GUIDELINES FOR USE OF HYDROGEN FUEL IN COMMERCIAL VEHICLES

Final Report

U.S. Department of Transportation
Federal Motor Carrier Safety Administration

November 2007

FOREWORD

This document is intended to be a safety reference for commercial vehicle fleet owners and operators that use vehicles or auxiliary power units powered by hydrogen. It was designed to provide commercial vehicle owners and operators with a basic understanding of the properties and characteristics of hydrogen, descriptions of the types of systems that might use hydrogen fuel on commercial vehicles, and practical guidelines for the safe use of hydrogen, both on vehicles and in vehicle maintenance and storage facilities.

Hydrogen properties and characteristics are significantly different from those of other commercial motor fuels, such as gasoline and diesel fuel, and commercial vehicle systems that use hydrogen fuel can also be significantly different from typical gasoline or diesel engines. An understanding of these differences is important to understanding what the operator of a vehicle powered by hydrogen should and should not do in order to maintain safety during transportation.

NOTICE

Technical Report Documentation Page (Form 1700.7)

1. Report No. **FMCSA-RRT-07-020**	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: **Guidelines for Use of Hydrogen Fuel in Commercial Vehicles**		5. Report Date: **November 2007** 6. Performing Organization Code
7. Author(s): **John M. Simon, CSP, Booz Allen Hamilton Inc.** **Stephen Brady, Booz Allen Hamilton Inc.** **Dana Lowell, M. J. Bradley & Associates** **Michael Quant, Booz Allen Hamilton Inc.**		8. Performing Organization Report No.
9. Performing Organization Name and Address: **Booz Allen Hamilton Inc.** **444 S. Flower Street, Suite 1850** **Los Angeles, California 90071**		10. Work Unit No. (TRAIS) 11. Contract or Grant No. **GS-23F-0025K**
12. Sponsoring Agency Name and Address: **U.S. Department of Transportation** **Federal Motor Carrier Safety Administration** **Technology Division (MC-RRT)** **1200 New Jersey Ave. SE** **Washington, DC 20590**		13. Type of Report and Period Covered **Final Report** 14. Sponsoring Agency Code **FMCSA**
15. Supplementary Notes:		

16. Abstract:

Over the next 50 years, hydrogen use is expected to grow dramatically as an automotive and electrical power source fuel. As hydrogen becomes commercially viable, the safety concerns associated with hydrogen systems, equipment, and operation are of concern to the commercial motor vehicle industry. This report is intended to provide guidelines for use of hydrogen fuel as an alternative fuel by a commercial vehicle fleet operator to ensure long-term safe operation.

17. Key Words: **alternative fuel, APU, auxiliary power units, buses, commercial vehicles, compressed fuel cell, guidelines, hydrogen, hydrogen gas, hydrogen injection system, hydrogen internal combustion engine, hydrogen safety, liquefied hydrogen, motorcoaches, trucks**		18. Distribution Statement **No restrictions.**	
19. Security Classif. (of this report) **Unclassified**	20. Security Classif. (of this page) **Unclassified**	21. No. of Pages: **94**	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	Inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	Feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	Yards	0.914	meters	m	m	meters	1.09	Yards	yd
mi	Miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					AREA		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	square meters	1.195	square yards	yd^2
ac	Acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.386	square miles	mi^2
		VOLUME					VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	Gallons	3.785	liters	l	l	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	cubic meters	35.71	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	cubic meters	1.307	cubic yards	yd^3
		MASS					MASS		
oz	Ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	Pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lbs)	0.907	megagrams	Mg	Mg	megagrams	1.103	short tons (2000 lbs)	T
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit Temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8 C + 32	Fahrenheit temperature	°F
		ILLUMINATION					ILLUMINATION		
fc	foot-candles	10.76	lux	lx	lx	Lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m2	cd/m2	cd/m2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

*** SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.**

ACKNOWLEDGEMENTS

This document was prepared by Booz Allen Hamilton Inc. and M.J. Bradley & Associates, Inc., under contract GS-23F-0025K with the Federal Motor Carrier Safety Administration (FMCSA), a subdivision of the U.S. Department of Transportation (DOT). The FMCSA project manager for this project was Mr. Quon Kwan, the Booz Allen Hamilton project manager was Mr. John Simon, and the principal author of this document was Mr. Dana Lowell of M.J. Bradley & Associates.

The authors are grateful to Mr. Paul Scott, ISE Corporation; Mr. Chris Morgan and Mr. Michael Chafee, California Highway Patrol; and Mr. Craig Michels, Alameda-Contra Costa Transit District for providing extensive peer review comments.

The authors would like to thank Mr. William Chernicoff of the DOT Research and Innovative Technology Administration for lending his expertise to help guide the project, and Mr. Bill Parsley of Quest Consulting Group for his help with technical editing. The authors would also like to thank the following organizations and individuals for hosting project team members and providing background information and valuable insights: the U.S. Environmental Protection Agency, Mr. Dennis Johnson; The California Fuel Cell Partnership, Mr. Adam Gromis, Ms. Jennifer Hamilton, Mr. Matthew Forrest, and Ms. Andrea Labue; the California Highway Patrol, Mr. Chris Morgan and Mr. Mike Chafee; the Santa Clara Valley Transportation Authority, Mr. Arthur Douwes; the Alameda Contra-Costa Transit District, Mr. Jaime Levin, Mr. Bob Bithell, Ms. Mallory Nestor-Brush, and Mr. Doug Byrne; ISE Corporation, Dr. Paul Scott, Mr. Jayson Cannon; UTC Power, Mr. Matthew Riley; Sunline Transit Agency, Mr. Tommy Edwards, Mr. Frank Shardy and Mr. Polo Del Toro; Daimler Chrysler Research & Technology North America, Mr. Joe Impullitti; and United Parcel Service, Mr. Jim Breeher and Mr. Adam Spitz, and Delphi, Mr. Steve Shafer.

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ACRONYMS

APU	Auxiliary power unit: For commercial trucks, APUs are small engines used to provide power for auxiliary loads, such as heating, air conditioning, and lighting in sleeper berths. In most trucks without an APU, this power for auxiliary loads is provided by the main engine. The use of an APU allows the operator to shut off the main engine while resting.
CNG	Compressed natural gas
CO	Chemical symbol for carbon monoxide
CO2	Chemical symbol for carbon dioxide
H2	Chemical symbol for molecular hydrogen
ICE	Internal combustion engine: A heat engine in which burning (combustion) of fuel takes place in a confined space called a combustion chamber. Diesel and gasoline engines are both internal combustion engines.
IR	Infrared: The part of the electromagnetic radiation spectrum in which the wavelength of the radiation is longer than that of visible light but shorter than that of radio waves. Infrared radiation has wavelengths between 750 nanometers and one millimeter.
KW	Kilowatt: A unit of measure for power, equal to 1,000 watts. One kilowatt is equal to 1.34 horsepower.
PEM	Proton Exchange Membrane: A semi-permeable membrane made of a plastic-like material, designed to allow hydrogen ions (protons) to pass through, but to be impermeable to gases like hydrogen and oxygen. In a proton exchange membrane fuel cell, the membrane acts as the electrolyte, separating the fuel and oxygen, but passing protons from the anode to the cathode.
PRD/TRD	Pressure relief device/thermal relief device: A device used to protect from overpressure inside a high-pressure storage tank. When the pressure inside the tank rises above a set threshold, a rupture disc inside the PRD breaks, allowing the tank to vent to reduce pressure inside. A TRD includes a material that melts at a set temperature. When the material melts, it opens the device, allowing the tank to vent. TRDs are used because exposure of a high-pressure tank to increased temperatures will increase pressure inside the vessel.
psi	Pounds per square inch: A unit of measure for pressure.
psia	Pounds per square inch absolute: Absolute pressure is measured relative to a perfect vacuum, so that the absolute measurement of atmospheric air pressure at sea level is 14.7 psia.
psig	Pounds per square inch gauge: Gauge pressure is measured relative to atmospheric air pressure at sea level, so that gauge measurements of atmospheric pressure at sea level are always 0 psig.

SOFC	Solid Oxide Fuel Cell: A type of high-temperature hydrogen fuel cell that uses a solid metal oxide electrolyte, which passes oxygen ions from the cathode to the anode. Solid oxide fuel cells do not need to be fueled with pure hydrogen gas because they support automatic reforming of gaseous hydrocarbon fuels such as methane within the device.
UV	Ultraviolet: The part of the electromagnetic radiation spectrum in which the wavelength of the radiation is shorter than that of visible light but longer than that of x-rays. Ultraviolet radiation has wavelengths between 10 and 380 nanometers.
VAC	Volts, alternating current: A volt is a measure of electric potential or electromotive force. Electrical current is the flow of electrons in one direction. With alternating current, the magnitude and direction of the current varies cyclically, usually as a sine wave. Electric generators produce alternating current.
VDC	Volts, direct current: A volt is a measure of electric potential or electromotive force. Electrical current is the flow of electrons in one direction. With direct current, the magnitude of the current may vary, but the direction of the current is constant. Batteries and fuel cells produce direct current.

EXECUTIVE SUMMARY

Today, virtually all commercial trucks are powered by diesel fuel, while private cars are fueled by gasoline. Supported by our National Energy Policy, a new generation of technologies is currently being developed that allow the use *of hydrogen* as a fuel to power cars and trucks. In the future, hydrogen may be used in one of three ways to power vehicles:

- To produce electricity in a fuel cell,
- As a replacement for gasoline or diesel fuel in an internal combustion engine,[1] or
- As a supplement to gasoline or diesel fuel used in an internal combustion engine.

This document is intended to be a safety reference for commercial vehicle fleet owners and operators that use vehicles or auxiliary power units powered by hydrogen fuel. It was designed to provide commercial vehicle owners and operators with a basic understanding of the properties and characteristics of hydrogen, descriptions of the types of systems that might use hydrogen fuel on commercial vehicles, and practical guidelines for the safe use of hydrogen, both on vehicles and in vehicle maintenance and storage facilities.

Hydrogen is the most abundant element in our universe. In addition to being a component of all living things, hydrogen and oxygen together make up water, which covers 70 percent of the earth. In its pure form, hydrogen is a gas at normal temperatures and pressures; it is the lightest gas (even lighter than helium), with only 7 percent of the density of air. If you get it cold enough (-423 °F), gaseous hydrogen will liquefy, and it can be transported and stored in this form.

There is virtually no “free” hydrogen on earth—all of it is combined with other elements (mostly oxygen or carbon) in other substances. Every molecule of water contains two hydrogen atoms and one oxygen atom. Hydrocarbon fuels such as coal, gasoline, diesel, and natural gas also contain hydrogen. In the case of gasoline and diesel fuel, there are approximately two hydrogen atoms for every carbon atom, while natural gas contains four hydrogen atoms for every carbon atom. To be used as a fuel, hydrogen is typically separated from either water (via electrolysis) or from a hydrocarbon fuel (via reforming).

Regardless of whether hydrogen fuel will be used in a fuel cell main engine, a fuel cell APU, or an internal combustion engine, there are different ways that it can be stored on the vehicle. Some fuel stations include liquid hydrogen storage, but on the vehicle, hydrogen is usually stored as a gas at high pressure. It is also possible to store a liquid fuel (gasoline, diesel, or methanol) onboard a vehicle and then use an onboard reformer to separate the hydrogen just before it is used in the fuel cell engine. While this requires additional equipment on the vehicle, it removes the need for high-pressure gas storage. These different storage technologies can introduce significantly different potential hazards, including very high pressure (gaseous hydrogen storage), very low temperature (liquid hydrogen storage), or high temperature (liquid fuel reforming).

