppliers. However, the elevated temperature would prevent all of the hydrogen in the cylinder from being adsorbed, limited as it would be by the ~ 800 psig (55 bar) equilibrium hydrogen pressure at 85 °C. Figure 5 and 9 together shows that if the refueling time could be increased to 10 hours, then the equilibrium pressure above the OV679 alloy would be ~ 300 psig (20.7 bar), which helps ensure more complete transfer of gas from the hydrogen cylinder. Alternatively, a boost pump could be purchased which would allow almost all of the contents of the hydrogen cylinder to be absorbed into the metal hydride alloy regardless of operating temperature.

For the discussion thus far, we have assumed that the kinetics of the Model 2.7FW1104 MH tank for both hydrogen desorption and adsorption are fast enough to support the hydrogen consumption rate of the fuel cell, as well as the rate of hydrogen delivery to the tank during refueling. In general, this assumption cannot be made without supporting desorption/adsorption data for the tank. The overall kinetics of the tank system are determined by the intrinsic MH reaction kinetics associated with Reaction 1, in addition to the effectiveness of the heat exchange hardware which determines how rapidly heat can be exchanged between the recirculating coolant and the MH bed. The 2.7FW1104 tank was designed for automotive applications, requiring fast hydrogen absorption for a short refueling time and rapid desorption to support the transient response requirement of either fuel cell or H₂ internal combustion engine (ICE) vehicles. Prior tests of the tank show that one tank can support a hydrogen desorption rate of 31 grams/minute. For operation of the *mhH₂LT*, the system hydrogen consumption rate is 3.45 grams/minute, giving a “per tank” hydrogen delivery requirement of 0.86 grams/minute. Thus, for desorption, the demonstrated kinetics of the 2.7FW1104 tank are fast enough to support *mhH₂LT* operation. For a 3 hour refueling, the *mhH₂LT* system needs an average adsorption rate of 66.7 grams/minute, which translates to an average absorption rate of 16.7 grams/minute per tank. Early experiments on the 2.7FW1104 MH tank have demonstrated a rapid 20 minute refueling to reach the full 3000 g hydrogen capacity for a single tank [15], corresponding to 150 grams/minute. These prior experiments demonstrate that the tank kinetics are more than sufficient for the shortest refueling time contemplated for an unsupported *mhH₂LT* unit.

We note here that the OV679 alloy is a high performance hydrogen storage material, releasing very pure hydrogen (99.9999%), with excellent volumetric hydrogen storage density (110 gH₂/L), but relatively poor gravimetric capacity (2.1 wt. %). The OV679 alloy is kinetically fast, absorbing and desorbing hydrogen quickly. Also, the enthalpy of hydrogen desorption from

OV679 is a very desirable 25.8 kJ/moleH₂, which limits the heating powers that are generated during hydrogen refueling, and the heating power needing to be supplied during fuel cell use. From the point of view of the overall feasibility of using MH hydrogen storage for the H₂LT application and ease of refueling, the OV679 alloy may represent the best that can be achieved using metal hydride storage of hydrogen. Work is progressing on complex metal hydrides with much higher gravimetric capacity [20], but it will be a very stiff challenge for them to ultimately improve upon the desirable combination of kinetics, thermodynamics, thermal properties and volumetric storage efficiency that the OV679 alloy provides. Thus, the results presented here are probably the best that can be achieved using metal hydrides to store hydrogen in a *mh*H₂LT system, with the exception of the overall mass of the hydrogen storage system which could be significantly improved with higher gravimetric capacity materials.

3-D model of the *mh*H₂LT:

A ProEngineer (PRO-E) 3-D model [21] of the *mh*H₂LT was developed to assess if the layout of the system would fit within the existing trailer configuration. We wanted to modify the original supporting trailer as little as possible to ensure that the lighting towers could be easily transported and mass manufactured as they are now. The resulting design successfully meets this requirement. The only minor changes that were made include lengthening the trailer and moving the wheel axle closer to the center of gravity of the system. These changes do not affect any important geometric parameters of the trailer.

