ITA White Paper
Fuel Cell Technology for Industrial Truck Applications
Industrial Truck Association
1750 K Street, NW, Suite 460
Washington, DC 20006
www.indtrk.org

1 Introduction 1
2 Fuel Cells and Associated Technologies 2
2.1 Technology Overview 2
2.2 Fuel Cell and Fuel Cell Hybrid Systems 4
2.3 Fuel Cell Propulsion On Board Industrial Trucks. 6
3 Fuel Storage 7
3.1 Compressed Hydrogen Gas 7
3.2 Metal Hydrides 8
3.3 Liquid Hydrogen 8
3.4 Other Forms of Hydrogen Storage 9
4 Fuel Generation and Dispensing 10
4.1 Hydrogen Fuel Generation 10
4.2 Daily Hydrogen Requirements. 13
4.3 Hydrogen Dispensing 14
5 Opportunities and Challenges 14
Acknowledgements 16
Appendix A: Industrial Truck Fuel Cell Related Codes and Standards Overview 17
Appendix B: Fuel Cell and Hydrogen Technology Developers 18
Appendix C: Bibliography and References 22

1 Introduction

A fuel cell is a type of energy conversion device that produces electricity from hydrogen—either high-purity hydrogen or hydrogen-rich reformate derived from other fuels. Fuel cells are currently being developed for a variety of stationary, automotive, off-road, and portable applications. Like batteries, direct hydrogen fuel cells produce no emissions (other than water), and therefore are suitable for use in confined environments, such as warehouses, manufacturing plants, and mines, or wherever air quality is a concern, such as at airports and in urban centers. Like engines, fuel cells can be refueled in a matter of minutes, and full power availability is sustained so long as fuel is available. The potential benefits of fuel cell-powered industrial trucks include the productivity gains associated with eliminating battery changing and charging procedures, freeing up facility space currently taken by the battery room, higher performing trucks (within their design limitations), and the ability of OEMs to optimize their designs with power system components distributed throughout their vehicles

This white paper on fuel cells and hydrogen fueling was prepared by the Fuel Cell Working Group of the Electric Power & Systems Committee for the benefit of the entire ITA membership. The intent of the document is to provide an overview of fuel cell and related technologies (such as fuel processors and electrolyzers), describe the benefits they can enable as well as the challenges they still face, and provide resources for further investigation. Comments and questions can be relayed to the Working Group through Christopher F. Merther, Manager, Technical Programs (cmerther@earthlink.net).

2 Fuel Cells and Associated Technologies

2.1 Technology Overview.

Fuel cells generate electricity from an electrochemical reaction between oxygen and hydrogen, creating water and heat as byproducts. Most fuel cells are able to use oxygen from air. The fuel cell may be designed to use either pure hydrogen or reformate (hydrogen derived from hydrocarbon or other fuels). The different types of fuel cells that have been developed are summarized below.

Table 2-1. Types of Fuel Cells Available

	Alkaline Fuel Cell	***Direct Methanol Fuel Cell***	***Molten Carbonate Fuel Cell***	***Phosphoric Acid Fuel Cell***	***Proton Exchange Membrane Fuel Cell***	***Solid Oxide Fuel Cell***
Short Name	AFC	DMFC	MCFC	PAFC	PEMFC	SOFC
Electrolyte	Potassium Hydroxide (KOH)	Polymer Membrane	Immobilized Liquid Molten Carbonate	Immobilized Liquid Phosphoric Acid	Ion Exchange Membrane	Ceramic
Operating Temperature	300-400°C	60 - 130°C	650°C	200°C	80°C	750-1000°C
Typical Electrical Power	Up to 20kW	<10kW	Up to 2 MW	>50kW	1 kW to 250kW	Up to 100 kW
Efficiency	45-60%	40%	45-60%	35-40%	40-60%	50-65%
Possible Applications	Spacecraft	Portable applications	Power Stations	Power Stations	Vehicles, Stationary, Portable	Small APUs to Power Stations

What is commonly referred to as a ‘fuel cell’ is a stack assembly made up of individual cells. Each cell consists of a cathode and an anode (the positive and negative electrode, respectively), an electrolyte, and a catalyst. Hydrogen fuel is fed into the anode side of the cell. Oxygen (from air) is fed into the cathode side. Utilizing a catalyst, the hydrogen molecules (H_2) are dissociated into hydrogen ions (protons) and electrons, as follows: $H_2 = 2e^- + 2H^+$. The protons pass through the electrolyte, while the free electrons are directed through a circuit to the cathode. As the electrons travel their separate path, they create the electric current used to power a load. At the cathode, the hydrogen ions combine with oxygen to create water according to the reaction: $2H^+ + \frac{1}{2} O_2 = H_2O$. The overall process is summarized in the following chemical equation:

$$H_2 + \frac{1}{2} O_2 = H_2O + 2e^- \text{ (+ heat)}$$

The fuel cell classification presented in Table 2-1 follows the convention of identifying fuel cells by the type of electrolyte they use. Of the various types of fuel cells that have been developed, Proton Exchange Membrane (PEM) fuel cells are the type widely regarded as being best suited to most vehicular applications (including forklifts), as well as in buildings and smaller applications. The principles behind the design and operation of a PEM fuel cell are shown in Figure 2-1.

Fuels cells are in limited use today in a variety of applications. Stationary power for industrial use ("distributed generation") is an area with significant market penetration for fuel cell systems. Most of these systems are PAFCs, but also include SOFCs and PEMFCs. Several companies are developing fuel cell products for residential-scale applications either as primary power or backup power, with several demonstration projects in process. In the transportation industry, virtually all major automotive OEMs are developing cars with fuel cell technologies, but commercial offerings are 5-10 years off. In transportation applications, hybrid configurations are common, using a fuel cell and an energy storage device such as a battery or ultracapacitor. In the lift truck industry, development work is underway, and field trials are being conducted by several developers.