1 *Natural gas can also be used to power an internal combustion engine, and hydrogen can be used to supplement this fuel as well. This document does not address natural gas engines.*

All motor fuels, including diesel fuel, gasoline, and natural gas also pose risks of fire and explosion if handled improperly. Hydrogen is no different. While there are risks, hydrogen can be as safe, or safer, than diesel and other fuels when vehicles and fuel stations are designed and operated properly. All fuels require particular design and handling practices based on their properties, and all present certain hazards when mishandled. Understanding the properties of hydrogen is necessary to understanding what is required to use it safely.

Hydrogen gas is colorless, odorless, tasteless, and noncorrosive—and it is nontoxic to humans. It has the second widest flammability range in air of any gas, but leaking hydrogen gas rises and diffuses to a nonflammable mixture quickly. Hydrogen ignites very easily and burns hot, but tends to burn out quickly. A hydrogen flame burns very cleanly, producing virtually no soot, which means that it is also virtually invisible. The extremely low temperature of liquid hydrogen poses a severe frostbite hazard to exposed skin.

In some ways, a gaseous hydrogen fuel leak is less dangerous than a leak of diesel fuel or gasoline. Leaking diesel fuel and gasoline can puddle and spread over a large area, and the puddles will persist because they evaporate slowly. Gaseous hydrogen leaks tend to be vertical, with only a relatively narrow area/volume in which a flammable mixture exists—the hydrogen quickly rises and dissipates in open air to nonhazardous levels.

If designed properly, the most likely location of a major hydrogen leak from a vehicle will be through the pressure relief device (PRD) on the hydrogen fuel storage cylinders, which should vent away from the occupied area of the vehicle. PRDs are designed to vent the entire contents of a hydrogen tank in only a few minutes—after which there is no lingering risk of hydrogen fire or explosion if the release was in the open air. Large hydrogen leaks inside buildings are more dangerous unless the facility has been designed to evacuate the leaked gas and to minimize ignition sources at ceiling level.

Leaking liquid hydrogen can pool and spread, but will quickly evaporate as it is heated by the surrounding air. The distance it will spread and the rate of evaporation will depend on the size of the leak and on ambient conditions. As it evaporates, the cloud of gaseous hydrogen formed over the spill may move horizontally as it rises and dissipates. This hydrogen cloud may be cold enough to cause frostbite to exposed skin and should be avoided.

While diesel fuel and gasoline leaks are easily visible and accompanied by a strong characteristic smell, gaseous hydrogen leaks are invisible and odorless. The only indication of a gaseous hydrogen leak may be a whistling noise similar to escape of other high-pressure gases. A liquid hydrogen leak may be accompanied by an area of fog surrounding the leaking hydrogen and/or the formation of frost on the tank or lines in the vicinity of the leak, because the super cold hydrogen cools the surrounding air and causes water vapor to condense.

Based on hydrogen’s chemical and physical properties, there are a number of general principles that govern safe design and use of hydrogen fuel. These are essentially the same principles that apply to the use of any gaseous fuel (e.g., natural gas), but their application may be slightly different based on the properties of hydrogen.

The most important safety principle in any situation is education—making anyone who will come into contact with a vehicle aware of a potential hazard. For hydrogen and other alternative-fueled vehicles, this is done with appropriate labeling to let users, emergency responders, and the public know that hydrogen is present.

As with other motor fuels, fire and explosions are the most significant everyday hazards associated with hydrogen. Also as with other fuels, a hydrogen leak from a vehicle's fuel or engine system, or from a fueling station, provides the starting point for all fire and explosion hazards. Safe design for using hydrogen, both for vehicles and for fuel stations and buildings, therefore, requires attention to these safety principles:

- Properly label all vehicles that use hydrogen fuel.
- Avoid fire and explosion by:
  - Avoiding leaks through proper design and maintenance,
  - Providing leak detection systems to detect leaks and, if a leak is detected, shut off the fuel system as soon as possible,
  - Removing ignition sources from areas where leaked hydrogen might be present, and
  - Properly ventilating all enclosed spaces where leaked hydrogen might accumulate.

These general principles translate into specific design and operating requirements for hydrogen-fueled vehicles, the facilities that will house or maintain them, and hydrogen fuel stations. In most aspects, commercial vehicles powered by hydrogen will be identical to those powered by diesel fuel, but some hydrogen-specific design elements are required. Likewise, operation of these vehicles will be similar to operation of diesel-fueled vehicles, with a few exceptions. Each vehicle manufacturer will develop their own designs, which are likely to vary significantly in the details, while adhering to the same general design principles noted above.

1. INTRODUCTION

1.1 BACKGROUND

Today, virtually all commercial trucks are powered by diesel fuel, while private cars are fueled by gasoline. While these petroleum-based fossil fuels have served society well for many years, their supply is limited, and their use creates pollution that contributes to poor air quality in many areas. Supported by our National Energy Policy, a new generation of technologies is currently being developed that allow the use *of hydrogen* as a fuel to power cars and trucks (see Table 1). In the future, hydrogen may be used in one of three ways to power vehicles:

- To produce electricity in a fuel cell,
- As a replacement for gasoline or diesel fuel in an internal combustion engine, or
- As a supplement to gasoline or diesel fuel used in an internal combustion engine.

Table 1. Why Hydrogen?

1	To reduce harmful pollution from vehicle exhaust
2	To reduce carbon dioxide (CO2) emissions, which contribute to global warming
3	To reduce our growing dependence on foreign oil

This document was developed by the Federal Motor Carrier Safety Administration as a reference for commercial vehicle fleet owners and operators who use hydrogen fuel in their vehicles, and it primarily focuses on safety. All motor fuels, including diesel fuel, gasoline, and natural gas pose risks of fire and explosion if handled improperly. Hydrogen is no different.

While there are risks, hydrogen can be as safe, or safer, than diesel and other fuels when vehicles and fuel stations are designed and operated properly.

While safe, hydrogen *is* different from other motor fuels, it has significantly different physical and chemical properties that affect how it must be safely stored and handled. Therefore, this document was designed to provide basic information about hydrogen properties and characteristics, as well as an overview of the vehicle systems than might use hydrogen fuel. It also provides basic guidelines for how vehicles, as well as fuel stations and maintenance facilities, should be designed and operated if hydrogen will be used. This information is provided so that fleet owners and operators will know what to look for—and what to do and not do—when using hydrogen fuel for their vehicles.

1.2 HYDROGEN USE AS A MOTOR FUEL

There are several ways that hydrogen can be used as a motor fuel. It can be used to directly replace gasoline or diesel fuel in specially designed internal combustion engines (ICEs), or it can be used to supplement these typical fuels in existing engines. In either of these cases, the vehicle drive system will be identical to those used on most gasoline-powered or diesel-powered vehicles. The engine will drive the vehicle's wheels through a transmission, drive shaft, and front or rear axle.

Hydrogen can also be used as the fuel source for a "fuel cell engine," in which case the vehicle's drive system will be very different. A fuel cell directly creates electricity, which can be used to power an electric motor to drive the vehicle's wheels. A fuel cell vehicle is, therefore, an electric vehicle, but one that creates its own electricity and does not need to be plugged in to recharge batteries. A small fuel cell can also be used to create electricity to directly power the auxiliary systems on a commercial truck (for example heating, air conditioning, and lighting in a sleeper berth), which are typically powered by the truck's main engine. Using such a fuel cell auxiliary power unit (APU) would allow the driver to shut off the truck's main diesel engine while resting, saving fuel and reducing pollution.

Regardless of whether the hydrogen will be used in a fuel cell main engine, a fuel cell APU, or an internal combustion engine, there are different ways that it can be stored on the vehicle. As described below, these different storage technologies can introduce significantly different potential hazards, including very high pressure (gaseous hydrogen storage), very low temperature (liquid hydrogen storage), or high temperature (liquid fuel reforming) (see Table 2).

Currently both fuel cells and hydrogen ICEs are in the early stages of commercialization. All of the major auto companies have fielded concept, prototype, or demonstration fuel cell sedans and sport utility vehicles in the last several years, with at least fifteen different models introduced since 2000 (Barnitt and Eudy, 2005; USFCC, 2006). Most of these vehicles have been operated by the companies themselves or have been fielded to government agencies and fleet customers as part of technology development or demonstration programs. The California Fuel Cell Partnership reports that its members have placed 134 light-duty fuel cell vehicles in service in California since 2000 (CAFCP, n.d.). In addition, there are currently nine fuel cell transit buses in service in the United States and Canada, and over 20 in Europe and Asia (Chandler and Eudy, 2006).

It is expected that commercial fuel cells will be introduced into government and transit bus fleets between 2010 and 2020, with sales to commercial vehicle fleets and the public sometime between 2020 and 2030 (DOE, 2002). It is also expected that the first use of hydrogen fuel in the commercial truck sector will be to power fuel cell APUs rather than to power fuel cell or hydrogen ICE main propulsion engines. At least one company has announced plans to introduce commercial fuel cell APUs as early as 2011 (Delphi, 2005).

Most current prototype fuel cell vehicles carry their hydrogen fuel as a compressed gas, and it is expected that this will continue to be the case for the earliest commercial vehicles. It may be desirable to store liquid hydrogen onboard a commercial vehicle because it has a higher energy density and would increase the range between fill-ups. However, onboard liquid hydrogen storage is more costly, and it is more likely that liquid hydrogen will be stored at fueling stations to supply gaseous hydrogen to vehicles. Other storage technologies, such as metal and chemical hydrides, are much further from commercial readiness (DOE, n.d.). Several fuel cell buses have been demonstrated that "reform," or extract hydrogen from, liquid methanol onboard (Georgetown University, 2003), and there are fuel cell APU systems under development that will derive their hydrogen from onboard reforming of diesel fuel or gasoline (Delphi, 2005). In addition, there are several commercial "hydrogen injection" systems available for retrofit on diesel engines (CHEC, n.d.). These systems produce small amounts of hydrogen by electrolysis of water carried on the vehicle, which is injected into the diesel engine along with the diesel fuel.

Table 2. Challenges of Using Hydrogen

1	Because hydrogen is normally gaseous, fueling requires very high-pressure compression and large, expensive, onboard vehicle storage systems.
2	A supply of hydrogen and a network of fuel stations must still be developed.

The remainder of this chapter provides a brief overview of the types of systems that might be found on a vehicle to store or use hydrogen fuel.

1.2.1 Hydrogen Fuel Cell Engines

Fuel cells are often compared to both internal combustion engines (ICEs) and batteries and, in fact, they share some characteristics with each. All three types of devices are used to transform one type of energy into another. A diesel engine turns chemical energy contained in diesel fuel into heat energy through combustion with oxygen from the air, and then turns that heat energy into mechanical energy, turning the vehicle's wheels through a transmission and drive shaft.

On the other hand, a battery is a galvanic cell; it uses reactions between chemicals stored inside to turn chemical energy directly into electricity, which can then be used to power a number of devices, including an electric motor to produce mechanical energy.