Figures 11 and 12 show the completed *mh*H₂LT 3-D PRO-E model. Figure 11 shows the outer sheet metal enclosure in place, along with various access panels to allow the user to control different *mh*H₂LT functions. The dimensions of the enclosure are 83.8 cm tall x 86.4 cm wide x 177.0 cm long. We estimate the mass of the *mh*H₂LT to be 1620 kg, slightly higher than the target 1587 kg.

Figure 11: 3-D model of the completed *mhH₂LT* with outer enclosure shown.

Figure 12 shows the *mhH₂LT* with the enclosure removed to reveal the system components inside, with the main components of the *mhH₂LT* labelled.

Figure 12: Image of *mhH₂LT* Unit with system components exposed. The rendering of the LED lighting is notional only.

In addition to the main components that make up the hydrogen storage and heat transfer system, there are other important features of the system that promote safe and effective use. There are various pressure regulators and check valves installed in the hydrogen manifold that ensure safe refueling and operation. There is a pressure regulator on the refueling panel that is rated for 0 – 415 bar. This regulates hydrogen pressure coming from the hydrogen refueling source. In the case of a hydrogen refueling station this allows for recharging from a 350 bar nozzle. There is a pressure regulator for the hydrogen entering the fuel cell that is rated for 0 – 7 bar. These are all standard items for high-pressure hydrogen storage systems. There are many possible layouts for the *mhH₂LT* electronics and fueling panels. Figure 3 shows the panel layout for the *H₂LT* unit used in the field tests.

The MH storage system is securely mounted onto the trailer in the *mhH₂LT* design. This is shown in Figure 13, where the MH tanks rest on saddles shown in turquoise that are strapped to a sturdy framework.

Figure 13: 3-D Model of the rear of trailer showing tank mounting.

Comparing the *mh*H₂LT with the Beta H₂LT and a MQ LT-12D Light Tower:

The environmental benefits of the H₂LT technology relative to current diesel-fueled mobile lights have been calculated [9] by the U.S. DOE Fuel Cell Technologies Office (FCTO) [22]. The diesel unit used for the comparison is the Multiquip LT-12D light tower, shown in Figure 14. The results of the comparison are given in Table I. All mobile light units are assumed to output 177,600 lumens, with LED lights used for the fuel cell systems and metal halide lights for the diesel-based system [9].

Figure 14: Multiquip diesel mobile light tower model LT-12D

Table I: Emissions and energy consumption savings associated with using one *mh*H₂LT unit each year in comparison to using a diesel fueled LT-12D light tower, assuming the hydrogen is generated by either renewable means or derived from Natural Gas (NG). The savings are the same for the *mh*H₂LT and the Beta H₂LT.

Annual H ₂ LT Benefits (per unit)	Renewable H ₂	NG-derived H ₂
Diesel Fuel Displaced per Year (gallons)	970	970
H ₂ Consumed per Year (kg)	375	375
CO ₂ (eq.) Savings per Year (kg)	11,292	7,055
(NMHC + NO _x) Savings per Year (kg)	68	68
PM Savings per Year (kg)	3.6	3.6
Fuel Energy Savings per Year, LHV (MJ)	86,917	86,917
Total Energy Savings per Year, LHV (MJ)	33,735	83,972

Notes: NMHC stands for non-methane hydrocarbons; PM stands for particulate matter. Renewable H₂ is produced by wind-based electrolysis of water; NG-derived H₂ is produced by steam reforming.