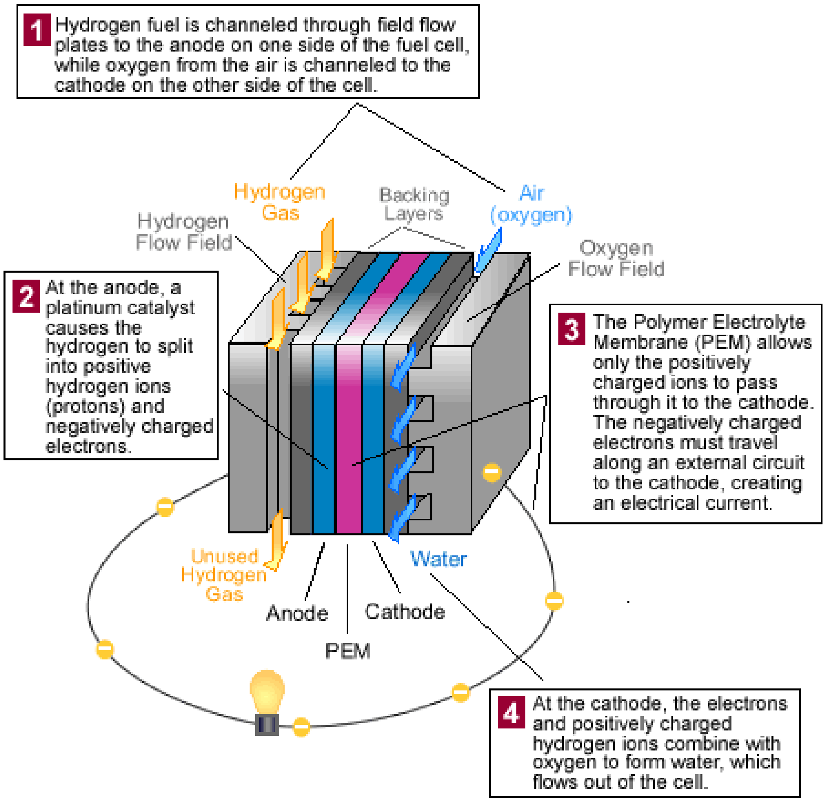

Figure 2-1. How PEM Fuel Cells Work (source: US DOE).

2.2 Fuel Cell and Fuel Cell Hybrid Systems

The basic components that make up a fuel cell *system* are a fuel processor (unless the system is "direct hydrogen," which uses pure hydrogen as the fuel), a fuel cell stack, and a power conditioner. Balance-of-plant components may include radiators or other heat exchangers, pumps, blowers, valves, and regulators. A schematic of a generic fuel cell system is shown in Figure 2-2.

If hydrogen is used as fuel, a valve and regulator are used to deliver fuel to the fuel cell anode from a hydrogen reservoir, such as a compressed gas tank. As long as the hydrogen is of the correct quality for the type of fuel cell being used, the fuel cell will combine it with oxygen from air to produce electricity, water and heat.

If there is no available source of pure hydrogen, other more readily available fuels such as natural gas, gasoline, propane, or methanol can be "reformed" in a fuel processor to produce a hydrogen-rich gas. The standard ways of processing fuels to create hydrogen are steam reforming, partial oxidation, and autothermal reforming (the latter a combination of the first two). High-temperature fuel cells, such as SOFC and MCFC, are able to reform hydrocarbon (HC) fuels directly within the stack, so no external fuel processor is needed. This is indicated by the dashed line in Figure 2-2.

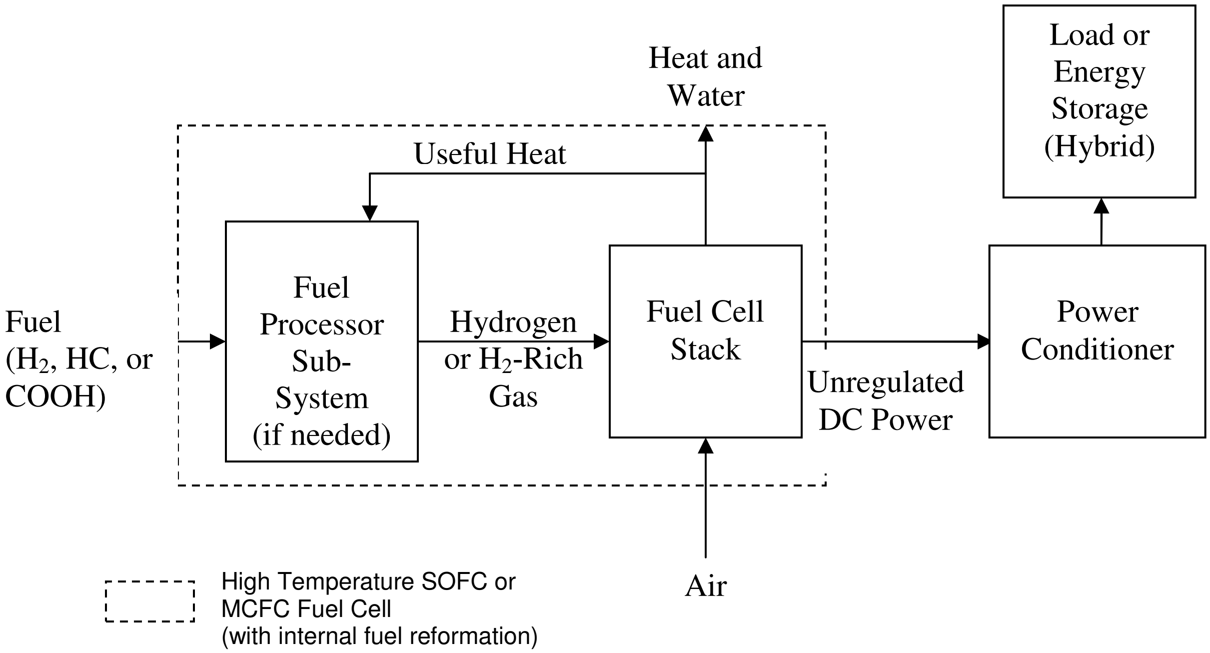

Figure 2-2. Fuel Cell System Schematic.

Fuel cells typically require very "clean" hydrogen or reformate (a hydrogen-rich feedstock reformed from gasoline, natural gas, or other fuel in a fuel processor) to allow them to operate efficiently and reliably for extended periods of time. For example, PEM fuel cells use a catalyst membrane to react hydrogen and oxygen that is sensitive to sulfur and carbon monoxide. Because of this, the hydrogen reformate produced from fuel processors must be purified before entering the fuel cell.

The power conditioner converts constant current and voltage output of the fuel cell into useful power. The type of power conditioner required depends on the application. Those with instantaneous transient loads need to react quickly to provide power when needed. An example of this is the use of ultracapacitors as power conditioners. A power conditioner can also be an inverter that converts the DC power output of the fuel cell into power that can be put back into the electrical grid if necessary, or used to power AC loads. Power conditioning can also provide other functions such as current or voltage regulation for the fuel cell, surge and short circuit protection, and connection to and management of energy storage.

The balance-of-plant (BOP) of a fuel cell system is comprised of the major components of the subsystems, other than the fuel cell stack and the fuel processors themselves. Power conditioners (such as DC/DC converter, ultracapacitors, or DC/AC inverters) are typically regarded as BOP. The BOP components associated with the fuel processors and fuel cell stacks vary depending on the technology type, but typically are compressor/expanders, pumps, controls, safety systems, and start up batteries. BOP components have a critical effect on the overall fuel cell system cost, durability, reliability and efficiency.

Fuel Cell Hybrids. According to Webster, a hybrid system is a powerplant, vehicle, or electronic circuit that has two different types of components performing essentially the same function. The rationale for hybrid systems in general is to take advantage of the strengths of each technology in order to create a system that performs "better" according to some important metric, such as efficiency, economy, or power density.