Like a diesel engine, a fuel cell requires fuel (hydrogen) and oxygen (air). However, like a battery, it is capable of directly producing electricity.

A fuel cell is also a galvanic cell; the hydrogen and oxygen do not combust inside the device. Instead, the hydrogen and oxygen react electrochemically and produce electricity. See Table 3 for a comparison of the major differences between fuel cells and ICEs and batteries.

Table 3. Comparison of Fuel Cells to ICEs and Batteries

	Internal Combustion Engine (ICE)	Battery
Fuel Cell Engine Similarities to:	• Both are supplied with air and a hydrogen-rich fuel. • Both have similar mechanical support systems (fuel system, air system, cooling system).	• Both are galvanic cells that directly generate electricity through electro-chemical reactions. • Both have an anode and a cathode in contact with an electrolyte. • With both, individual low-voltage DC cells are combined in series to attain higher voltage and power.
Fuel Cell Engine Differences from:	• In a fuel cell, hydrogen reacts with oxygen electrochemically not by combusting as in an ICE. • A fuel cell directly generates electricity not mechanical energy. • A fuel cell does not produce harmful tail pipe emissions or CO_2.	• A fuel cell does not need to be recharged like a battery; it is refueled by the H_2 and O_2. • In a fuel cell, the anode and cathode are gases (H_2 and O_2); while in a battery, they are metal.

As with a battery, the electricity produced by a fuel cell can be used to power any number of devices. In the case of a vehicle, it is most often used to power an electric motor to move the vehicle down the road. A fuel cell vehicle is, therefore, an electric vehicle, powered by an electric motor.

Fuel cells have been around for a long time and have been used in the United States space program since the 1960s (College of the Desert, 2001c). It has only been in the last few years, however, that they have been developed for use in conventional vehicles.

There are a number of different fuel cell technologies that employ different chemical reactions to combine hydrogen and oxygen to produce electricity. The most common technology used in vehicles is called a Proton Exchange Membrane (PEM) fuel cell. See Figure 1, which shows the layout and operation of a PEM fuel cell. Also see Appendix A for a more in-depth description of the construction of a PEM fuel cell and the chemical reactions that take place in the cell.

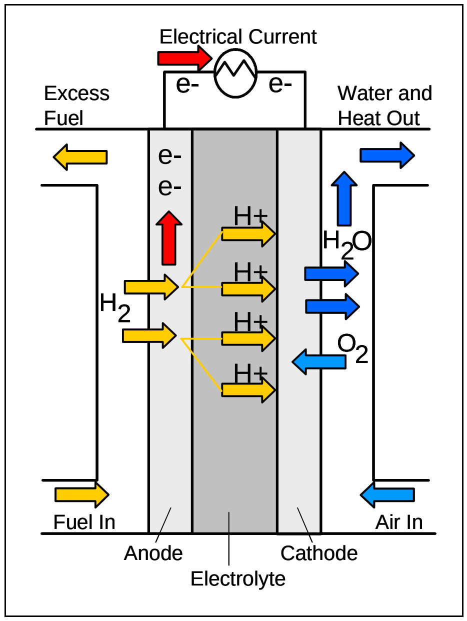

Figure 1. Operation of a Proton Exchange Membrane Fuel Cell

Source: DOE, 2006.

The maximum voltage that one PEM "cell" can produce is 1.2 VDC, but the actual voltage depends on how much current is being drawn from the cell. The cell can put out the greatest amount of power at between 0.5 and 0.6 volts, so that is where they are generally designed to operate. To create a device powerful enough to power a large vehicle, up to 1,200 cells are connected in series, to produce a peak power of 100 kW or more at between 300 and 600 VDC (nominal). Physically the individual PEM cells are usually stacked together, separated by a cooling plate between each set of cells. These cooling plates circulate a mixture of water and ethylene glycol to remove excess heat created during operation of the cells. These cooling plates are part of a cooling system that is similar in both design and function to the cooling systems used with diesel engines. A collection of individual fuel cells used to create a practical device is usually referred to as a fuel cell "stack" (see Figure 2).

Figure 2. PEM Fuel Cell Stack

Source: DOE, 2006.

The fuel cell stack must be supported by a number of auxiliary systems that together make up the "fuel cell engine." In addition to a cooling system, the fuel cell engine needs a fuel system, an air system, and a water management system. See Figure 3 for a generic schematic of a PEM fuel cell engine. In a PEM fuel cell, engine hydrogen and air are saturated with water and fed into the fuel cell stack. Inside each PEM cell, the hydrogen and air react with each other across a thin plastic-like film, called a proton exchange membrane, but they never mix. Electricity is produced by each cell, and water and a small amount of heat are the only by-products. Excess water not needed to humidify the gases is exhausted, with air, out the tailpipe.

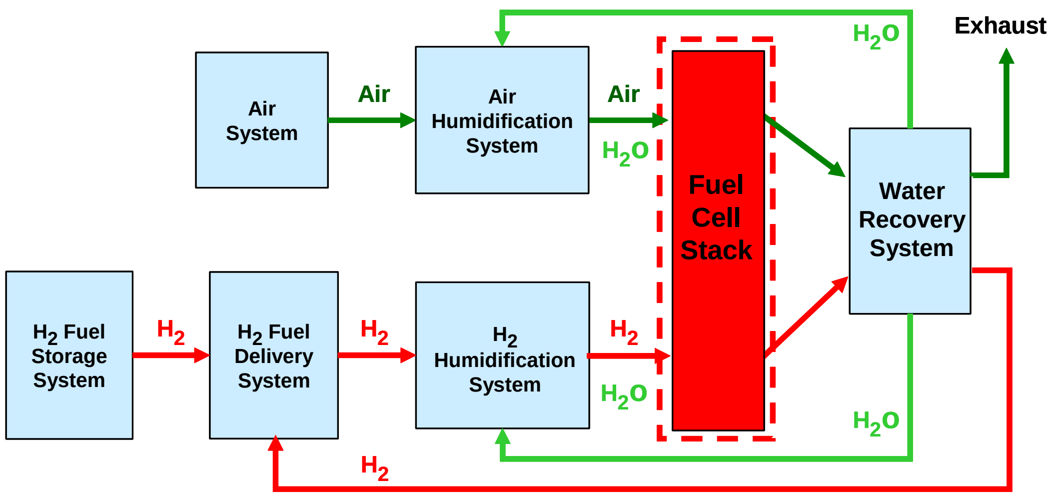

Figure 3. Generic PEM Fuel Cell Engine Schematic

PEM fuel cells generally operate at relatively low temperatures (140 to 180 °F) and pressures (from 0 to 15 psig). The exact layout and details of a fuel cell engine and its subsystems will depend on the specifics of the design and its specified operating parameters. Packaging and layout of the fuel cell engine in the vehicle can also vary significantly. See Figure 4 for a photo of a fuel cell engine and electric drive motor that was installed in a transit bus.

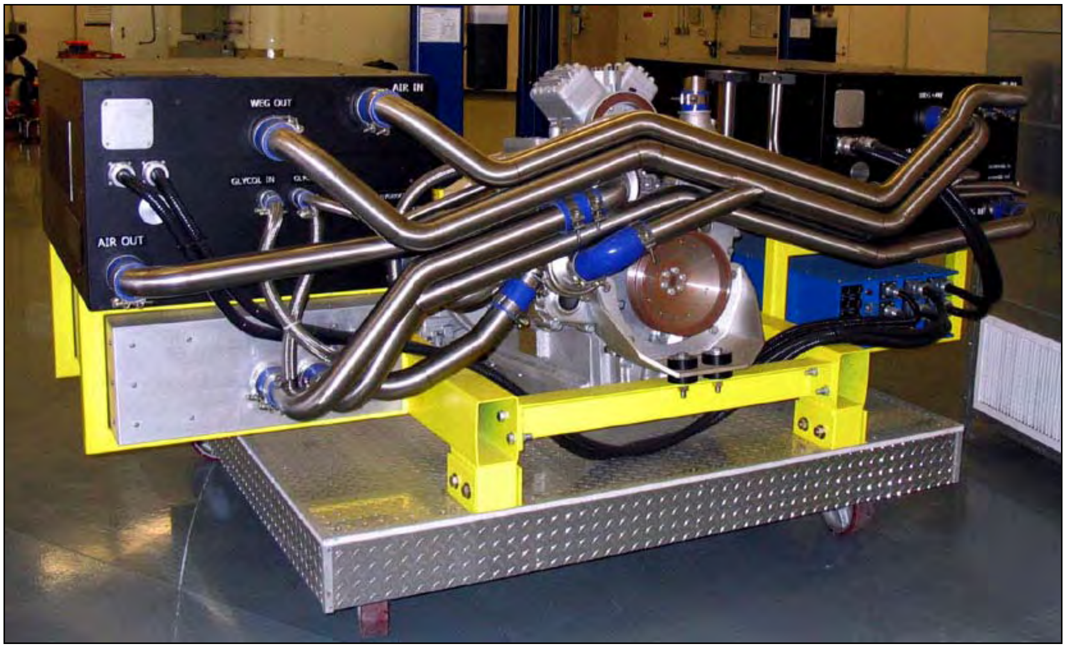

Figure 4. PEM Fuel Cell Engine and Electric Drive Motor for a Transit Bus
Photo courtesy of AC Transit.

PEM fuel cell engines fueled by hydrogen produce virtually none of the volatile organic hydrocarbon or nitrogen oxide tailpipe emissions that come from combustion of fuel in gasoline and diesel engines, and which together produce ground-level ozone, or “smog” in the atmosphere in the presence of sunlight. They also produce virtually none of the harmful particulate emissions produced by diesel engines and zero carbon dioxide emissions. Carbon dioxide is a major by-product of fuel combustion in diesel and gasoline engines. As a so-called “greenhouse gas,” carbon dioxide is a contributor to global warming.

In addition to reduced exhaust emissions, the potential benefits of using hydrogen fuel cells to power commercial vehicles include lower total energy use due to improved efficiency of the fuel cell compared to an internal combustion engine. The actual “wells-to-wheels” efficiency of a fuel cell vehicle will depend on how the system is designed, as well as how the hydrogen fuel is produced. Many fuel cell vehicles are designed with a hybrid propulsion system that incorporates a large battery to supplement the fuel cell. The battery provides power during acceleration, allowing the fuel cell to be smaller. It is also used to capture energy that is normally wasted in braking, which can later be re-used, increasing net efficiency, especially in stop-and-go city driving. See Figure 5 for a comparison of “wells-to-wheels” fuel use (liters per mile)[2] for vehicles with different types of power sources. This figure is illustrative only and does not include all potential combinations of fuel and propulsion technology.