The benefits accrued to using a fuel cell mobile light (the emissions and energy savings are the same for the *mh*H₂LT and the Beta H₂LT), shown in Table I, depend on how the hydrogen is manufactured, either via reforming of natural gas (NG) or by renewable (wind-based electrolysis) methods. These results assume the light towers are used for 180 days a year for 10 hours a day. One fuel cell mobile light unit (either Beta H₂LT or *mh*H₂LT) fueled with renewable H₂ reduces CO₂ (eq) emissions by 11,292 kg per year, with concomitant savings in other criteria pollutants. One fuel cell mobile light unit fueled with NG-derived hydrogen reduces CO₂ (eq.) emissions by 7,055 kg/year. Expressed another way, a fuel cell mobile light fueled with renewable hydrogen releases only 10% of the CO₂ (eq.) emissions as the comparable LT-12D diesel light tower, whereas a fuel cell mobile light fueled with NG-derived hydrogen releases 44% of the CO₂ (eq.) emissions as the LT-12D diesel light tower. Note that these emissions are for the entire pathway from hydrogen production through to the creation of photons. The PEM fuel cell mobile light technology is zero-emissions as the point of use. Using a hydrogen fuel cell mobile light displaces 970 gallons of diesel fuel per year, and saves 83,972 MJ of total energy if the hydrogen is produced by steam-methane reforming of NG and 33,735 MJ if the hydrogen is produced by the renewable, but more energy intensive, wind-based electrolysis of water.

One can compare the physical dimensions of the *mh*H₂LT with the Beta H₂LT and the current diesel light tower LT-12 D to reveal the differences in stored deliverable energy densities. Through this comparison, we can assess the feasibility, benefits, and detriments of introducing metal hydride hydrogen storage into a piece of mobile fuel cell equipment such as the H₂LT. These comparisons are shown in Table II.

Table II: Comparison of physical parameters and storage performance of *mh*H₂LT with the Beta H₂LT and LT-12D mobile lights. The Beta H₂LT stores 8.4 kg of hydrogen; the LT-12D stores 30 gallons of diesel fuel.

Physical Attribute	<i>mh</i> H ₂ LT	Beta H ₂ LT	LT-12D
Enclosure Dimensions (“h” x “w” x “l”, cm)	83.8 x 86.4 x 177.0	86.4 x 116.8 x 181.4	78.7 x 86.4 x 142.2
Enclosure Volume (L)	1281	1829	967
Light Tower Mass, fueled (kg)	1619	1132	786
Enclosure and Contents Mass (kg)	945	467	385
Duration at 177,600 lumens output (hours)	58	40.6	48
Engine Thermal Efficiency (%)	47	47	25
Engine Nameplate Power Output (kW)	5	5	6
Stored Fuel Capacity (kg H ₂ , or gallons diesel)	12	8.4	30
Stored Fuel Energy, LHV (MJ)	1436	1005	4076
Noise Spec at 23 feet (dB)	42	42	73
DSV Electrical Energy Density (MJ/L)	0.527	0.258	1.053
DSG Electrical Energy Density (MJ/kg)	0.714	1.01	2.65
Refueling Time (no external cooling water)	3 - 8 hours	14 mins	4 mins

Notes: Nameplate Power Output is equivalent to maximum rated power output. DSV stands for Delivered System Volumetric; DSG stands for Delivered System Gravimetric. By “delivered” electrical energy we mean the energy content of the fuel multiplied by the efficiency of either the fuel cell (47%) or the diesel generator (25%).

In Table II, the mobile light enclosures contain the fuel storage (H₂ or diesel), engine (fuel cell, diesel generator) and all required manifolding, valving, pumps and other B.O.P items. These enclosures are quite compact in their design, with little wasted space, thereby allowing a real-world practical estimate of the system volumetric and gravimetric deliverable electrical energy storage densities for these technologies. None of these enclosures are sound conditioned. Thus, the dramatically quieter (42 dB) H₂LT and *mh*H₂LT specs reflect the intrinsically low-noise character of PEM fuel cells compared to diesel generators (73 dB).

We see from Table II that the metal hydride tank technology in the *mh*H₂LT provides a doubling of the delivered system volumetric (DSV) electrical energy density within the enclosure space, compared to the H₂LT, but is still 50% less than that afforded by the diesel-based LT-12D system. As a comparison, a typical 12-V lead-acid battery has a volumetric stored electrical energy density of ~ 0.440 MJ/L [23].

