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Hydrogen Storage Solutions in Support of DOD Warfighter Portable Power Applications

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BACKGROUND

From Personal Digital Assistants (PDAs) to cell phones our high-tech world, today, is demanding smaller, lighter weight and higher capacity portable power devices. Nowhere has this personal power surge been more evident than in today's U.S Warfighter. The modern Warfighter is estimated to carry from 65 to 95 pounds of supplies in the field with over 30 pounds of this dedicated to portable power devices [1]. These devices include computer displays, infrared sights, Global Positioning Systems (GPS), night vision and a variety of other sensor technologies. Over 80% of the energy needed to power these devices comes from primary (disposable) batteries. It is estimated that a brigade will consume as much as 7 tons of batteries in a 72 hour mission at a cost of $700,000 [2].

A recent comprehensive study on the energy needs of the future warrior published by the National Academy of Science in 2004 [3] made a variety of recommendations for average power systems from 20 to 1,000 watts. For lower power systems recommendations included pursuing science and technology initiatives focused on 1) 300 watt-hours per kilogram (Wh/kg) secondary battery technologies 2) smart hybrids and 3) fuel cells (with greater than 6 wt% hydrogen storage).

Improved secondary (rechargeable) batteries may be the ideal solution for military power systems due to their ease of use and public acceptance. However, a 3X improvement in their specific energy density is not likely anytime soon. Today's Lithium Ion batteries, at about 150 Wh/kg, fall well short of the energy density that is required. Future battery technology may not be the answer since many experts do not predict more than a 2X improvement in Lithium battery systems over the next 10 years [4]. That is why most auto companies have abandoned all electric vehicles in favor of fuel cells and hybrid vehicles. Fuel cells have very high specific energy densities but achieving high energy values will depend on the energy density and the storage method of its fuel. Improved methods of safely and efficiently storing larger amounts of hydrogen will be a key development area for portable fuel cell power systems. Despite their high potential energy, fuel cells exhibit low power densities. That is why many systems today are going hybrid. Hybrid systems typically combine low energy and high power components with high energy and low power components. Typical configurations include capacitors and fuel cells or batteries and fuel cells. If done correctly, a hybrid system often can have both high energy and high power density even higher than any of the individual components.

HYDROGEN

Hydrogen at 33,000 Wh/kg has one of the highest specific energy densities of any other fuel. Table 1 compares the specific energy density of various popular fuels:

Table 1. Specific Energy Density of Various Fuels

Fuel	Specific Energy Density Wh/kg
JP-8 and Gasoline	12,000
Methanol	5,600
Ethanol	7,500
Hydrogen	***33,000***
Hydrogen (6%)	***2,000***

From Table 1 it is obvious why hydrogen is often viewed as a high energy fuel and why it is used as the fuel of choice for NASA in rockets and space exploration. Another advantage of hydrogen is its higher energy conversion efficiency when used in a fuel cell (50 to 60%) versus an internal combustion engine (15 to 25 %). With 6 wt% storage and a 50% energy conversion efficiency, a hydrogen fuel cell system could generate an energy density of 1000 Wh/kg or almost 7 times that of today's Lithium Ion batteries.