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2 *One liter per mile is equivalent to 0.26 gal/mile.*

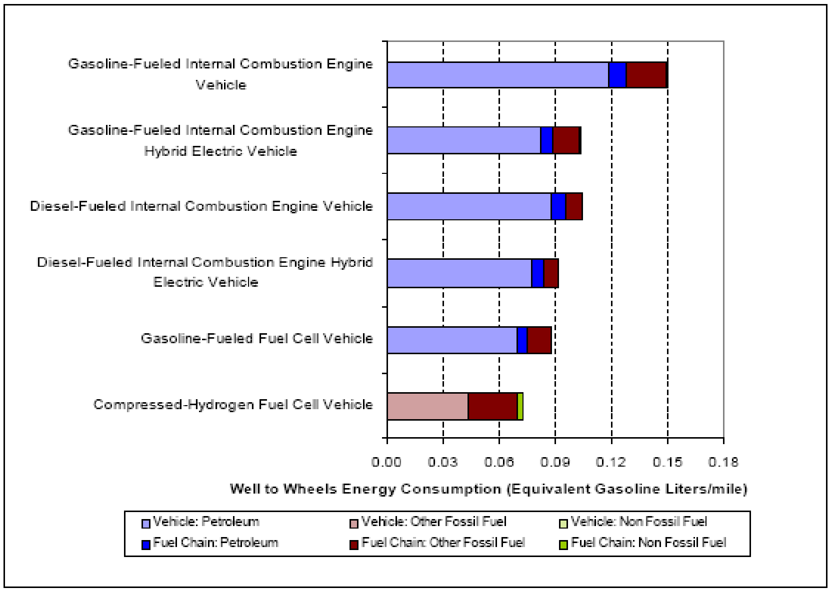

Figure 5. Wells-to-Wheels Fuel Use for Different Propulsion Systems

Source: ADL-DOE Fuel Choice for Fuel Cell Vehicles Study Results, February 2002.

Usually pure hydrogen is used to fuel a PEM fuel cell engine. While a mixture of hydrogen and carbon dioxide can be used, other "contaminants" must be kept to a minimum in the fuel supplied to the cells, especially carbon monoxide (CO) and sulfur. Both CO and sulfur can reduce the activity of the platinum catalysts used in the PEM cells, reducing the amount of power that the cells can produce (EG&G, 2004).

1.2.1.1 Solid Oxide Fuel Cell APUs

Like PEM fuel cells, solid oxide fuel cells (SOFCs) are galvanic cells that directly produce electricity from hydrogen and oxygen through an electrochemical reaction. However, SOFCs are constructed of different materials and use a different chemical reaction from PEM fuel cells.

SOFCs operate at much higher temperatures than PEM fuel cells – between 1,100 °F and 1,800 °F. When combined with a small fuel reformer they can also use diesel fuel or gasoline vapors as fuel, eliminating the need to carry hydrogen gas onboard.

In an SOFC, the electrolyte is not a plastic-like material as it is in a PEM cell; it is a ceramic material made of a solid metal oxide, usually zirconia oxide. This electrolyte does not need to be coated with an expensive platinum catalyst as in a PEM cell. As with a PEM fuel cell, the major by-products of the reactions inside the cell are electricity, water, and heat. See Figure 6. Also see Appendix A for a more detailed description of the construction of SOFCs and the chemical reactions that take place inside the cells.

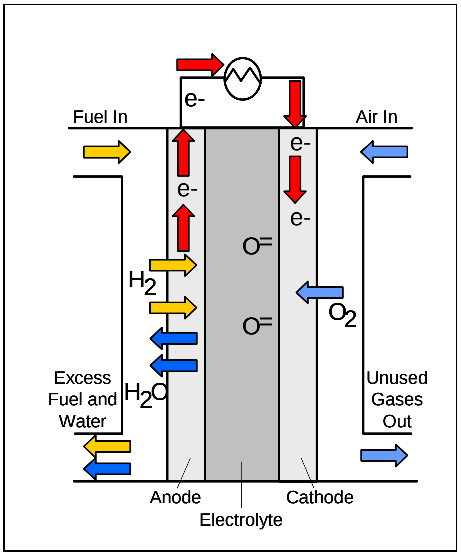

Figure 6. Operation of an SOFC Fuel Cell

Source: DOE, 2006.

Unlike a PEM cell, an SOFC does not need to be fueled with pure hydrogen gas. Because SOFCs operate at such high temperature and because oxygen ions are transferred through a solid oxide electrolyte material—not hydrogen ions—SOFCs support automatic "reforming" of gaseous hydrocarbon fuels like methane (natural gas) within the device. Reforming is the chemical process of separating the hydrogen from the carbon atoms in a hydrocarbon fuel (see Section 1.4). Diesel fuel and gasoline vapors can not be internally reformed by an SOFC, but can be used to fuel an SOFC if it is combined with a relatively simple fuel reformer/processor.

When using diesel fuel, the "reformate" produced by the fuel processor and introduced as the fuel at the anode of the SOFC will include hydrogen, nitrogen, carbon monoxide, and CO_2. The exhaust from the SOFC will also include CO_2 and nitrogen, as well as water and waste heat.

SOFCs operate at much higher temperatures than PEM fuel cells—between 1,100 °F and 1,800 °F—so the waste heat created during operation is also at a higher temperature and can, therefore, more easily be put to use, for example, to heat the interior of a vehicle as is typical of the waste heat from an ICE.

There are at least fifteen companies that have demonstrated prototype or commercial SOFC systems (HARC, 2004). Most of these systems are small, producing from 200 watts to 25 kilowatts of power. Several manufacturers are developing low-power systems specifically for use as an auxiliary power unit (APU) on commercial trucks (DELPHI, 2005)

Truck APUs are used to provide electrical power and sometimes heat to power truck accessories such as cabin lighting, air conditioning, and heating. Most often used with sleeper berth-equipped, truck-tractors they allow these loads, which are normally supplied by the truck's main engine, to be supplied even when the main engine is off.

Without an APU, many long-haul truckers end up idling their main engines for eight hours a day or more while resting in the sleeper-berth. This practice is wasteful and results in unnecessary harmful exhaust emissions. Testing by the U.S. Environmental Protection Agency has shown that a commercial truck's main engine typically consumes about one gallon of fuel per hour while idling, while a properly sized ICE APU will burn only about one fifth as much (EPA, 2002). The use of an APU instead of main engine idling can therefore save a truck operator money and reduce pollution at the same time.

In comparison to an ICE APU, an SOFC APU could be more efficient, smaller and lighter, quieter, and produce fewer exhaust emissions (DELPHI, 2005). Because an SOFC with a fuel processor can be fueled directly with diesel fuel, there would be no need to carry compressed hydrogen on the vehicle (see Section 1.4).

1.2.2 Hydrogen Internal Combustion Engines

Theoretically any typical spark-ignited engine, like the gasoline engines used in most cars, can operate on a range of liquid or gaseous fuels, including hydrogen. However, due to differences in the chemical properties of the various fuels, the designs of engines optimized for each are quite different.

Because of the wide flammability range of hydrogen, an internal combustion engine (ICE) operating on hydrogen can operate with a much leaner air/fuel mixture than a typical gasoline engine, which improves efficiency. A hydrogen ICE developed by Ford Motor Company can operate with an air fuel ratio as high as 86:1, compared to 14.7:1 for typical gasoline engines (see Figure 7). This results in about a 25 percent improvement in efficiency (NEW-CARS, 2003).

Because hydrogen is a light gas, it displaces more volume in the combustion chamber than gasoline vapors, and super-charging is generally required to get equivalent power output as the same sized gasoline engine. Other design changes compared to typical gasoline engines may be required to reduce the possibility of pre-ignition, or knock, because of hydrogen's low ignition energy. These may include the use of a disk-shaped combustion chamber to reduce turbulence in the cylinder, the use of more than one spark-plug, and the use of multiple exhaust valves (College of the Desert, 2001b).

Figure 7. Ford V10 Hydrogen Engine

Photo courtesy of Ford Motor Company.

Besides the potential for better fuel economy because of improved efficiency, hydrogen ICEs offer other advantages over gasoline and diesel engines, including reduced exhaust emissions. Because there is no carbon in the fuel, a vehicle powered by a hydrogen ICE would have zero emissions of the greenhouse gas CO_2. Tailpipe emissions of nitrogen oxides and volatile organic hydrocarbons would also be lower.

Typically the hydrogen fuel for a hydrogen ICE is carried on the vehicle as a high-pressure compressed gas (see Section 1.3 for a description of hydrogen storage systems).

In addition to Ford, at least two other companies have developed hydrogen ICEs for cars, either as prototypes or commercial products (CHHN, 2004). There are also fourteen buses currently operating in Berlin, Germany, and one in Thousand Palms, California, which are powered by heavy-duty hydrogen ICEs (Chandler and Eudy, 2006).

1.2.3 Hydrogen Injection Systems

A hydrogen injection system for a diesel engine produces small amounts of hydrogen and oxygen on demand by electrolyzing water carried onboard the vehicle. The electricity required is supplied by the engine's alternator or 12/24-volt electrical system (see Section 1.5 for a description of electrolysis). The hydrogen and oxygen are injected into the engine's air intake manifold, where they mix with the intake air. In theory, the combustion properties of the hydrogen result in more complete combustion of diesel fuel in the engine, reducing tailpipe emissions and improving fuel economy (CHEC, n.d.). Limited laboratory testing of a hydrogen injection system installed on an older diesel truck engine operated at a series of constant speeds showed a 4 percent reduction in fuel use and a 7 percent reduction in particulate emissions with the system on (ETVC, 2005).

A hydrogen injection system for a diesel engine produces and uses significantly less hydrogen than a hydrogen fuel cell or hydrogen ICE, and does not require that compressed or liquid hydrogen be carried on the vehicle. The system is designed to produce hydrogen only when required, in response to driver throttle commands. When the system is shut-off, no hydrogen is present on the vehicle.

1.3 HYDROGEN STORAGE ON VEHICLES

A sufficient amount of hydrogen to provide satisfactory driving range must be stored onboard a hydrogen-powered vehicle. This is a significant challenge because, at normal temperature and pressure, a given volume of hydrogen is very light and contains very little energy. Hydrogen vehicle fuel storage systems on commercial vehicles are larger, heavier, and more expensive than diesel vehicle fuel storage systems. Given the limitations of onboard hydrogen storage, hydrogen-powered commercial vehicles may not provide comparable operating range to typical diesel-powered commercial vehicles.

There are five ways that the hydrogen can be stored on the vehicle:

- As a high-pressure gas,
- As a very low temperature liquid,
- Chemically bound or physically absorbed onto a material such as a solid “hydride,” As a component of a liquid hydrocarbon fuel (which is reformed), or
- As a component of water (H20) (which is hydrolyzed).

Currently the most common method of onboard hydrogen storage for vehicles powered by fuel cells and hydrogen ICEs is as a compressed gas. This is likely to continue to be true for the foreseeable future.

1.3.1 Compressed Hydrogen Storage

When stored as a gas, hydrogen can be fed directly into a fuel cell or ICE without further processing. However, like all gases hydrogen is difficult to compress. In order to get enough fuel onto a vehicle to be able to go several hundred miles between fill-ups, but without taking up too much space, the hydrogen must be stored at very high pressure. Most current vehicle systems store hydrogen at a pressure of 5,000 pounds per square inch (psi). In the future, hydrogen storage pressures may be as high as 10,000 psi (DOE, n.d.).

Even at these pressures, a gaseous hydrogen storage system will be much larger and heavier than the diesel fuel tanks on current trucks. Hydrogen with the same amount of energy as 100 gallons of diesel fuel, if stored at 5,000 psi, would take up over twelve times as much space—over 170 cubic feet. Because high-pressure storage tanks must be very strong to contain the pressure, the total weight of such a system when full would be over 2,500 pounds—almost four times more than the weight of a full 100 gallon diesel tank (College of the Desert, 2001a).