To estimate the real-world practical H₂LT and *mh*H₂LT delivered system gravimetric (DSG) electrical energy densities, we report the mass of the hardware within the enclosures, including the enclosures themselves in Table II. We see from Table II that the *mh*H₂LT has a DSG electrical energy density of 0.714 MJ/kg whereas the H₂LT value is 1.01 MJ/kg. Thus the heavier MH tank technology in the *mh*H₂LT introduces a 30% mass gravimetric energy density penalty,

with the *mh*H₂LT having 70% of the system hydrogen and electrical energy gravimetric storage densities as the H₂LT unit within their respective enclosures. The DSG electrical energy density for the LT-12D is 2.65 MJ/kg. To give these DSG energy density numbers a context, a typical lead-acid battery has a stored gravimetric energy density of ~ 0.190 MJ/kg [23].

The H₂LT unit has been refueled in a number of different ways [9]. The unit has been refueled to 350 bar pressure from hydrogen stations, in some cases with pre-cooling of the hydrogen via the SAE J2601 fill protocol. The SAE TIR J2601 H35B fill involves pre-cooling of the hydrogen to -20 °C (-4 °F) to reduce compression heating of the storage vessel [24]. For the hydrogen station fills, the refueling time was ~ 10 mins. The H₂LT has also been refueled by cascade fill from an IGX/GTM mobile hydrogen refueler (77 kg refueler capacity at 250 bar) to 220 bar (5.8 kg of hydrogen transferred), for which the fill time was 14 minutes. The H₂LT has also been fueled using cascade fill from a standard hydrogen six-pack (Type 1A steel cylinders) initially pressurized to 145 bar. After the cascade fill, the H₂LT pressure was 83 bar (1.8 kg of hydrogen transferred) after a 15 minute fueling time. A boost pump could be used in conjunction with hydrogen cylinder filling to allow a more quantitative transfer of hydrogen from the six-pack.

Prior work by Ovonic showed that one Model 2.7FW1104 3 kg MH tank could be refilled in 20 minutes with a 10 °C coolant flowing at 10 gpm from a 200 gallon reservoir of fluid. Based on this performance, the *mh*H₂LT system could also theoretically be refilled in a 20 minute period if 10 °C chilled water is available and can be flowed through the *mh*H₂LT manifold at a sustained total flow rate of 40 gpm (10 gpm through each of the four tanks). For remote deployment where refueling heat must be dissipated by water already on-board the *mh*H₂LT unit, the refueling time would be between ~3 – 8 hours, depending on the ambient air temperature. Since 12 kg of hydrogen are required to fill the *mh*H₂LT, and a standard hydrogen six-pack contains ~3 kg of hydrogen each, then four such six packs would be required. The 3 – 8 hour refill time requires the hydrogen pressure to be maintained above 800 psig, the equilibrium hydrogen pressure for the OV679 alloy at ~ 85 °C. If longer refill times can be accommodated, thereby reducing the temperature of the metal hydride during refueling, then the required refill hydrogen pressure can be reduced according to Figures 5 and 9. A reduced hydrogen refueling pressure would allow a more efficient use of the hydrogen in the six-packs. If longer fill times cannot be accommodated, then a boost pump could be used to keep the filling pressure at 800 psig (55 bar) as the hydrogen supply in the six-pack dwindles. Overall, the analysis indicates that a *mh*H₂LT unit could be successfully refueled in a remote location within a single 8-hour work shift using commercial hydrogen cylinders or via mobile refueling.

System Safety:

The field-testing conducted of the H₂LT from 2009 – 2014 presented difficult physical challenges for the PEM fuel cell system [9]. With coordination provided by Caltrans and U.C.

Davis, a H₂LT system was deployed with the winter road crews of Caltrans District 3 which encompasses Sacramento California and the nearby Sierra mountains including Lake Tahoe, CA. In the course of the deployment and for refuelings, the unit was towed up and down rough mountain roads over 1100 miles without a single occurrence of a system hydrogen leak. This was a strong test of the physical durability and stability of the hydrogen systems (fuel cell, tankeage, manifolding), as there is very little suspension on the H₂LT to cushion the ride as it was being towed. To our knowledge, fuel cells have never been exposed to the shock and vibration that occurred in the field test with Caltrans. The hydrogen tanks are mounted with steel mounting brackets for firm seating, and are protected from impact threats by steel stabilizer bars. These are important design aspects of the H₂LT that increase system reliability and safety. The fuel cell and hydrogen storage system and manifolding performed without failure in all of the field-tests, indicating the high-pressure composite tanks, hydrogen manifolding and Altery PEM fuel cells are sufficiently robust for the construction equipment application.