Although they may be used as either static or transient power sources, fuel cell systems typically do not respond well to instantaneous high loads. BOP components such as valves, blowers and pumps are typically the limiting factor. Batteries and ultracapacitors may be paired with fuel cells to handle the high current demands, such as vehicle peak load requirements, and to handle regeneration. Even if the fuel cell system is designed to handle peak loads, a battery- or ultracapacitor-fuel cell hybrid system may afford a lower cost alternative than a stand-alone fuel cell system.

The primary battery characteristic typically necessary within hybrid systems for industrial trucks is the ability to supply peak load currents as required by the vehicle. Batteries are likely to be sealed valve regulated or maintenance-free. Batteries may be of various chemistry types, such as lithium ion, lead acid, and nickel metal hydride. Various battery designs may be utilized such as golf cart, motive power, and automotive, depending on the specific requirements of the application.

Relative to many battery technologies, ultracapacitors have high power density with long life at low depths of discharge. They are generally capable of tens of thousands of cycles at instantaneous power demands, and are also capable of high charge acceptance. There are symmetric types (C/C) and asymmetric types (Ni, Li, Pb/C).

2.3 Fuel Cell Propulsion On Board Industrial Trucks.

The two most discussed methods for incorporating fuel cells into lift trucks are: 1) A one-to-one (1:1) replacement for the existing battery, and 2) a system having components located throughout the truck, much as we now package other truck sub-systems.

In the first case, the fuel cell power system would occupy the same overall dimensions, have the same weight and be located in the same place as the existing battery. Users would simply replace the battery with the fuel cell power system. The 1:1 replacement could consist of any feasible type of fuel cell or fuel cell hybrid along with the fuel storage, electronics, and balance-of-plant. The primary benefit of this approach is that existing trucks could be converted to fuel cell operation with little or no modification. The downsides of this approach are the performance benefits lost due to these same packaging constraints, and the costs associated with packaging all of the components in the envelope of the existing battery compartment.

In the second case, the fuel cell power system is designed into the forklift by the forklift OEM and the battery compartment is eliminated. The various components, including the fuel cell stack, electronics, fuel and cooling systems and any hybrid components, can be distributed throughout the truck. The battery compartment is eliminated. This gives forklift OEMs the opportunity to revise the overall layout of the truck. Operator compartment size and shape, and even overall truck dimensions, can be rethought. Electric truck designers will face challenges familiar to their gas truck counterparts, including those of fuel systems and radiators. At the same time, designers will have the opportunity to reduce total costs by combining fuel cell power system components (power electronics, for instance) with those already on the truck.

3 Fuel Storage

For mobility applications, including off-road vehicles such as industrial trucks and airline ground support equipment, there are several options are possible for the storage of hydrogen fuel. These technologies are described in the sections below.

3.1 Compressed Hydrogen Gas

Currently, compressed hydrogen gas (CHG) is the most readily available and simplest means of hydrogen storage. Because of their capacity to store hydrogen safely at high pressure (>5000 psi), CHG storage tanks provide relatively good energy storage density. Type 3 and Type 4 are the two primary types of tanks that are being considered for mobile fuel cell applications.

Type 3 tanks have an aluminum linings and carbon fiber outer shells. These tanks have been tested for 5,000 psi storage. Manufacturers of these tanks are in the process of obtaining certification for 10,000 psi storage. Type 3 tanks are currently being used by a number of OEMs in the automotive industry.

Type 4 tanks have polymer linings and carbon fiber outer shells. These tanks are typically used to store hydrogen at 5,000 psi but have recently been certified by the European Integrated Hydrogen Program (EIHP) to work at 10,000 psi. The main advantage of Type 4 tanks is that there is no issue with hydrogen impurities or contaminants since the polymer layer cannot be damaged by hydrogen. Like Type 3 tanks, Type 4 tanks are being used by many automotive manufacturers on their concept hydrogen vehicles.

CHG tanks are designed to minimize leaks and protect against impact and abrasion. They come with pressure regulators, pressure and temperature sensors and check valves to monitor leaks. A Kevlar overwrap is used to protect against impact and abrasion and foam domes are used at the ends to protect the valves and domes.

ISO is currently working on standards for CHG. It will take approximately another year (until 2006) before this standard is complete. When complete, it is expected that most manufacturers will design their tanks to meet this standard. Currently EIHP, KHK (Japan) and NGV 2000 are the agencies that have standards in place.

The ISO standard will most likely require manufacturers to design their tanks for 15 years. The tanks will be tested for a number of cycles (around 10,000 to 15,000 cycles from low pressure to 125% of rated pressure), and monitored for damage or leaks. They will most likely use an MRI type machine to test for failure due to fatigue.

At 5,000 psi a 34 liter tank can hold approximately 0.8 kg of hydrogen. One kilogram of hydrogen has approximately 32 kWh of energy, roughly equivalent to the energy content of a gallon of gasoline. If pressure is raised to 10,000 psi capacity is increased by 60%.

3.2 Metal Hydrides

Metal hydrides represent another high-density hydrogen storage technology that might be viable for industrial truck applications. Hydrogen can be absorbed in certain alloys to form metal hydrides (MH) that can later released as pure hydrogen gas. Heat and pressure are used in this process. An increase in pressure or decrease in temperature results in storage (absorption). An increase in temperature or decrease in pressure will break the hydrogen bonds and release the hydrogen as pure gas (desorption). Pressure vessel tanks (up to 1500-2000 psi) are constructed with heat exchange tubes and filled with high porosity MH powder to provide a large surface area and uniform heat management. This method of storing hydrogen can achieve volumetric energy densities surpassing CHG at 10,000 psi. The gravimetric energy density is relatively low because the metal alloys are heavy and only store about 1 to 5% hydrogen by weight. The extra weight is an advantage for lift truck applications because it can be used as counterbalance.

Cooling must be provided to the on-board hydride storage tank during the filling operation, using a chiller or other heat sink at the refueling site. The heat energy required to release the hydrogen during operation can come from the fuel cell stack itself, if the system is designed to accommodate this process.

While the cost of metal hydride storage is higher than compressed gas, it is usually regarded as safer and can store more energy in the same volume. Also, since hydrogen need not be compressed to as high a pressure, fuel costs for hydride storage will be lower than CHG. These characteristics make metal hydrides a potential candidate for lift truck applications.

3.3 Liquid Hydrogen

At 20K (-253ºC) and ambient pressure, hydrogen exists in a liquid state. The greatest advantage afforded by liquid hydrogen (LH_2) storage is volumetric density. Figure 3.1 compares the volumetric and the gravimetric density of LH_2, CHG, cryogenic CHG (at 150K), batteries, diesel, and gasoline storage systems (not just the hydrogen, hydride, or hydrocarbon fuels themselves, but the containment vessels, heat exchangers, and insulation, if any, associated with each form of storage). Note that the scales are logarithmic. Systems near the bottom are much bulkier than those at the top; systems on the left are much heavier than those on the right.