In a diesel tank, the weight of the fuel would be over 90 percent of the total, while in a gaseous hydrogen storage system, the opposite is true—the weight of the hydrogen fuel would only be 10 percent of the total, with the remaining 90 percent the weight of the tank.

High-pressure storage cylinders can be made of metal (steel or aluminum) or they can be made with a thin metal or plastic liner that holds the gas, covered with a composite overwrap that provides most of the strength. The designs for these cylinders are subjected to rigorous qualification tests to ensure that they can withstand the forces that they might be subjected to in service on a vehicle, including in a crash.

Hydrogen storage systems for commercial vehicles will likely be composed of multiple storage cylinders connected to a common manifold. See Figure 8, which shows an automotive hydrogen fuel storage system that includes two high-pressure storage cylinders. Systems composed of more than one storage cylinder will normally include a manual isolation valve for each cylinder that can be used during servicing, as well as one or more electrically activated valves that can be used to automatically isolate the fuel supply in the case of a leak or other system problem.

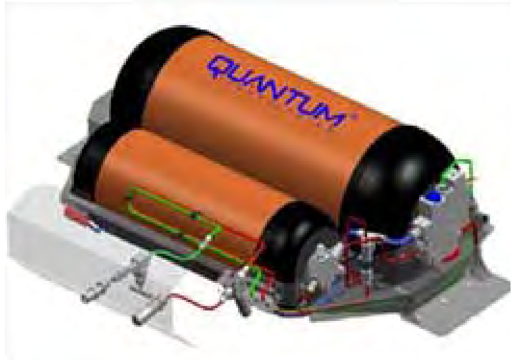

Figure 8. Gaseous Hydrogen Storage System

Source: DOE.

All high-pressure hydrogen storage cylinders must also be equipped with a pressure relief device (PRD) and/or a thermal relief device (TRD) to protect against cylinder rupture if the pressure inside the cylinder gets too high. A PRD includes a metal disk designed to rupture at a set pressure, releasing the gas inside the cylinder (Air Products, 2004). The most likely reason for overpressure in a hydrogen fuel cylinder is a vehicle fire. If engulfed in flames, the pressure inside the tank will rise as the temperature rises. TRDs are, therefore, made with a plug of fusible metal that begins to melt and deform at a set temperature (Air Products, 2004). As the plug deforms, it can no longer hold the pressure inside the cylinder and gas escapes. Some devices combine both a rupture disk and a fusible plug. PRDs and TRDs are not pressure relief valves (see Section 1.3.2). Once the disc ruptures or the fusible plug melts, all of the gas in the cylinder escapes, and they cannot be reset; they must be replaced.

Typically, the outlets from all PRD/TRDs are run into a common manifold that exits the vehicle at or near the roof line to ensure that any escaping gas is directed upward away from vehicle occupants or pedestrians.

Fueling with compressed hydrogen is similar to fueling with other high-pressure gases, such as compressed natural gas (CNG). The on-vehicle fueling ports and fueling nozzles used are very similar to those used with CNG, though they are designed to operate at higher pressures.[3]

1.3.2 Liquid Hydrogen Storage

Very few fuel cell or hydrogen ICE vehicles have been deployed with onboard liquid hydrogen storage. Liquid hydrogen storage systems are smaller and lighter than comparable compressed hydrogen storage systems, but are more complex and expensive and have other disadvantages. Bulk liquid hydrogen storage systems are more commonly used at centralized vehicle fueling stations.

The boiling point of hydrogen at atmospheric pressure is –423 °F; above that temperature hydrogen exists as a gas, and it will only liquefy if the temperature drops below the boiling point. Compressors and heat exchangers can be used to lower the temperature of hydrogen gas to produce liquid hydrogen, which must then be kept at this very low temperature or it will "boil

3 *The maximum pressure for fuel systems on typical heavy-duty CNG vehicles is 3,600 psi.*

off" again as a gas. To maintain its temperature, liquid hydrogen is stored in specialized, heavily insulated, containers called "dewars," "cryotanks," or "cryogenic vessels."

A typical cryogenic container is made of metal and is double-walled. The inner tank is wrapped in multiple insulating layers and is enclosed by the second outer metal tank. Air is removed from the space between tank walls to create a vacuum. This design minimizes heat transfer by radiation, convection. or conduction.

Even the best cryotanks allow some heat through the tank walls. As the liquid hydrogen inside absorbs the heat, some of it evaporates, raising the tank pressure. Cryotanks are generally designed to operate near atmospheric pressure and are not designed to hold high pressures. Therefore, as tank pressure rises, some gaseous hydrogen must be vented to relieve the pressure.

All cryotanks are equipped with pressure relief safety valves for gas venting. In a pressure relief valve, a spring holds a plunger against the valve opening with a specific amount of pressure. When the pressure inside the tank rises above the spring pressure, the plunger moves back against the spring and the valve opens, releasing some gas. As gas vents, the pressure inside the tank falls. When the pressure falls enough, the spring pushes the plunger back against the valve opening, closing the valve. Pressure relief valves are different from PRD/TRDs (see Section 1.3.1) because they are designed to open and close numerous times during their life, and to vent only part of the tank contents each time they open.

The amount of venting from an on-vehicle liquid hydrogen storage system will depend on the design of the system, the ambient temperature, and how often the vehicle is used. Many of the cryogenic tanks currently in use for bulk storage and delivery can store liquid hydrogen for a week or more without any venting loss (Linde, n.d.). Nonetheless, vehicle storage facilities and maintenance operating plans need to account for the possibility of hydrogen venting, particularly from vehicles parked indoors for long term.

See Figure 9 for an illustration of a liquid hydrogen fuel system for a vehicle. In addition to the super-insulated cryotank, a typical on-vehicle liquid hydrogen storage system will include a filling port, a safety (pressure relief) valve, and a heat exchanger. The safety valve is connected to a line or plenum, which directs vented hydrogen gas through a diffuser out of the top of the vehicle. Inside the tank, there is a filling line, a gas extraction line, a liquid extraction line, one or more level probes, and an electric heater. The heater is used to raise the pressure inside the tank to force out hydrogen gas in response to fuel demand. Mounting hardware holds the tank securely to the vehicle.

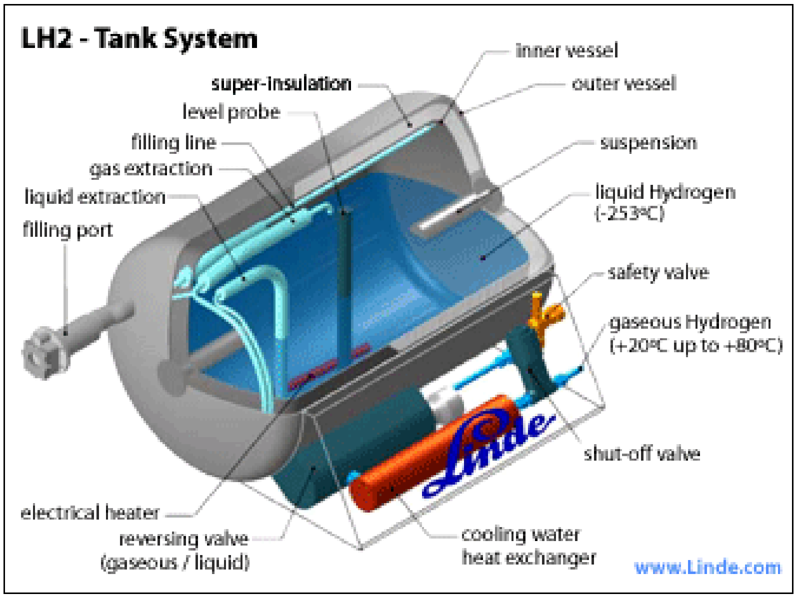

Figure 9. Liquid Hydrogen Fuel System

Source: DOE.

The gas released from the liquid hydrogen storage tank is extremely cold. Before entering the fuel cell or hydrogen ICE fuel delivery system, the gas passes through the heat exchanger, which raises the temperature. Typically the heat exchanger is connected to the same cooling system used to control the fuel cell stack or ICE temperature. Once through the heat exchanger, the hydrogen is close to the operating temperature of the fuel cell stack or ICE.

In the past, some fueling couplings used with liquid hydrogen required heating and rinsing to separate the two parts and to disconnect them from the vehicle after fueling. Newer designs have improved the safety and speed of fueling operations through the use of a special coaxial "cold withdrawal coupling." This allows the operator to immediately disconnect from the vehicle after refueling has stopped and to rapidly refuel multiple vehicles without waiting for the coupling to warm up in between (Linde, n.d.).

The fueling operation used with liquid hydrogen is similar to fueling with compressed hydrogen. The connection between the vehicle and the fuel station is manual. To fuel, the operator inserts the male part of the coupling from the fuel station into the female part of the coupling on the vehicle. When a positive connection is made, the operator turns a lever to lock the coupling and fuel starts to flow (see Figure 10).

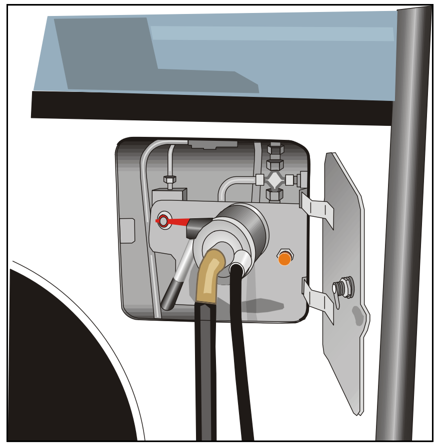

Figure 10. Liquid Hydrogen Fueling

There is a data connection in the fuel coupling connected to the vehicle's control system. Using signals from the probes inside the storage tank, the vehicle signals the fuel station when the tank is full. After the liquid hydrogen has stopped flowing, the operator unlocks the coupling and removes it.

On-vehicle liquid hydrogen storage systems will be larger than the diesel fuel tanks on current trucks, but smaller than compressed hydrogen storage systems. Liquid hydrogen with the same amount of energy as 100 gallons of diesel fuel would take up four times as much space as the diesel fuel, but less than one third as much space as the same amount of gaseous hydrogen stored at 5,000 psi. The weight of the liquid hydrogen storage system would be about 50 percent greater than the weight of the diesel fuel system when full, but less than half the weight of the compressed hydrogen fuel system (College of the Desert, 2001a). As with compressed hydrogen storage, the weight of the containment vessel for liquid hydrogen accounts for the majority of the total weight of the system.

The size and weight advantage of liquid hydrogen storage compared to compressed hydrogen storage is balanced by higher cost and complexity of the storage system, the energy required to liquefy the hydrogen, and ongoing hydrogen venting. Given these disadvantages, to date very few fuel cell or hydrogen ICE vehicles have been deployed with onboard liquid hydrogen storage. Bulk liquid hydrogen storage at a centralized vehicle fueling station is much more common. Bulk liquid hydrogen storage tanks have similar construction to onboard vehicle storage tanks.

1.3.3 Hydrogen Storage in Materials

There are a number of other ways to store hydrogen in solid or liquid materials, for release on demand. The two most studied approaches are adsorption of hydrogen into solid metal hydrides and "chemical" storage as part of a chemical hydride. Both of these approaches are inherently safer than storing hydrogen as a high-pressure gas or a cryogenic liquid, and the process of releasing the hydrogen from the storage medium is less complex than reforming of hydrocarbon fuels. At present, these systems are heavy and bulky and require further development to be practical.