A *mh*H₂LT unit has not been constructed and subjected to such comprehensive field testing. The experience with the H₂LT, however, indicates the hydrogen manifolding and fuel cell would have no reliability issues. The 2.7FW1104 metal hydride tank was the result of collaboration between Ovonic and Dynetek from 2002 to 2004. These tanks with the heat exchanger (but without the metal hydride) underwent many rigorous tests during its development, including burst test, bonfire test and cycle test to confirm physical integrity [15]. However, the tank was a prototype and has not been submitted for DOT approval.

During operation of the *mh*H₂LT, the average pressure within the tankeage would be ~300 psig (20.7 bar). This is a considerably lower pressure than the 350 bar operational pressure of the H₂LT. The lower pressure of the *mh*H₂LT offers increased operational safety. The OV679 alloy in powder form is classified as a pyrophoric solid material. Inside the 2.7FW1104 tank, the powder is contained in an internal “compartment structure” that was designed to be a part of the tank’s heat exchanger system. This structure helps to limit the amount of alloy that would be exposed to air (and subsequently self-ignite) if the tank were breached. In addition, were hydrogen to be inadvertently released from the MH bed, the temperature of the bed would drop as heat was scavenged from the hydride bed and its surroundings. This cooling would inhibit further hydrogen release from the MH tank and also slow down further oxidation. As a practical matter, we see no safety issues associated with deploying a *mh*H₂LT system assuming the needed DOT tank certifications are acquired and precautions are taken in mounting and protecting the metal hydride tankeage, as was done for the *mh*H₂LT design.

Hydrogen Storage System Cost:

The current cost of the H₂LT hydrogen storage system is ~\$12,000 for the four SCI ALT 836U tanks (\$2500 each), manifolding, valves and gauging. The current cost of the *mh*H₂LT hydrogen

storage system is much higher. In 2009, one Ovonic Model 2.7FW1104 tank was priced at \$25,000. The cost would be similar today and is due to the expensive carbon fiber overwrap, as well as the prototype heat exchanger within the vessel and the alloy raw materials cost. Bringing the metal-hydride and high-pressure composite tank manufacturing costs down is a priority topic for the U.S. DOE and industry.

The purpose of the carbon fiber overwrap is to provide high-pressure capability while reducing the tank weight relative to that of a stainless steel tank. For a pressure vessel containing MH materials, there are two components contributing to the pressure rating of the tank: first, the tank must withstand the pressures of hydrogen gas present in the tank during use and refueling. Second, the tank must withstand the strain resulting from the volume expansion of the MH material as it is hydrogenated from the (lower-volume) dehydrogenated state. This latter requirement determines the MH vessel pressure rating (and hence carbon fiber thickness and cost). Even though the MH tank can be slowly refueled with a lower hydrogen pressure, the tank pressure rating can't be relaxed too much due to the need to accommodate strain during the MH volume expansion during refueling.

Relationship to Prior Work

In 2006 Bowman and colleagues [25] at the Jet Propulsion Laboratory (JPL) performed an unpublished conceptual design of a fuel cell mobile lighting system for the U.S. Air Force. The proposed unit was based on a retrofit to a Unicore NF-2D Floodlight Set (i.e., a light cart), with a metal hydride hydrogen storage system storing 1 kg of hydrogen in a lanthanum-rich mischmetal AB₅ alloy integrated to a 2 - 4 kW liquid-cooled PEM fuel cell. A number of laboratory-scale desorption tests were performed on small tanks filled with 25 grams of the LaNi_{4.8}Sn_{0.2} alloy, supporting the conceptual design [25]. The modified Unicore system was demonstrated at Hickam Air Force Base in Hawaii by Hawaii Hydrogen Carriers LLC.