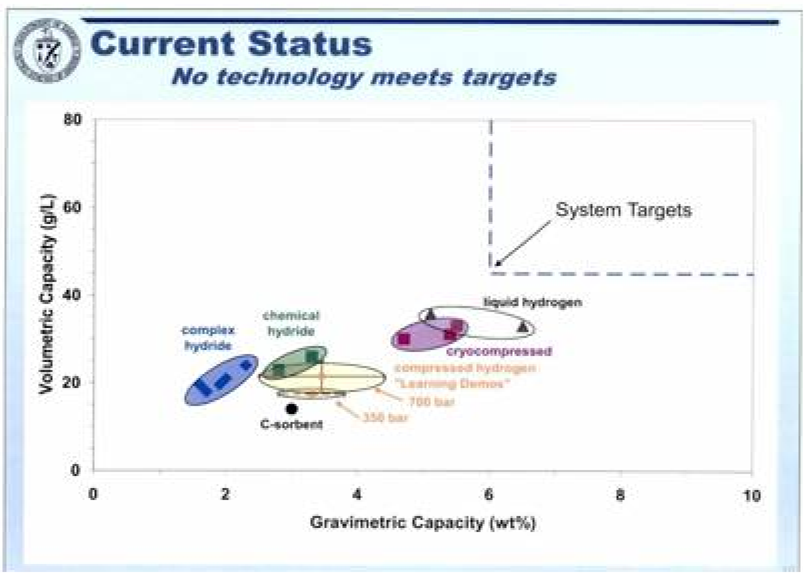
While hydrogen has a very high specific or gravimetric energy density the opposite is true with respect to its volumetric density in watt-hours per liter (Wh/L). As a gas hydrogen must be compressed to pressures of 5000 psig or higher to obtain a reasonable volumetric energy density. Even liquefied hydrogen only has a volumetric energy density about a fourth of that of gasoline. Luckily, today research on more efficient ways of storing hydrogen is actively being pursed all over the world for a variety of hydrogen applications from automobiles to laptops.

HYDROGEN STORAGE

The Savannah River National Laboratory (SRNL) has been working with the Department of Energy (DOE), other National Laboratories, universities and industry to develop high capacity, low weight hydrogen storage materials for automotive applications. This has often been referred to as the hydrogen "Grand Challenge". The goal of the DOE Hydrogen Program is to develop onboard hydrogen storage for passenger vehicles that achieves greater than a 300 mile driving range without compromising passenger/cargo space, performance or cost. This requires meeting targets which include: hydrogen capacity, operating temperature range (-40 to +85C), hydrogen supply rate/refueling rate (0.2 grams of hydrogen per second per kilowatt of power/refueling time less than 3 minutes for 5 kg of hydrogen), system cost, fuel cost, safety, reliability, cycle life, efficiency etc.[5].

Over the past several years, while many new materials have been developed under the DOE program, most have fallen short of the challenging automotive-based targets. Figure 1 shows the current status of the DOE program with respect to the gravimetric and volumetric targets. Because hydrogen exists as such a light weight gas, storing it at a high gravimetric and volumetric hydrogen density has been one of the greater hydrogen storage challenges. From Figure 1 the DOE system targets of 45 grams per liter (g/l) and 6 wt% hydrogen for 2010 and 80 g/l and 10 wt% hydrogen for 2015 are represented by the box in the top right hand corner of the graph. Also in Figure 1 some preliminary system results for various hydrogen storage materials are plotted and compared to compressed and liquid hydrogen systems. It is obvious form Figure 1 that none of the materials developed to date, including compressed gas and liquid hydrogen, meet the current DOE capacity targets when compared on an overall system basis.

Figure 1. Current Status of DOE Hydrogen Storage Targets [5].



To help achieve their hydrogen storage goals, DOE has funded three multi-disciplinary Centers of Excellence in hydrogen storage materials development and a new Center of Excellence in hydrogen storage engineering and systems development. The three materials Centers in Metal Hydrides, Chemical Hyrides and Adsorbents are all led by various DOE National Laboratories with participation by various university, industrial and other National Lab partners. SRNL has recently been selected by the DOE to lead the new Hydrogen Storage Engineering Center, which is tasked to work with the other three centers to develop and test subscale engineered systems of the most promising candidate hydrogen storage materials.

While the DOE hydrogen storage challenge is still moving forward, based on automotive requirements, SRNL believes that many of the new materials that have been developed may already have potential for portable power applications. For example, many portable power applications do not require the same cost targets that are required by the transportation marketplace. Also options like fuel cartridge swapping and replacement are much more doable and economical for smaller portable power systems than for onboard vehicle systems.