Metal hydride storage systems are based on the fact that some metals can adsorb significant amounts of hydrogen under high pressure and moderate temperatures. The hydrogen is either adsorbed onto the surface of the metal or actually incorporated into the crystalline lattice of the solid metal. When heated to some higher temperature at low pressure, the hydrogen is released from the metal. In a vehicle hydrogen storage system, waste heat from the fuel cell or ICE engine would typically be used to release the hydrogen (DOE, n.d.). Such a system could potentially be "re-fueled" onboard the vehicle by connecting it to a high-pressure hydrogen source.

Chemical hydrides are compounds that include significant numbers of hydrogen atoms chemically bound to other types of atoms, for example, sodium borohydride, which is composed of one sodium atom, one boron atom, and four hydrogen atoms ($NaBH_4$). In a hydrogen storage system based on a chemical hydride, the hydrogen is released on demand through a chemical reaction with either water or an alcohol. The solid hydride is made into a slurry with an inert liquid, and when hydrogen is required, water is added, releasing hydrogen (DOE, n.d.). Unlike metal hydrides, chemical hydrides cannot be regenerated on the vehicle; after releasing all of its hydrogen the spent slurry must be removed and regenerated off-site.

Current metal and chemical hydride fuel storage systems are heavy and bulky; they can only store and release 6 percent or less of their weight as hydrogen (DOE, n.d.) (i.e., only 6 percent of the total weight of the system is the hydrogen fuel; the rest of the weight is the container). These systems have even lower energy densities than compressed gaseous hydrogen storage systems. More work is required to develop truly practical storage systems for vehicles based on these technologies.

1.4 REFORMING OF LIQUID FUELS

All liquid hydrocarbon fuels (gasoline, diesel fuel, kerosene, and methanol), as well as natural gas, contain significant hydrogen, which is chemically bound to carbon. Both diesel fuel and gasoline contain about two hydrogen atoms for every carbon atom, while natural gas contains four.

"Reforming" of a hydrocarbon fuel is a chemical process that converts the natural gas or liquid fuel into a hydrogen-rich gas. The product of this process is called "reformate," and when used to fuel a PEM fuel cell, it is typically composed of a mixture of hydrogen gas, carbon dioxide, nitrogen, and water vapor. Reformate used to fuel an SOFC can also contain carbon monoxide. Depending on the fuel being reformed and the process used, the reformate could be anywhere from 40 to 75 percent hydrogen by volume (College of the Desert, 2001a).

There are a number of processes that can be used to reform different fuels. Fuel reforming often requires several different steps, each of which involves flowing the fuel or partially processed reformate across a catalyst bed in a closed vessel, or "reactor." These reactors are generally constructed like heat exchangers. with the working fluid flowing through one set of channels coated with some kind of a catalyst, and another fluid (thermal oil or water-ethylene glycol) flowing through another set of channels to either add or take away heat. Each process step may also require the addition of air or water to the inlet flow stream. The catalyst coating promotes chemical reactions in the vessel, which usually occur at relatively high temperatures and pressures. The necessary process heat may be produced by combusting some of the liquid fuel and/or depleted reformate after it leaves the fuel cell stack, in a burner. As a whole, the fuel reformer unit is close to being a “solid state” device, with very few moving parts.

Natural gas and alcohol fuels, like methanol, are easier to reform than gasoline or diesel fuel and also yield a reformate with higher hydrogen content. Both gasoline and diesel fuel are a mixture of different hydrocarbons, including aromatics and olefins that tend to form polymer gums and carbon during reforming, which can block the reformer catalyst sites (College of the Desert 2001a). Reforming of gasoline and diesel fuel, especially for use in a PEM fuel cell, usually requires additional processing steps.

Hydrogen is often produced at a centralized hydrogen fueling station by reforming natural gas on site. If so, additional processing steps are used to remove the carbon dioxide and other impurities from the reformate to produce very pure hydrogen gas. This hydrogen is then compressed for on-site storage and delivery to vehicles.

Different reformer designs are possible, but most will likely be packaged into a “hot box” that incorporates all of the process steps, including the process heater or burner, into a relatively compact unit housed in a single enclosure (see Figure 11). The plumbing inside this box may be very complicated, with the different systems feeding each other. The device will likely also have interconnections with the fuel cell stack outlet (for depleted reformate), the fuel cell water recovery system, the fuel cell cooling system, and the liquid fuel storage system.

The reformate leaving the fuel reformer is generally at approximately the same temperature and pressure at which the fuel cell stacks operate.

For SOFC APUs, the fuel reformer and SOFC stacks may be packaged into a single unit in a common enclosure, with only external fuel line, process air intake, exhaust outlet, and electrical connections to other vehicle systems.

Onboard reformers can also be used with fuel cell vehicles so that compressed or liquid hydrogen does not need to be carried on the vehicle. For example, Georgetown University has fielded a fuel cell transit bus operated on methanol fuel that is reformed onboard. The methanol fuel processor on this bus uses low temperature steam reformation and selective oxidation to make the hydrogen-rich reformate, which is fed to a PEM fuel cell.

In steam reformation, the methanol must first be vaporized and mixed with steam. The steam/methanol mixture then passes across a heated catalyst bed in the steam reformer, which converts the methanol and water to hydrogen gas, carbon dioxide, and carbon monoxide. Because PEM fuel cells cannot tolerate carbon monoxide, the reformate must go through a second catalytic process called selective oxidation, which converts the carbon monoxide into carbon dioxide. The final reformate is approximately two-thirds hydrogen, with the balance CO_2, water, nitrogen, and less than 20 parts per million CO. The required heat for the process is provided by oxidizing the depleted reformate in a catalytic burner after it exhausts from the fuel cell stacks. See Figure 11 for a picture of this methanol fuel processor.

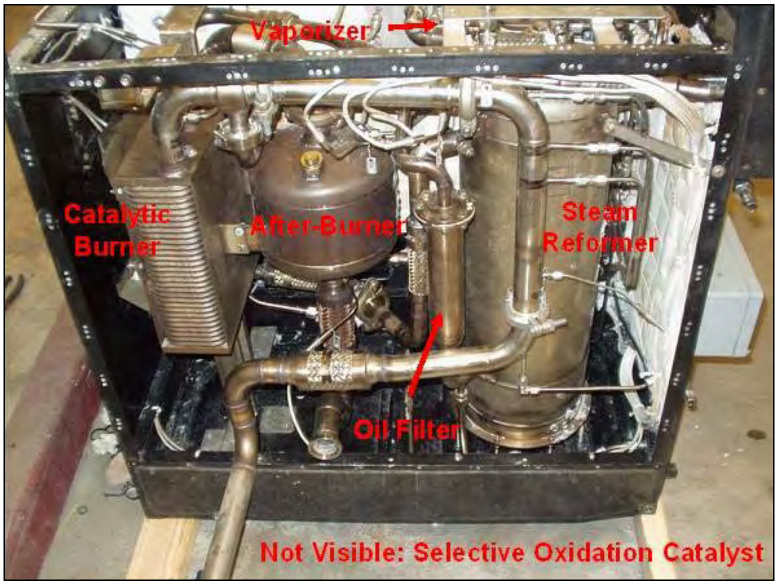

Figure 11. Onboard Methanol Reformer for a Bus
Photo courtesy of Georgetown University.

At least two companies are also working on a fuel reformer/processor to reform diesel fuel to power an SOFC APU. Unlike a PEM fuel cell, an SOFC can tolerate CO, so this fuel processor is based on catalytic partial oxidation and does not require the second, selective oxidation processing step.

Compared to onboard storage and use of compressed or liquid hydrogen in a PEM fuel cell engine or SOFC APU, onboard reforming of hydrocarbon fuels creates more tailpipe emissions. In particular, the vehicle will emit carbon dioxide, as well as small amounts of nitrogen oxides created during fuel reforming.

1.5 ELECTROLYSIS OF WATER

The most abundant source of hydrogen on earth is water—every molecule of water contains one oxygen atom and two hydrogen atoms. It is relatively simple to separate the hydrogen in water from the oxygen using electricity to run an electrolyzer. An electrolyzer is a galvanic cell composed of an anode and a cathode submerged in a water-based electrolyte.

In many ways, the operation of an electrolyzer is the opposite of operating a hydrogen fuel cell. In a fuel cell, hydrogen and oxygen are supplied to the anode and the cathode, and they combine to form water while creating an electrical current that can be put to use (see Section 1.2.1 and Appendix A). In an electrolyzer, an electrical current is applied between the anode and the cathode, which causes the water in the electrolyte to break down, releasing oxygen gas at the anode and hydrogen gas at the cathode (see Figure 12).

Water and an onboard electrolyzer cannot be used to power a fuel cell or hydrogen ICE vehicle because of the large amount of electricity required to operate the electrolyzer. An electrolyzer *can* be used at a centralized fueling station to produce hydrogen, which is then compressed for on-site storage and delivery to vehicles. For a centralized electrolyzer, the electrical energy could be supplied from the electrical grid or from a dedicated renewable source, such as a wind turbine or solar cell array.

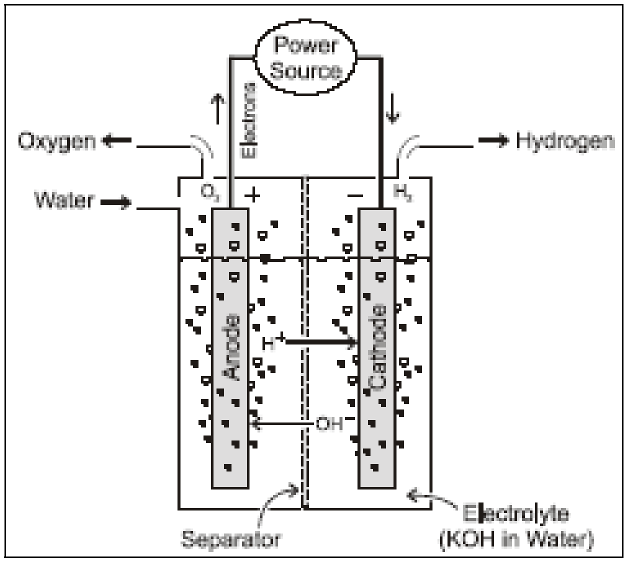

Figure 12. Electrolysis of Water to Produce Hydrogen and Oxygen

Source: College of the Desert, 2001a.

Onboard electrolyzers *are* used with hydrogen injection systems for diesel engines (see Section 3.5). In this case, only a small amount of hydrogen and oxygen are produced to supplement, not replace, the diesel fuel used in the engine. The electricity to operate the electrolyzer is typically supplied by the engine's alternator or 12/24-VDC electrical system.

2. PROPERTIES OF HYDROGEN

Hydrogen is the most abundant element in our universe. In addition to being a component of all living things hydrogen and oxygen together make up water, which covers 70 percent of the earth. In its pure form, a hydrogen molecule is composed of two hydrogen atoms (H_2) and is a gas at normal temperatures and pressures. It is the lightest gas (even lighter than helium) with only 7 percent of the density of air. If you get it cold enough (–423 °F), gaseous hydrogen will liquefy, and it can be transported and stored in this form.