There have been a number of modeling and experimental studies of thermally integrating a metal hydride bed to a PEM fuel cell. MacDonald and Rowe [26] examined the ability of a metal hydride storage system (44 grams H₂ in an AB₂ type alloy) to supply hydrogen to a 1200 kW PEM fuel cell when the MH tanks were situated directly in the hot air exhaust stream of the fuel cell. Jiang and co-workers [27] investigated using the waste heat from a ~200 W PEM fuel cell to desorb hydrogen from a MH bed using a common liquid coolant loop for thermal integration. Pfeifer et al. [28] characterized a high-temperature 1 kW PEM fuel cell thermally coupled to a NaAlH₄ hydrogen storage system (~80 gram H₂ capacity) via an oil cycle. Førde and co-workers [29] examined a 1.2 kW PEM fuel cell thermally coupled to a MH bed (Ce-modified LaNi₅-type material, 260 gram H₂ capacity) via a common water coolant loop.

These prior studies focused entirely on using fuel cell waste heat to desorb hydrogen from the MH bed during fuel cell operation, with no investigation of heat dissipation from the MH bed during hydrogen refueling. Our work considers both the dehydrogenation requirements as well as the rehydrogenation thermal issues. For fuel-cell-based equipment in “unsupported” environments, rehydrogenation thermal management determines the feasibility of using fuel cells in non-motive mobile equipment such as construction equipment and aviation GSE.

Summary

An engineering design and performance study has been conducted of a fuel cell mobile light tower that incorporates a 5 kW Altergy Systems fuel cell, Grote Trilliant LED lighting and storage of hydrogen in the Ovonic interstitial metal hydride OV679. The *mhH₂LT* system is compared directly to the H₂LT and a comparable diesel-fueled light tower with regard to size, performance, delivered energy density and emissions. The metal hydride hydrogen light tower (*mhH₂LT*) stores 12 kg of hydrogen in considerably less space than the corresponding H₂LT system that stores 8.4 kg of hydrogen employing 350 bar storage, although the *mhH₂LT* unit is heavier. For a light tower producing 177,600 lumens of light, the *mhH₂LT* unit would provide 43% longer duration than the H₂LT, for a total duration of 58 hours. Our analysis indicates that the 5kW fuel cell provides sufficient waste heat to supply the desorption enthalpy needed for the hydride material to release hydrogen. Hydrogen refueling of the *mhH₂LT* system is possible even without external sources of cooling water by making use of a fan already installed on the PEM fuel cell for thermal management. In such cases, refueling times of ~ 3 – 8 hours can be achieved, depending on the temperature of the ambient air. Shorter refueling times (~ 20 minutes) are possible if external chilled water is available for MH bed cooling during rapid hydrogen refueling. Overall, the analysis results indicate that it is technically feasible to use MH hydrogen storage in portable fuel cell mobile lighting equipment deployed in remote areas, although the MH tank technology needs to come down in cost to be used in commercial fuel cell mobile light towers.

Acknowledgements:

It is our pleasure to acknowledge funding of this project from The Boeing Company via the Boeing/Sandia CRADA SC02/1651.14.00. George Roe, formerly Senior Manager for Subsystems Technology in the Phantom Works organization, conceived the Fuel Cell Mobile Light Project and asked Sandia to lead an effort to bring fuel cell technology to aviation ground support equipment back in 2008.

The authors wish to thank colleagues at Sandia National Laboratories who have assisted with the analysis conducted in this report. Sal Birtola conducted 3-D modeling of the *mhH₂LT* and developed component engineering drawings. George Sartor provided engineering advice and

consulting. We thank Joe Pratt for helpful discussions of refueling interstitial MH beds in material handling equipment and for a critical review of the manuscript. L.E. Klebanoff thanks Tom Felter for ongoing encouragement of this work.