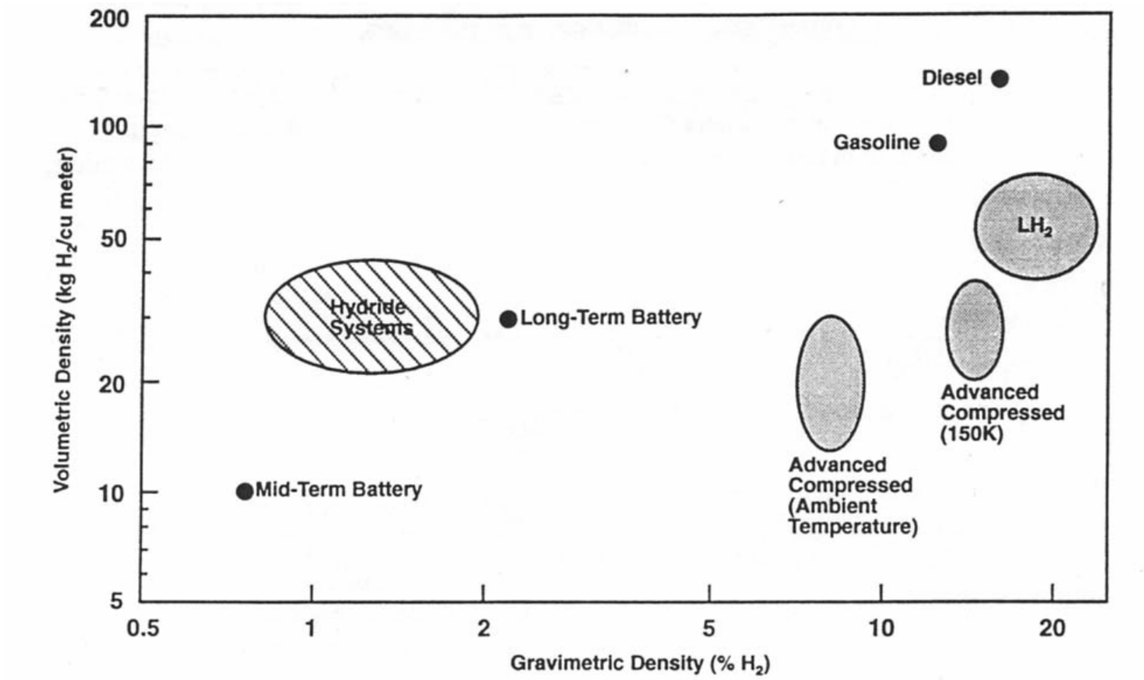

Figure 3.1 Gravimetric and Volumetric Densities of LH2, CHG, and Cryogenic CHG Compared with the Densities of Batteries, Gasoline, and Diesel.
(Source: Arthur D. Little, Inc. and Air Products and Chemicals, Inc.)

The disadvantages of liquid hydrogen storage are cost, safety, and evaporation (boil-off). Cost issues include the cost of liquefaction (discussed in Section 4.1, below), handling, and the cost of the tank itself, which must be double-wall, vacuum super-insulated tanks maintained at a temperature of 20K and with a maximum overpressure of 5 bar. The safety concerns are mainly associated with the problems of using a cryogenic fuel, such as pressure build-up following plugged valves, or the effects of sudden tank failure (from a collision, for example) releasing all the mechanical, thermal and chemical energy stored in the system. The boil-off issue results from the fact that hydrogen will gradually evaporate from even the best insulated systems (about 2% per day), and this must be effectively contained or utilized.

Notwithstanding the cost, complexity and other challenges associated with the use of liquid hydrogen as a motive fuel, it is still considered a viable option for on-board hydrogen storage by some automotive OEMs, among others. Given the advantages of LH_2 with respect to volumetric densities of other forms of hydrogen storage, along with the fact that there is a long history of safe handling and use of liquid hydrogen in the industrial gas sector and space programs, it should not be dismissed as an option out of hand.

3.4 Other Forms of Hydrogen Storage

There are two other types of storage methods under development:

- Carbon nanotubes
- Glass microspheres

Carbon nanotubes are small tubes of carbon that store the hydrogen within the tubes' structure. The method is similar to metal hydrides where the hydrogen is absorbed into small cavities. From a safety perspective this method is attractive since the hydrogen is not stored under high pressure. The research is in an early stage and the results are inconclusive.

Glass microspheres are beads of glass, microscopic in size. Heating the spheres increases the permeability of their walls, allowing high-pressure hydrogen gas to permeate the glass. Upon cooling, the permeability decreases, locking the hydrogen inside the bead. To release the hydrogen, the glass beads are heated allowing the hydrogen gas to leak. This method has the potential to be as safe as the metal hydride tanks with the same storage capacity but with less weight.

Both methods are still in a very early development phase and there are currently no commercial products available on the market. It will probably be some time before these methods are mature enough for commercialization.

4 Fuel Generation and Dispensing

4.1 Hydrogen Fuel Generation

There are two basic methods for providing hydrogen fuel for use in industrial truck applications: 1) Delivered from large industrial gas producers, and 2) onsite generation. Since hydrogen does not occur freely in nature, it must be made or converted from other energy sources. The most common methods of hydrogen production are natural gas steam reformation, water electrolysis and coal, biomass or other hydrocarbon-based gasification. Steam reforming of natural gas is the predominant source of hydrogen today. Water electrolysis is well established but is generally used for generating small amounts of hydrogen on-site. Most other technologies are still in the development stages.

There are several industrial gas companies that can deliver hydrogen to the customer's site for use in fuel cell powered industrial trucks. These companies have the ability to deliver the hydrogen in standard industrial cylinders for small vehicle fleets or demonstrations, CHG tube trailers for larger fuel uses, and in cryogenic liquid form for heavy hydrogen consumers. Standard industrial cylinders, such as those commonly used for welding or in labs, hold about 0.8 kg of hydrogen. Compressed gas tube trailers can hold between 100 and 300 kg of hydrogen, while liquid hydrogen trailers can hold around 3500 kg of hydrogen. Liquefaction adds approximately $0.50 to $0.75 per kg to the price of the delivered hydrogen (assuming electricity at $0.05/kWh). Depending on the fuel source pressure and on-board storage method in the industrial truck (CHG or metal hydride), the delivered hydrogen may need to be compressed using a mechanical compressor before it can be dispensed to the vehicle.

There are presently two methods for onsite generation of hydrogen: 1) Natural gas steam reformation, and 2) water electrolysis. Steam reforming of natural gas produces a gas with a 3:1 ratio of hydrogen to CO. To remove CO (poisonous to a PEM fuel cell), and to increase the yield of hydrogen a CO shift reactor can be used to convert the CO to CO_2. The hydrogen-rich gas can be used in some PEM fuel cells that are designed for the direct use of reformate. Otherwise, Pressure Swing Adsorption (PSA) is used to remove the impurities such as water, CO, CO_2 and N_2 and methane from the output stream of the reformer. The purity of the output of the reformer with PSA can reach 99.99%+, clean enough for use in all PEM fuel cells.