There is virtually no "free" hydrogen on earth; all of it is combined with other elements (mostly oxygen or carbon) in other substances. Every molecule of water contains two hydrogen atoms and one oxygen atom. Hydrocarbon fuels such as coal, gasoline, diesel, and natural gas also contain hydrogen. In the case of gasoline and diesel fuel, there are approximately two hydrogen atoms for every carbon atom, while natural gas contains four hydrogen atoms for every carbon atom.

In order to directly use hydrogen as a fuel (whether in a fuel cell or in an internal combustion engine), it must be separated from these other elements. The hydrogen fuel used in vehicles is either derived from water (by electrolysis) or from a gaseous or liquid hydrocarbon fuel (by reforming). After being separated it must be stored—first at the fuel station and then on the vehicle. Some fuel stations include liquid hydrogen storage, but on the vehicle, hydrogen is usually stored as a gas at high pressure. It is also possible to store a liquid fuel (gasoline, diesel, and methanol) onboard a vehicle and then use an onboard reformer to separate the hydrogen just before it is used in the fuel cell engine. While this requires additional equipment on the vehicle, it removes the need for high-pressure gas storage.

This chapter provides an overview of the properties of both gaseous and liquid hydrogen that are necessary to understand how hydrogen differs from more familiar motor fuels, such as gasoline and diesel fuel, and what is required to handle and use it safely. While there are risks, hydrogen can be as safe, or safer, than diesel and other fuels when vehicles and fuel stations are designed and operated properly. All fuels require particular design and handling practices based on their properties, and all present certain hazards when mishandled. Understanding the properties of hydrogen is necessary to understanding what is required to use it safely.

Building on the discussion of hydrogen properties, this chapter also provides an overview of the general principles that govern safe design and use of hydrogen fuel. These principles inform the design and operating guidelines presented in chapters 3 through 5.

2.1 GASEOUS HYDROGEN

Hydrogen gas is colorless, odorless, tasteless, and noncorrosive, and it is nontoxic to humans. It has the second widest flammability range in air of any gas, but leaking hydrogen rises and diffuses to a nonflammable mixture quickly. Hydrogen ignites very easily and burns hot, but tends to burn out quickly. A hydrogen flame burns very cleanly, producing virtually no soot, which means that it is also virtually invisible.

2.1.1 Flammability, Ignition, and Luminosity

A mixture of hydrogen and air will burn when there is as little as 4 percent hydrogen or as much as 75 percent hydrogen in the mix[4] *This is a very wide flammability range.*

In comparison diesel fuel vapors in air will burn over a range of 0.6 percent to 5.5 percent. With less than 0.6 percent diesel in the mixture it is too lean to ignite, and with more than 5.5 percent diesel in the mixture it is too rich. Natural gas will burn over a range of 5 percent to 15 percent.

It takes very little energy to ignite a hydrogen-air mixture—a common static electric spark may be sufficient.

As shown in Table 4, it takes less than one tenth of the energy to ignite a hydrogen air mixture as it does to ignite a mixture of gasoline vapors in air. Over much of its flammable range, common static electricity would be enough to ignite a hydrogen-air mixture. In some cases, the electrostatic charges or heating created by the flow of hydrogen from a leaking vessel would be enough to ignite the leaking hydrogen (Murphy, et al., 1995; Argonne, 2003).

Table 4. Hydrogen Flammability Range and Ignition Energy

	Hydrogen	Gasoline	Diesel (#2 - Low Sulfur)	Methane (CNG)
Auto-ignition Temperature	932°F (500°C)	495°F (257°C)	480°F (250°C)	999°F (537°C)
Ignition Energy in Air	0.02 mJ	0.24 mJ	N/A	N/A
Flame Temperature in Air	4010°F (2045°C)	3987°F (2197°C)	N/A	3484°F (1918°C)
Lower Flammable Limit	4 percent	1.4 percent	0.6 percent	5 percent
Upper Flammable Limit	74 percent	7.6 percent	5.5 percent	15 percent
Buoyancy: Gas or Vapor Density Relative to air (at STP)	0.07	2 to 4	4 to 5	0.6
Boiling Point at 1 atm.	–422°F (–252°C)	80 to 437°F (25 to 225°C)	350 to 650°F (180 to 345°C)	–259°F (–162°C)

Source: Data from Chemical Properties Handbook, edited by Yaws, C.L., 1999, McGraw-Hill.

Hydrogen flames burn very cleanly, producing virtually no soot. It is the soot created by most fuel that makes a flame visible. In addition, much of the energy radiated by a hydrogen flame is in the ultraviolet range, rather than the infrared or visible ranges of the light spectrum. Therefore, a hydrogen flame is virtually invisible to the human eye in day light, though the energy being

4 *At room temperature and one atmosphere pressure.*

released by the flame may create a visible “shimmer” in surrounding air due to changes in the air density. At night, hydrogen flames are visible to the unaided human eye, and in daylight, they can be “seen” by an ultraviolet light sensor.[5] If a hydrogen flame ignites other nearby materials, flames or smoke may also be visible from them. See Figure 13.

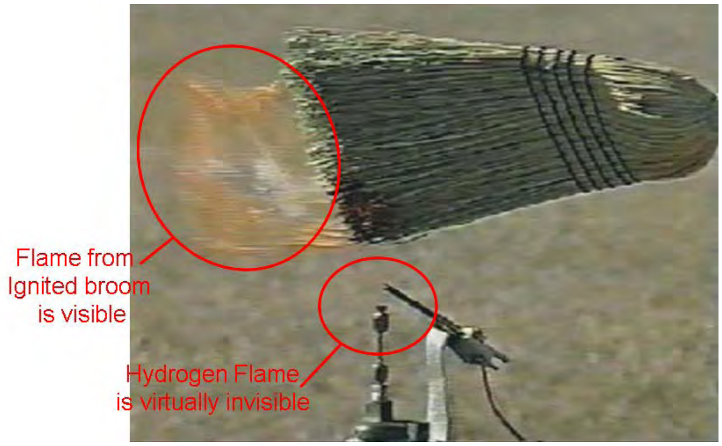

Figure 13. Hydrogen Flame
Source: College of the Desert, 2001c.

2.1.2 Odor and Toxicity

Hydrogen gas has no color, taste, or smell. Therefore, a gaseous hydrogen leak cannot generally be detected by human senses alone, except perhaps by human hearing.[6] Other gaseous fuels, such as methane (natural gas), are also naturally colorless and odorless. However, sulfur-based odorants[7] are usually added to pipeline natural gas specifically to aid in detecting leaks. The sulfur in these odorants can poison the catalysts used in automotive fuel cell systems, and satisfactory substitute odorants compatible with fuel cells have not yet been developed.

Hydrogen sensors must be used to detect hydrogen leaks.

There are a number of technologies used to sense hydrogen, but many sensors rely on a catalyst that contains palladium, which breaks the chemical bonds between the atoms in a hydrogen molecule. The hydrogen atoms then diffuse into the catalyst, changing its electrical properties (e.g., resistance, capacitance). This change is proportional to the hydrogen concentration and can, therefore, be used to measure hydrogen levels in the air (Speer, 2004).

Hydrogen is not toxic to humans or animals. However, if leaking into an enclosed space, hydrogen gas can displace oxygen in the air and would pose an asphyxiation hazard in high enough concentrations. The risk of asphyxiation from hydrogen leaking into an open area is virtually non-existent because hydrogen is so buoyant that it will rise and diffuse to very low concentrations quickly. Even in an enclosed area the danger from a small leak is slight, but may

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5 Very little of the energy given off by a hydrogen flame is in the infrared part of the light spectrum. Infrared sensors are better suited to hydrocarbon fires.

6 Escaping hydrogen gas may produce an audible noise, depending on the size and rate of the leak.

7 These include mercaptans and thiophanes.

be greater from a large leak that releases a significant volume of hydrogen relative to the size of the space.

2.1.3 Buoyancy and Diffusivity

Hydrogen is the smallest and lightest known molecule, and therefore is the “lightest” gas. Hydrogen has only 7 percent of the density of air, which means that a given volume of air will weigh fourteen times as much as the same volume of hydrogen gas at atmospheric pressure.

Because it is so light and the molecules are so small, hydrogen leaking from a vessel rises and diffuses very quickly in air. The rate of diffusion for hydrogen in air is over ten times the rate for gasoline and other fuel vapors (Raj, 1998). This means that leaked hydrogen will quickly dissipate in open air to the point that the mixture is no longer flammable.

2.1.4 Effect on Materials

Hydrogen is the smallest of all molecules, and it can diffuse through materials that other gases cannot. Seals and connections in high-pressure hydrogen storage systems must, therefore, be designed very carefully, with attention to both the materials used and the geometry of the mating surfaces of joints.

Over time, constant exposure to hydrogen can cause many materials to loose strength and develop small cracks. This phenomenon is called hydrogen embrittlement, and it can cause leakage or catastrophic failure in hydrogen tanks and lines. The mechanisms of hydrogen embrittlement are not well-understood, but certain factors are known to effect the rate of embrittlement, including hydrogen concentration, pressure, and temperature.

Stainless steel is more resistant to hydrogen embrittlement than ordinary steels, and both pure aluminum and many aluminum alloys are even more resistant than stainless steel if the gas is dry (Ringland, 1994). All components of hydrogen fuel systems must be constructed of materials known to be compatible with hydrogen.

During maintenance and overhaul, only manufacturer-approved replacement parts specifically designed for use in hydrogen systems must be used. Parts that “look the same,” even if they fit properly, could result in failures over time if they are made from incompatible materials.

2.1.5 High-Pressure Storage

Hydrogen gas contains a lot of energy per pound, but like all gases it is difficult to compress. In order to get enough hydrogen fuel on a vehicle to operate for several hundred miles or more between fill ups, it must be stored at very high pressures—typically between 5,000 and 10,000 pounds per square inch (psi). Gaseous hydrogen fuel with the same amount of energy as one gallon of diesel fuel would only weigh about one third as much, but would occupy almost seven times the volume if stored at 10,000 psi.[8] If stored at only 3,000 psi, the hydrogen would occupy almost seventeen times the volume of the diesel fuel.

The use of high-pressure storage does introduce some potential hazards due to the large amount of mechanical energy in the compressed gas. However, the high-pressure storage tanks used to hold compressed hydrogen are designed with a high margin of safety, and designs are verified with extensive qualification testing. See Figure 14 for photos of the types of tests required for certification of a high-pressure storage tank design. High-pressure storage tanks are also protected from excessive pressure build-up inside the tank using pressure relief devices (PRD) and/or temperature relief devices (TRD). These devices act to vent hydrogen to relieve pressure in the tank if it gets so high that there will be danger of a rupture.