Table 2 shows some of the high capacity hydrogen storage materials that are being investigated by SRNL and the others for the DOE hydrogen storage program. While many of these appear to have the potential to meet the DOE 2010 system target of 6 wt% hydrogen most can not meet many of the other DOE targets because of their higher operating conditions or costs making them unsuitable for onboard passenger vehicle systems. Many of these candidate materials with hydrogen capacities from 10 to almost 20 wt% may be ideal candidates for military portable power applications - leading to system specific energy densities from 1500 to 3000 Wh/kg.

Table 2. High Capacity Hydrogen Storage Materials

Formula	Weight % Hydrogen
NH3BH3	19.6 (12% practical)
LiBH4	18.3 (requires high temperatures)
Al(BH4)3	16.8
Mg(BH4)2	14.8
LiAlH4	10.6
NaBH4	10.6 (7.6% with 50% H2O)
AlH3	10.0
NaAlH4	7.4 (5.6% practical)

Many of the materials in Table 2 also have very high volumetric hydrogen capacities. For example Alane (AlH3) has twice the hydrogen capacity of liquid hydrogen making it good potential candidate for portable power systems. Some of the systems in Table 2 can simply be heated to release some or all of their hydrogen others can be slowly reacted with water or other liquids to release their contained hydrogen as well as some of the hydrogen from reaction with the water. Sodium borohydride (NaBH4) is an example of this type of material that with a catalyst can react with water to provide hydrogen. NaBH4 has already found some uses in military and other portable power applications.

DOD WARFIGHTER PORTABLE POWER CENTER

SRNL proposes a unique Warfighter Portable Power Development Center focusing on 20-200 W, soldier power systems. SRNL plans to team with universities, National Laboratories and industrial partners to further enhance its already strong capabilities and talents. The unique feature of the center is its focus on inviting manufacturers and developers of fuel cells, batteries, capacitors and other electrochemical components and devices to partner in integrating their components and devices into a final product, which functions as a complete military power pack – a SYSTEM solution. Figure 2 shows a schematic of the proposed Center's organization and its inter-relationships.

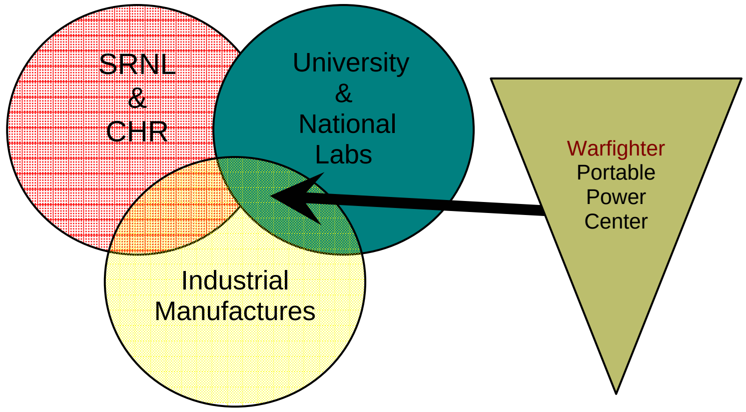


Figure 2. Warfighter Portable Power Center Schematic

The driver for this type of center is twofold. One is the need to substantially increase the operational life and reduce the weight of battery packs often used by the military. The other driver is to leverage off of the many novel hydrogen storage materials and systems that are coming out of the DOE and other federal hydrogen program. The goal of the Center is to develop complete power source systems for a variety of portable Warfighter applications. The primary approach of the Center will be to identify several > 10 wt% hydrogen storage systems and to combine them with fuel cells and other energy storage devices to arrive at an optimal power source solution. For example, a recent DOD challenge sought the development of a 20 watt warfighter system that lasts through a 96 hour mission and weighs less than 4 kg. This requirement can be restated as a power system with specific energy density of 500 Wh/kg. Table 3 compares several Soldier Energy Sources for 20W and 100W average power for 72 hours missions [3].