There are several companies that make small-scale natural gas reformation products that can be used to provide hydrogen fuel for industrial trucks. These companies have developed units that can be installed onsite, typically outdoors, and produce 50 to 200 kg of hydrogen per day. The efficiency of these types of hydrogen generators is around 75% for natural gas-to-hydrogen conversion efficiency. At 75% efficiency, it takes approximately 18 MBTUs of natural gas to make 100 kg of hydrogen. Furthermore, these generators require 3 to 4 kWh of electricity per kg of hydrogen produced. The relationship between the cost of hydrogen and natural gas, excluding capital, compression and storage costs, is shown in Figure 4-1.

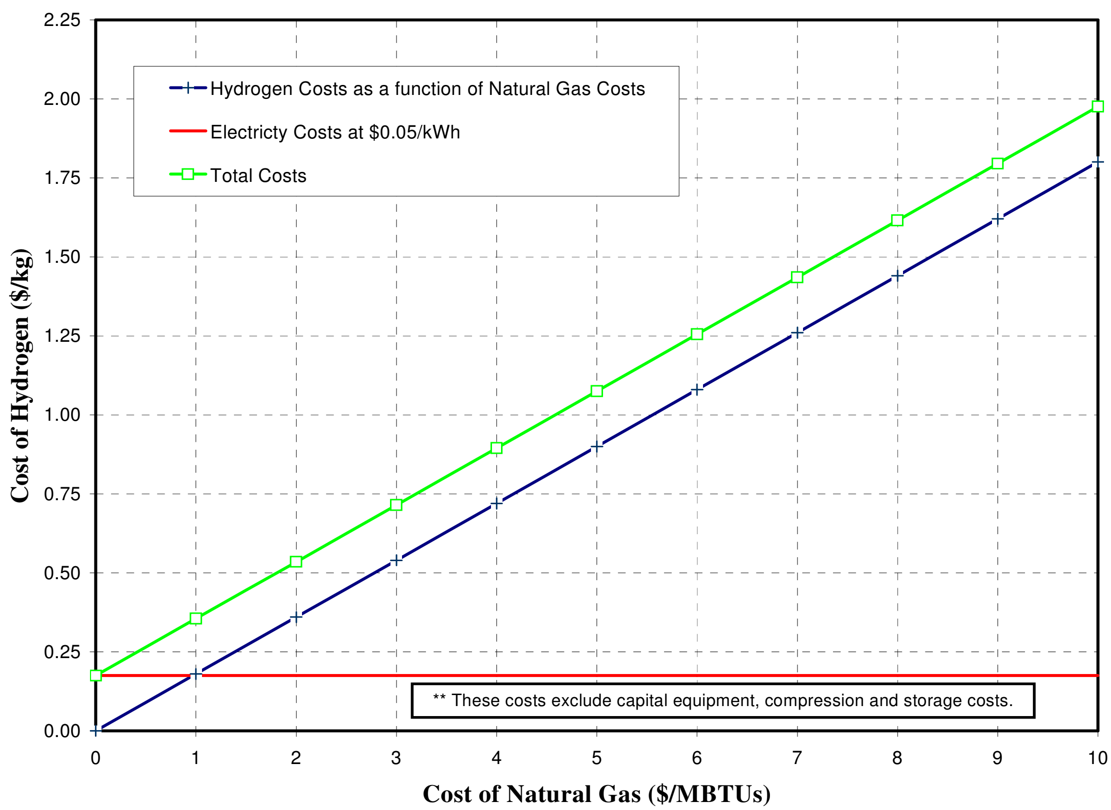

Figure 4.1: Estimated Hydrogen Costs as a Function of Natural Gas Costs for Small Scale Reformers.

In water electrolysis, electricity is used to decompose the water into its base components as described in the following equation:

H_2O + electricity = H_2 + ½ O_2

There are two common types of electrolyzers, Alkaline and Proton Exchange Membrane (PEM), each with pros and cons. Alkaline electrolyzers are the more mature technology and have a proven track record for reliability and are considered to be slightly more energy efficient. Alkaline electrolyzers are available from Stuart Energy and Teledyne Energy Systems. PEM electrolyzers are relatively new but can provide higher power density that can lead to more compact hydrogen generators. PEM electrolyzers are available from Proton Energy Systems, Norsk Hydro, and Hydrogenics, among others. The energy efficiency of electrolyzers range from 60 to 75% depending on the technology and unit size. Figure 4-2 provides estimates of hydrogen costs as a function of electricity cost when using an electrolyzer, excluding capital, compression and storage costs.

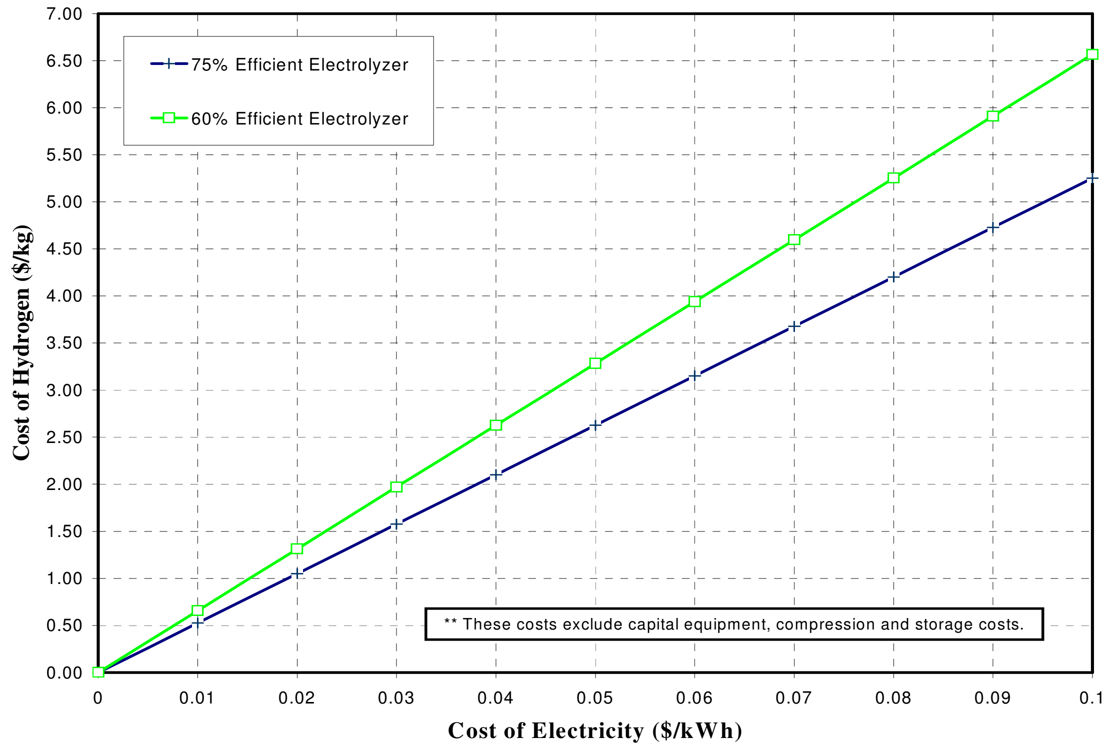

Figure 4-2: Estimated Hydrogen Costs as a Function of Electricity Costs for Electrolyzers.