Thanks are extended to Mike Zelinsky formerly of Ovonic Hydrogen Systems and now with Ovonic Battery Company, who provided important technical information on the OV679 alloy 2.7FW1104 MH tank technology upon which the *mhH₂LT* design is based.

The authors thank Tien Nguyen of the U.S. DOE Fuel Cell Technologies Office for providing calculation results for the environmental benefits of the H₂LT technology. The authors also thank Bob Bowman for providing a copy of the unpublished Reference 25. We appreciate help and encouragement in the Fuel Cell Mobile Light Project from Greg Moreland of SRA International and contractor to the DOE EERE Fuel Cell Market Transformation Program.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References:

1. J.O. Keller, L.E. Klebanoff, S. Schoenung, and M. Gillie "The Need for Hydrogen-based Energy Technologies in the 21st Century," Chapter 1 in "*Hydrogen Storage Technology, Materials and Application*," ed. L.E. Klebanoff (Taylor and Francis, Boca Raton, 2012), p. 3.
2. L.E. Klebanoff, J.O. Keller, M.H. Fronk and P. Scott, "Hydrogen Conversion Technologies and Automotive Applications," Chapter 2 in "*Hydrogen Storage Technology, Materials and Applications*," ed. L.E. Klebanoff (Taylor and Francis, Boca Raton, 2012) p. 31.
3. L.E. Klebanoff and J.O. Keller, "5 Years of Hydrogen Storage Research in the U.S. DOE Metal Hydride Center of Excellence (MHCoE)," *International Journal of Hydrogen Energy* **38** (2013) 4533-4576.
4. S. McWhorter, C. Read, G. Ordaz and N. Stetson, "Materials-based hydrogen storage: Attributes for near-term, early market PEM Fuel Cells," *Current Opinion in Solid-State and Materials Science* **15**, 29 (2011).

5. J.S. Breit and J. Szydlo-Moore, "Fuel Cells for Commercial Transport Airplanes: Needs and Opportunities," 45th AIAA Aerospace Sciences Meeting and Exhibit, AIAA Paper 2007-1390, January 8-11 (2007), Reno Nevada.
6. J.W. Pratt, J. Brouwer and G.S. Samuelsen, "Performance of Proton Exchange Membrane Fuel Cell at High-Altitude Conditions," *Journal of Propulsion and Power*, **23**, 437-444 (2007).
7. L.E. Klebanoff and C. Cornelius, "Analysis of Hydrogen Storage for a Fuel Cell Emergency Power System (FCEPS) for Commercial Aircraft", Final Project Report to Boeing, July 18, 2007 SAND Report No. SAND2007-4542P.
8. J.W. Pratt, L.E. Klebanoff, K. Munoz-Ramos; A. A. Akhil; D.B. Curgus and B.L. Schenkman, "Proton Exchange Membrane Fuel Cells for Electrical Power Generation On-Board Commercial Airplanes," *Applied Energy* **101**, 776 (2013).
9. L.E. Klebanoff, J.S. Breit et al., "Fuel Cell Mobile Lighting: A Fuel Cell Market Transformation Project," to be published in the *International Journal of Hydrogen Energy* (2014).
10. L.E. Klebanoff, J.W. Pratt, T.A. Johnson, M. Arienti, L. Shaw and M. Moreno, "Analysis of H₂ Storage Needs for Early Market Non-motive Fuel Cell Applications," Sandia National Laboratories, SAND Report No: SAND2012-1739 (2012).
11. Torsten Erbel, Multiquip Inc., private communication to L.E. Klebanoff.
12. L. Klebanoff, C. Song and T. Johnson, "Design of a H₂/Fuel Cell Mobile Lighting System for Aviation Ground Support Applications," Project Report to the Boeing Company, August 10 (2009), unpublished
13. B. Chao and L. Klebanoff, "Hydrogen Storage in Interstitial Metal Hydrides," Chapter 5 , in "*Hydrogen Storage Technology, Materials and Applications*", ed. L.E. Klebanoff (Taylor and Francis, Boca Raton 2012), p. 109.
14. T. Johnson and P. Benard, "Solid-state H₂ Storage System Engineering: Direct H₂ Refueling," Chapter 10 in "*Hydrogen Storage Technology, Materials and Applications*," ed. L.E. Klebanoff (Taylor and Francis, Boca Raton, 2012), p. 347.