Table 2. Comparison of Various Soldier Power Systems

Technology	**Specific Energy Density Wh/kg**	**Average Power, W**
PEM/H_2 (5000 psi)	1,033	20
PEM/$NaBH_4$	556	20
DMFC	478	20
Li ion (SOA*)	170	20
PEM/H_2, 6%	659	100
DMFC	581	100
Li ion (SOA*)	170	100

*SOA = State of the Art

From Table 2, it can be seen that several Proton Exchange Membrane (PEM) fuel cell systems using either direct hydrogen, metal hydride or direct methanol all have the ability to achieve system energy densities in excess of 500 Wh/kg. Also all of the fuel cell systems have specific energy densities 3 to 5 times that of the latest Lithium ion secondary battery technology. By further increasing the hydrogen storage density in these fuel cell systems to 10 wt% it could easily lead to systems with energy densities in excess of 1000 Wh/kg.

While increasing the specific energy density of Warfighter power systems is one of the main objectives of our program, the Center also plans to optimize the power systems to military conditions and operations. These include improving their ease of use and reliability in the field and harsh environments, employing hybrid technologies to minimize the impact of using air breathing devices, minimizing heat and noise signals, and lowering overall system and deployment costs.

The Center is aimed at providing the military with a complete solution to the future Warfighter power needs.

PARTNERSHIPS

As described earlier the objective of the DOD Warfighter Portable Power Center is to partner with commercial fuel cell, battery, vessel and other component manufacturers as well as university and other National Laboratory experts to develop and test complete power systems for military applications. To expedite this effort SRNL will partner with the Center for Hydrogen Research (CHR) a unique non-profit organization and facility located adjacent to SRNL facilities near Aiken, South Carolina.

The Center for Hydrogen Research

The CHR is a 60,000 square foot, $10.0 million facility designed for hydrogen research, development, and commercialization. CHR tenants include the Savannah River National Laboratory, Toyota Technical Center R&D lab, offices for the International Fusion Experiment project, and University of South Carolina - Aiken research on bio-hydrogen. The CHR and SRNL have under development a $1.0 million DOE-sponsored project to evaluate backup fuel cell power using metal hydride storage and electrolysis technologies. The CHR has also operates a hydrogen refueling station and a hydrogen fueled internal combustion vehicle.

The role of the CHR is both to provide the creative environment and to serve as a catalyst to bring scientists and technologists from various organizations and disciplines together to help solve problems and develop unique solutions. The needs of the Warfighter for high capacity and reliable power are an excellent example of the type of problems the CHR can address. The unique feature of the proposed Center is its focus on inviting manufacturers and developers of fuel cells, batteries, capacitors and other electrochemical components and devices to partner in integrating their component parts and devices into a final product, which functions as a complete military solution.

Savannah River National Laboratory

SRNL has over 50 years of experience in developing and applying hydrogen technology, both through its national defense activities and its hydrogen energy activities with the DOE and industry. The hydrogen technical staff at SRNL comprises over 90 scientists, engineers and technologists, and it is believed to be the largest such staff in the U.S. Forty of the SRNL hydrogen professionals have research facilities in the CHR. SRNL has ongoing R&D initiatives in a variety of hydrogen storage areas, including metal hydrides, complex hydrides, chemical hydrides and carbon nanotubes. SRNL has over 25 years of experience in metal hydrides and solid-state hydrogen storage research, development and demonstration.

The SRNL has been active in teaming with academic and industrial partners to advance hydrogen technology and has participated in projects to convert public transit and utility vehicles for operation on hydrogen fuel. Some major projects include the H2Fuel Bus and an Industrial Fuel Cell Vehicle (IFCV) also known as the GATOR™. Both of these projects were funded by DOE and cost shared by industry.

SRNL is a recognized international leader in hydrogen storage with added expertise in hydrogen production, fuel cells and battery technology. SRNL has excellent access to worldwide hydrogen technology information and is the DOE lead for the Hydrogen Storage Engineering Center of Excellence.

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