Hydrogen Compression Requirements. When fueling high-pressure tanks, most forms of hydrogen generation/delivery will require some level of mechanical compression. Hydrogen compressors are found to have adiabatic efficiencies between 50 to 70% today depending on compressor design. With electricity cost of $0.05/kWh, hydrogen compression can add $0.15 to $0.20/kg to the cost of fuel dispensing for high-pressure tanks depending on the starting pressure of the fuel source. Furthermore, hydrogen compressors will require regular maintenance to prevent leaks and maintain efficiency.

Refueling metal hydride tanks has lower compression costs, since the tanks are usually at 1500 psi or less, but the tanks have additional heat exchange requirements that add to the capital and operational costs of using them.

4.2 Daily Hydrogen Requirements.

To determine the method of hydrogen delivery and storage requirements we must determine the expected consumption of hydrogen per day. Each type of industrial truck and application will require differing amounts of hydrogen. To make this analysis simple, we have picked three types of trucks, one from each Class (I, II and III) and assume they each use 1, 2 or 3 batteries per day. For Class III trucks (rider-pallet trucks) we will use a 24V, 600 Ah battery, for Class II trucks (narrow aisle trucks) we will use a 36V, 875 Ah battery and for Class I trucks we will use a 48V, 850 Ah battery. The useful energy in each battery (80% capacity) will be approximately 11.2, 24.4 and 31.7 kWh, respectively.

Fuel cell "engines" that would be used in the industrial truck market are estimated to be approximately 55% energy efficient on a LHV basis (33.35 kWh/kg). Assuming this energy conversion efficiency, then 1 kg of hydrogen will provide approximately 18.3 kWh of usable energy to the industrial truck. Figure 4-3 shows the estimated hydrogen use per day as a function of the number of battery changes and truck class. This chart shows that a Class I sitdown truck could require up to 5 kg of hydrogen per day. If a facility has 50 sitdowns then they could need up to 250 kg of hydrogen per day.

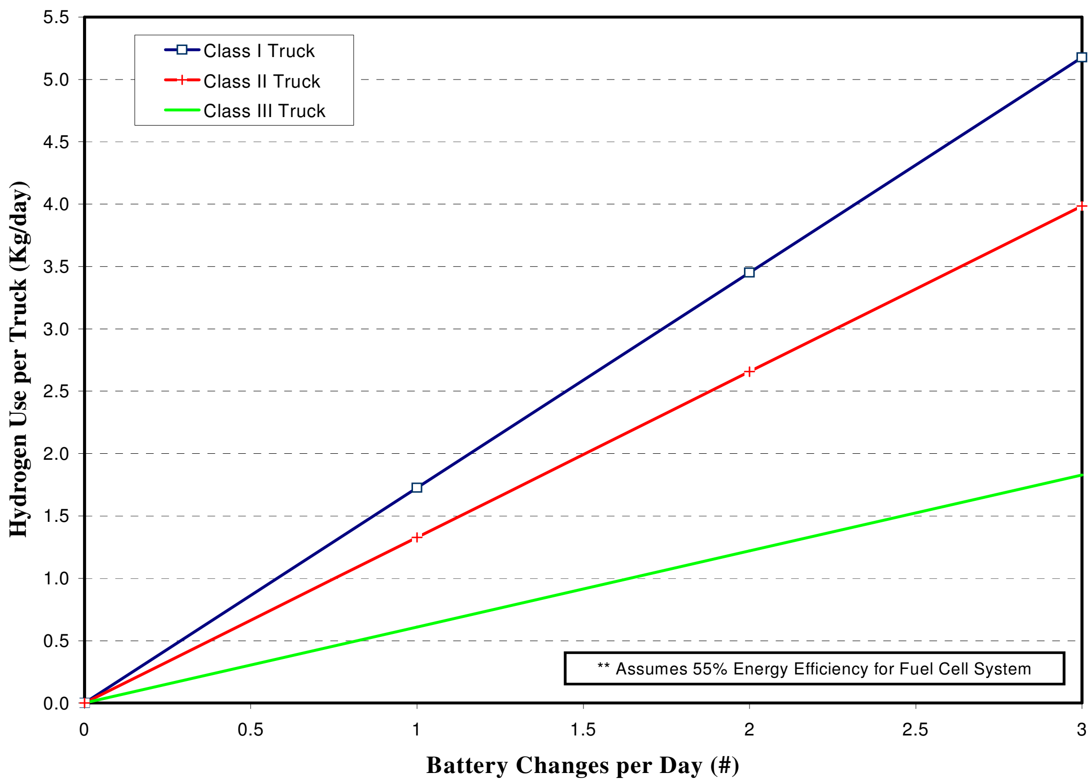

Figure 4-3: Hydrogen Use per Truck as a Function of the Number of Battery Changes and Truck Class

4.3 Hydrogen Dispensing.

Hydrogen dispensers are the user interface for the industrial operator. In simplified terms, a dispenser is designed to fill the tank as fast and fully as possible while managing tank temperature and pressure. When filling high-pressure tanks, the dispenser is connected to a high-pressure fuel source and controls some valves to manage the fuel flow. If the customer is familiar with fueling natural gas trucks, fueling with hydrogen will be very similar from the operator's perspective. The fill times with high-pressure storage are typically less than 2 minutes.

Hydrogen is stored in tanks at the refueling site similar to those used for compressed natural gas (CNG) storage. The storage pressure is determined by the pressure at which the hydrogen is stored on the industrial vehicle. To move the hydrogen from the generator into storage, a high pressure compressor is used.

Hydrogen is dispensed from the storage tanks into the industrial vehicle using equipment virtually identical to that used at CNG refueling stations. Special personnel are not required to dispense the hydrogen. Trained industrial vehicle operators can easily perform the refueling function.

Hydrogen generation systems are intended to be located at the user site to offer immediate availability of hydrogen. The hydrogen generating system will be located outside, next to (or on the roof of) the building structure, using guidelines provided by Codes and Standards. Three NPFA Standards will apply to the system – 50A gaseous hydrogen systems, 52 CNG vehicle code and hydrogen, 55 storage and use. Contact should be made with state and local fire marshals to determine what additional codes and installation regulations apply.