15. B.S. Chao, R.C. Young, V. Myasnikov, Y. Li, B. Huang, F. Gingl, P.D. Ferro, V. Sobolev and S.R. Ovshinsky, “Recent Advances in Solid Hydrogen Storage Systems”, Mat. Res. Soc. Symp. Proc. Vol. 801- BB1.4, 27 (2004).
16. Lytron Website, <http://www.lytron.com/heat-exchangers/heat-exchangers-overview.aspx>
17. McMaster-Carr Website, <http://www.mcmaster.com/>
18. C.M. White, R.R. Steeper and A.E. Lutz, Int. Journal of Hydrogen Energy **31**, 1292 (2006).
19. John J. Bertin, “Engineering Fluid Mechanics”, 2nd ed. (Prentice Hall, Upper Saddle River, 1987).
20. V. Stavila, L.E. Klebanoff, J.J. Vajo and P. Chen “Development of On-board Reversible Complex Metal Hydrides for Hydrogen Storage,” V. Stavila, L.E. Klebanoff, J.J. Vajo and P. Chen, Chapter 6 in “*Hydrogen Storage Technology, Materials and Applications*,” ed. L.E. Klebanoff (Taylor and Francis, Boca Raton, 2012), p. 133.
21. Pro-E (renamed PTC Creo in 2010) is a 3D design modeling software package sold by PTC Inc. (formerly Parametric Technology Corporation).
22. GHG and criteria pollutant savings estimates for the *mhH₂LT* are courtesy of Tien Nguyen (DOE FCTO) who provided calculations of total energy associated with producing and delivering diesel fuel, as well as hydrogen from Natural Gas (NG) and renewable methods (wind-based electrolysis), along with the appropriate GHG emissions associated with the relevant production and delivery paths. The calculations were based on the Argonne GREET Model <https://greet.es.anl.gov/>, and a report from the National Renewable Energy Laboratory (NREL) <http://www.nrel.gov/docs/fy10osti/46612.pdf> .
23. Lead-acid battery gravimetric and volumetric stored energies taken from data provided for the Trojan T-1275 flooded 12 V lead-acid battery, product of the Trojan Battery Company.
24. A description of the SAE J2601 hydrogen fueling protocol for light-duty vehicles can be found at: [http://www.energy.ca.gov/contracts/notices/2012-07-10_workshop/presentations/SAE Jesse Schneider Fueling Protocol.pdf](http://www.energy.ca.gov/contracts/notices/2012-07-10_workshop/presentations/SAE_Jesse_Schneider_Fueling_Protocol.pdf)

25. R. C. Bowman, Jr., P.R. Wilson, and J.W. Reiter, "Conceptual Design Study of Hydride Storage for Fuel Cell Power Systems in USAF Applications," Final Report to Advanced Power Technology Office (APTO), January 31, 2006, unpublished.
26. B.D. Macdonald and A.M. Rowe, "A thermally coupled metal hydride hydrogen storage and fuel cell system," J. Power Sources **161** (2006) 346 - 355.
27. Z. Jiang, R.A. Dougal, S. Liu, S.A. Gadre, A.D. Ebner, J.A. Ritter, "Simulation of a thermally coupled metal-hydride hydrogen storage and fuel cell system," J. Power Sources **142** (2005) 92 – 102.
28. P. Pfeifer, C. Wall, O. Jensen, H. Hahn, M. Fichtner, "Thermal coupling of a high temperature PEM fuel cell with a complex hydride tank," Int. J. Hydrogen Energy **34** (2009) 3457 - 3466.
29. T. Førde, J. Eriksen, A.G. Pettersen, P.J.S. Vie, Ø. Ulleberg, "Thermal integration of a metal hydride storage unit and a PEM fuel cell stack," Int. J. Hydrogen Energy **34** (2009) 6730 – 6738.