5 Opportunities and Challenges

While fuel cells and related technologies may afford significant benefits to industrial truck manufacturers, owners, and operators, there are a number of issues to be addressed before implementation can become widespread. These include the following:

- Codes and Standards. Codes and standards for the use of fuel cells in enclosed environments, and for the safe handling, on-site generation, and dispensing of hydrogen are still being developed. Appendix A gives an overview of the regulatory activity underway as it relates to industrial trucks. The fact that standards development is still underway will make obtaining local permits and licenses more difficult in many localities.
- Operating and Storage Environment. Fuel cell systems have sophisticated water and thermal management components that are affected by ambient temperature. For instance, sub-freezing environments may require systems to be equipped with liquid water recovery systems, since water normally released as vapor will instead condense in a freezer. Storage of most fuel cell power systems in sub-freezing environments will also require special design provisions.

- Cost. The capital cost of early fuel cell systems will likely be higher than for standard power sources such as batteries. However, this is mitigated by cost-of-ownership benefits that certain customers, such as large fleet owners, may decide are sufficiently compelling. As production volume rises over time, capital costs will decline and the initial investment required will come within range of a greater proportion of users.
- Hybrid System Design. Combining fuel cells with batteries or ultracapacitors afford both technical and economic advantages over non-hybrid fuel cell systems. However, the refinement of hybrid designs for industrial trucks will require collaboration among OEMs, suppliers, and end-users and possibly the development of new or optimized technologies.
- Autonomy. Carrying sufficient fuel on board to meet the expectations of customers for run-time will depend on the specific hydrogen storage technology used.
- Weight and CG. Fuel cells systems may weigh less than the batteries they are replacing, or the center of gravity may be different. If so, additional ballast may be required in the fuel cell system tray, the truck, or both.

It may be desirable for ITA to develop requirements and procedures to address some of the technical issues identified here as a follow-on activity. ITA members may also wish to become involved in the promulgation of codes and standards for the use of fuel cell systems on-board industrial trucks.

Acknowledgements

The creation of this White Paper was a team effort based on the substantial contributions of the following members of the ITA Electric Power and Systems Committee.

Contributors:
George Ayrton, EnerSys
Mike Berger, Exide
Gus Block, Nuvera Fuel Cells
Blake Dickinson, Aerovironment
Jay Eadie, Fuel Cell Solutions
Steve Lorenz, Sevcon
Wayne Mabry, MCFA
Steve McDermitt, Crown
Charlie Myers, Nuvera Fuel Cells
Ketan Ranade, Toyota Materials Handling
Ken Sanders, East Penn Manufacturing Co.
Peter Taube, Danaher Motion
Ken Van Hook, MCFA

ITA Support:
Chris Merther

Appendix A: Industrial Truck Fuel Cell Related Codes and Standards Overview

The following is a brief look at the state of codes and standards that relate to industrial trucks and fuel cells in North America or may be of interest to manufacturers of materials handling equipment. Many are still under development.
There are many additional fuel cell related standards, including those for automotive,stationary, portable and residential systems.
Given the evolving technical and regulatory 'state of the art' readers are encouraged to review the references organizations for more detailed information.

While there is significant North American fuel cell and hydrogen standards activity, a number of the US standards efforts (UL 2264, for example) are intended to fulfil or eventually feed into the international standards process.

Title	Description
UL 2267 - Standard for Fuel cell Power Systems For Installation in Industrial Electric Trucks	The requirements cover fuel cell power systems intended to be installed in type E, EE, ES and EX industrial trucks used in locations as defined in the Fire Safety Standard for Powered Industrial Trucks including Type Designations, Areas of Use, Conversions, Maintenance and Operations NFPA 505, and the National Electrical Code NFPA 70. The fuel cell power systems are intended to be connected to or integrated with industrial trucks to supply electrical power. These requirements anticipate the use of designs that are fueled by various fuels including hydrogen gas. A draft has been distributed for continued work.
UL 2264 - Standard for Gaseous Hydrogen Generation Appliances	The standard will consist of three sections, 2264A covering Water Electrolysis, 2264B covering Water Reaction, and 2264C covering Fuel Processing. Sections A and C are intended to present US national differences to the ISO TC197 WG 8 & 9 so that we can one standard instead of several.
NFPA 50A: Standard for Gaseous Hydrogen Systems at Consumer Sites, 1999 Edition	Covers the general principles recommended for the installation of gaseous hydrogen systems on consumer premises where the hydrogen supply to the consumer premises originates outside the consumer premises and is delivered by mobile equipment.
NFPA 50B: Standard for Liquefied Hydrogen Systems at Consumer Sites, 1999 Edition	Covers the general principles recommended for the installation of liquefied hydrogen systems on consumer premises where the liquid hydrogen supply to the consumer premises originates outside the consumer premises and is delivered by mobile equipment.
AS 2508.2.002-1992 Safe Storage and Handling Information Card - Hydrogen (compressed)	Sets out essential information on hazards and safe handling practice for personnel employed in stores and warehouses in which this material is stored. Summarizes emergency procedures for dealing with leaks, spills and fires. Includes first aid instructions as well as relevant dangerous goods labels, Hazchem and NFPA codes and UN number of substances.
NFPA 55 Standard for the Storage, Use and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, cylinders, Equipment and Tanks	Applies to the installation, storage, use and handling of compressed gases and cryogenic fluids in portable and stationary containers, cylinders, equipment and tanks.
SAE J2574 - Terminology	Automotive fuel cell terminology
SAE J2578 - General Fuel Cell Vehicle Safety	Provides criteria for integration of fuel cell systems into the vehicle.
SAE J2579 - Fuel Systems for Fuel Cell Vehicles	Provide criteria for systems containing or processing fuel or other hazardous materials. Including: Fuel Storage, Fuel Processing, Fuel Cell Stacks and other systems handling hazardous fluids
SAE J 2600 Compressed Hydrogen Vehicle Fueling Connection Devices	This document applies to the design, safety and operation of nozzles and receptacles, having operating pressures of 250, 350, 500 or 700 bars, for hydrogen fuelled vehicles.
SAE J 2601 Compressed Hydrogen Vehicle Fueling Communication Devices	Vehicle/refueling station wireless communication targeted for safety enhancement and achievement of a 100% fast fill (<3min).
SAE J2594, Fuel Cell Recyclability Guidelines	This SAE Recommended Practice identifies and defines the preferred technical guidelines relating to the safe integration of fuel cell system, fuel storage, and electrical systems into the overall Fuel Cell Vehicle. Purpose The purpose of this document is to provide introductory mechanical and electrical system safety guidelines that should be considered when designing fuel cell vehicles for use on public roads. Field of Application This document covers fuel cell vehicles designed for use on public roads.
SAE J2615, Testing Performance of Fuel Cell Power Systems for Automotive Applications	Provides a framework for performance testing of fuel cell systems (FCS¿s) designed for automotive applications with direct current (DC) output. The procedures described allow for measurement of performance relative to claims by manufacturers
ISO - Technical committee No. 197 – Hydrogen Technologies	Standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen. This includes numerous working groups covering most aspects of hydrogen handling and storage. See CSA or specific ISO publications.
ISO 13984:1999	Liquid hydrogen -- Land vehicle fuelling system interface
ISO/TR 15916:2004	Basic considerations for the safety of hydrogen systems
ISO/PAS 15594:2004	Airport hydrogen fuelling facility operations
ISO 14687:1999	Hydrogen fuel -- Product specification

For more complete descriptions, see: http://fuelcellstandards.com/
http://www.hydrogensafety.info/latest/3.html

Appendix B: Fuel Cell and Hydrogen Technology Developers

Fuel Cell Developers

Virtually all the US developers of fuel cells, and many developers of related technologies storage systems, hydrogen generators, etc., are members of the US Fuel Cell Council. Links to these companies can be found at http://www.usfcc.com/usfcc/members.html.

Fuel Cell Lift Truck Solutions Providers
Several companies are focusing specifically on developing fuel cell power systems for industrial trucks. In North America, these companies are:

Cellex Power Products, Inc.
David Pfeil
(604) 248-3557
13155 Delf Place
Richmond, BC
V6V 2A2
CANADA
http://www.cellexpower.com/

East Penn Manufacturing Co., Inc.
Evan Wescoe, Sr. Vice President, Sales and Marketing
Lyon Station, PA 19536
(610) 682-6361
http://www.dekabatteries.com/

General Hydrogen Corporation
Business Development Office
411 West Main Street
Gallatin, Tennessee 37066
(877) 238-9450
http://www.generalhydrogen.com

Hydrogenics, Inc.
985 McLaughlin Road
Mississauga, Ontario
Canada L5R 1B8
(905) 361-3660

http://www.hydrogenics.com/default.asp

Nuvera Fuel Cells
Gus Block, Director, Business Development
20 Acorn Park Drive
Cambridge, MA 02140
(617) 245-7553
www.nuvera.com

Delivered Merchant Hydrogen

Air Products Inc.
7201 Hamilton Boulevard
Allentown, PA 18195-1501
(800) 654-4567
http://www.airproducts.com/Products/LiquidBulkGases/HydrogenEnergyFuelCells/default.htm

---

Air Liquide
US Regional Office locations can be found at:
http://www.airliquide.com/en/corporate/about/overview/presence.asp?subcid=US&buid=3

BOC
Kristina Schurr
575 Mountain Avenue
Murray Hill, NJ 07974
(908) 771-1510
kristina.schurr@boc.com
http://www.boc.com/markets/hydrogen_energy/

Linde Gas
Mr. Jaco Reijerkerk
+49 89 7446 2362
http://www.linde-gas.com/international/web/lg/com/likelgcomn.nsf/docbyalias/nav_hydrogen

---

Praxair, Inc.
39 Old Ridgebury Road
Danbury, CT 06810
(800) - PRAXAIR
http://www.praxair.com/praxair.nsf/1928438066cae92d85256a63004b880d/c0f710821a5313a885256563007abf01?OpenDocument

On-Site Generation using Natural Gas Reformation

H_2Gen Innovations
Sandy Thomas
4740 Eisenhower Ave
Alexandria, VA 22304-4806
http://www.h2gen.com/

HyRadix Inc.
Dave Cepla
175 West Oakton Street
Des Plaines, IL USA 60018-1834
Phone: 1-847-391-1200
http://www.hyradix.com/

Nuvera Fuel Cells
Charlie Myers
20 Acorn Park Drive
Cambridge, MA 02140 USA
Phone: (617) 245-7616
www.nuvera.com

Water Electrolysis

Stuart Energy
Robert Cambell
5101 Orbitor Drive, Mississauga
Ontario, Canada L4W 4V1
tel: +1 905.282.7700
http://www.stuartenergy.com/

Hydrogenics, Inc.
Ayman Monged
985 McLaughlin Road
Mississauga, Ontario
Canada L5R 1B8
Phone: 905.361.3660
http://www.hydrogenics.com/default.asp

Proton Energy Systems
Everett Anderson
(203) 678-2000 x229
10 Technology Drive
Wallingford, CT 06492
http://www.protonenergy.com/

Teledyne Energy Systems, Inc.
10707 Gilroy Road
Hunt Valley, Maryland 21031-1311 U.S.A.
Phone: 410.771.8600
http://www.teledyneenergysystems.com/

Appendix C: Bibliography and References

Hydrogen and Fuel Cell General Information

Websites:
http://www.rebresearch.com/H2links.html
http://www.fueleconomy.gov/feg/fcv_PEM.shtml
http://www.hydrogen.org/index-e.html
http://www.fuelcells.org/
http://www.eere.energy.gov/hydrogenandfuelcells/
http://www.dodfuelcell.com/fcdescriptions.html
http://www.hyweb.de/index-e.html
http://www.sae.org/fuelcells/fuelcells.htm

Books and Articles:
http://www.fuelcell-info.com/public/341.cfm. Links to hydrogen and fuel cell books on Amazon.com.

L. Blomen and M. Mugerwa, *Fuel Cell Systems*, Plenum, 1993.

A. Heintzman and E. Solomon, eds., *Fueling the Future: How the Battle Over Energy is Changing Everything,* Anansi, 2003.

G. Hoogers, ed., *Fuel Cell Technology Handbook*, CRC Press, 2003.

K. Kordesch and G. Simader, *Fuel Cells and Their Applications*, VCH, 1996.

J. Larminie and A. Dicks, *Fuel Cell Systems Explained*, Wiley, 2003.

National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs,* information from The National Academies Press, http://books.nap.edu/catalog/10922.html.

Adam Piore, Hydrogen Economy, *Newsweek*, April 8, 2002, http://www.keepmedia.com/pubs/Newsweek/2002/04/08/310106/?extID=10047&data=hydrogen_fuel

Metal Hydrides

Websites:

www.FuelCellStore.com	Hydrogen Storage page.
www.Sciencedirect.com	Renewable and Sustainable Energy Reviews; Li Zhou, "Progress and Problems in Hydrogen Storage Methods."

FuelCell-magazine.com — Fuel Cell 2004 presentation 6/10/04: Michael A Zelinsky, “A Solid Approach to Hydrogen Storage.”

www.txohydrogen.com — Rosa Young, “Solid Hydrogen Storage/Overview.”

Liquid Hydrogen

Websites:

http://www.euweb.de/fuel-cell-bus/storage.htm
http://www.hydrogen.co.uk/what's_new/liquidh2_studygroup.htm

Articles:

K. Pehr, Aspects of Safety and Acceptance of LH_2 Tank Systems in Passenger Cars, *International Journal of Hydrogen,* Vol. 21, No. 5, pp 387-395, 1996.

S. Hynek (Arthur D. Little, Inc.), Robert Moore (Air Products and Chemicals, Inc.), *Liquid Hydrogen: Infrastructure and Vehicular Storage,* White Paper (available through Nuvera Fuel Cells).