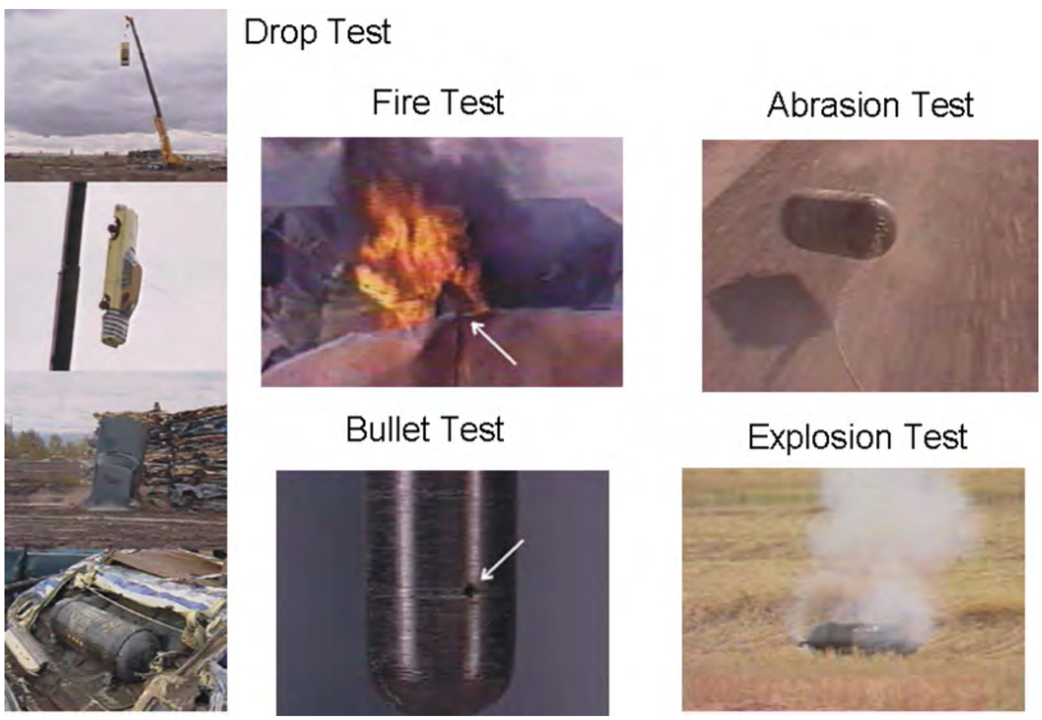

Figure 14. High-Pressure Storage Vessel Qualification Tests

Source: Photos courtesy of College of the Desert, 2001a.

High-pressure storage tanks must be protected from abrasion or damage by road debris, and both the tanks and lines should be adequately protected from vibration to minimize the possibility of leaks.

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8 *Not including the weight and volume of the hydrogen tank itself.*

2.1.6 Gaseous Hydrogen Leaks

Because hydrogen molecules are so small, leaking hydrogen gas rises and diffuses quickly. A gaseous hydrogen leak tends to create a very vertical, fairly narrow area in which the hydrogen-air mix is flammable. Outside of this region, the hydrogen concentration is too low for the mixture to burn. Depending on size and flow rate, the leak may produce a hissing sound similar to other gas leaks.

Gaseous hydrogen leaks may self-ignite due to static electricity or heating created by the flow of hydrogen. If the leak does ignite, the flame will be virtually invisible in daylight.

2.2 LIQUID HYDROGEN

Liquid hydrogen is gaseous hydrogen that has been cooled to the point that it condenses. To get hydrogen to condense to a liquid it must be cooled to −423ºF—just a few degrees warmer than "absolute zero," which is as cold as anything can get. Liquid hydrogen is referred to as a "cryogenic liquid" because it is so cold, and must be stored in specially insulated containers.

As liquid hydrogen absorbs heat, some of the liquid "boils off" and vaporizes. Once it has vaporized, the resultant hydrogen gas has the same properties and presents the same hazards as discussed above. However, while in liquid form, it presents additional hazards related to the extreme cold of the liquid. In addition, liquid hydrogen leaks behave somewhat differently than gaseous hydrogen leaks.

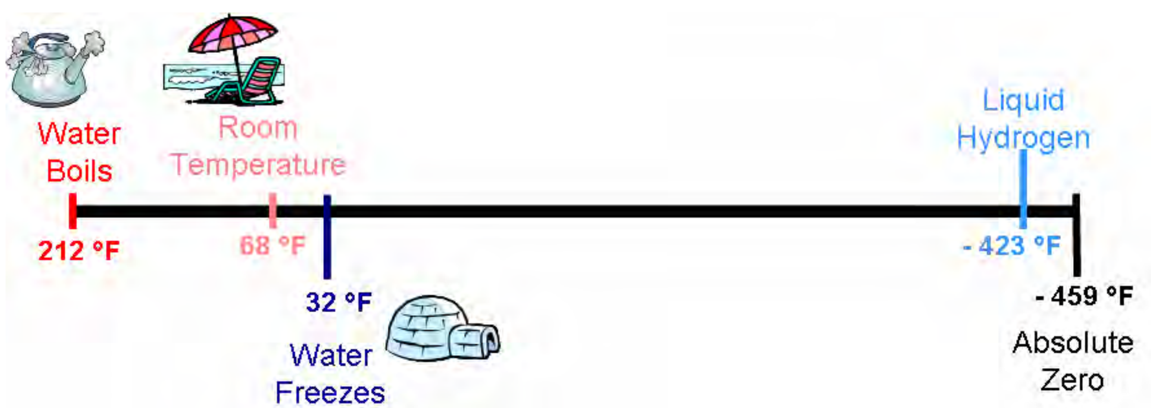


Figure 15. Liquid Hydrogen Temperature

2.2.1 Low Temperature Storage

Liquid hydrogen storage vessels must also be well-insulated to maintain the temperature of liquid hydrogen over long periods. No matter how well-insulated, however, it is inevitable that eventually some heat will be absorbed through the vessel walls, which will cause some hydrogen in the tank to vaporize. As hydrogen vaporizes, it raises the vapor pressure inside the tank. If not relieved, the increased pressure might eventually cause the tank to rupture.

The extremely low temperature of liquid hydrogen poses a severe frostbite hazard to exposed skin. All vessels, hoses, and lines that carry liquid hydrogen, either on a vehicle or at a fueling station, should be protected to avoid casual contact by people.

Liquid hydrogen tanks are always equipped with pressure relief valves to relieve pressure in the tank as necessary. These valves are different from the PRD/TRDs used with gaseous hydrogen storage tanks. Liquid hydrogen pressure relief valves are designed to open when the vapor pressure inside the tank rises above a set pressure, and then to close again when the pressure inside the tank falls below a different set pressure. PRD/TRDs open as required to relieve pressure, but do not close again. Once a PRD/TRD opens, it must be replaced before the tank can be filled again.

2.2.2 Effect on Materials

The extremely low temperature of liquid hydrogen makes many materials brittle and easily broken. This includes most metals, including many grades of carbon steel and low alloy steels, and many of the materials typically used for sealing joints in liquid storage systems, such as rubber and many plastics. Liquid hydrogen storage systems must be constructed from very specific materials that can maintain their strength at low temperatures. Liquid hydrogen storage tanks and lines are usually constructed from stainless steel, and nonwelded joints may be sealed with o-rings made from specialized materials specifically tested to be compatible with the extremely low temperature of liquid hydrogen.

2.2.3 Liquid Hydrogen Leaks

Leaking liquid hydrogen may spread on the ground for a short distance, but the liquid will quickly evaporate, creating a cloud of gaseous hydrogen over the liquid pool. The distance of spread and the rate of evaporation will depend on the size of the leak and on ambient conditions. The hydrogen cloud over the liquid pool will be very cold and dense, but will rise and dissipate as it is warmed by surrounding air. Often the cold hydrogen will condense water vapor in the air, creating a visible fog in the area of the leak. Frost or ice may also form on the storage vessel or lines in the area of the leak.

The cloud of cold gaseous hydrogen may move horizontally as it warms and rises, and may extend beyond the area of visible fog. This hydrogen cloud may be cold enough to cause frostbite to exposed skin and should be avoided.

Leaking liquid hydrogen is so cold that it can liquefy the oxygen and nitrogen in surrounding air. If liquid oxygen drips onto combustible material (for example, asphalt), it will significantly increase the fire hazard. This is not of major concern for the volumes of liquid hydrogen likely to be carried on a typical commercial vehicle. However, liquid hydrogen storage tanks at fuel stations, which are likely to contain a much greater volume of fuel, should always be constructed over pads made of noncombustible material, such as concrete.

For the same reason, the insulation on the exterior of all liquid hydrogen storage tanks and lines, both at the fuel station and on a vehicle, should be vapor sealed to ensure that air cannot contact the cold inner surface.

2.3 COMPARISON OF HYDROGEN TO OTHER MOTOR FUELS

This section directly compares the properties of gaseous and liquid hydrogen to those of diesel fuel to contrast the safety issues of hydrogen to those of more common motor fuels. Two specific areas will be highlighted: the behavior of fuel leaks, and the characteristics of fire and explosions with these fuels.

2.3.1 Leaks

In some ways a gaseous hydrogen fuel leak is less dangerous than a leak of diesel fuel or gasoline. Leaking diesel fuel and gasoline can puddle and spread over a large area, and the puddles will persist because they evaporate slowly (Amerada Hess, 2001).

Gaseous hydrogen leaks tend to be vertical with only a relatively narrow area/volume in which a flammable mixture exists;[9] *the hydrogen quickly dissipates in open air to nonhazardous levels.*

If designed properly, the most likely location of a major hydrogen leak from a vehicle will be through the PRD, which should vent away from the occupied area of the vehicle. PRDs are designed to vent the entire contents of a hydrogen tank in only a few minutes, after which there is no lingering risk of hydrogen fire or explosion if the release was in the open air. Large hydrogen leaks inside buildings are more dangerous unless the facility has been designed to evacuate the leaked gas and to minimize ignition sources at ceiling level.

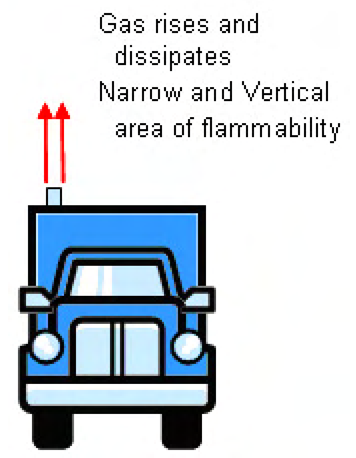
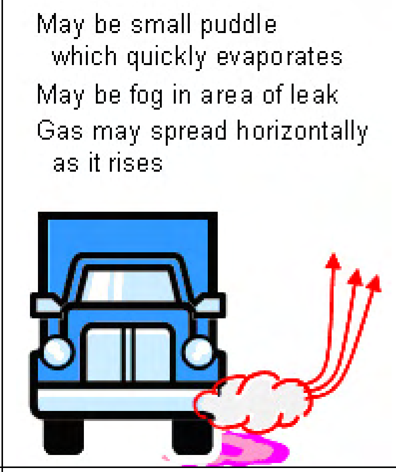
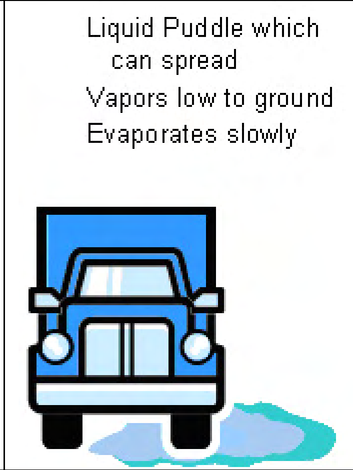
Leaking liquid hydrogen can pool and spread, but will quickly evaporate as it is heated by the surrounding air. As it evaporates, the cloud of gaseous hydrogen formed over the spill may move horizontally as it rises and dissipates.

While diesel fuel and gasoline leaks are easily visible and accompanied by a strong characteristic smell, gaseous hydrogen leaks are invisible and odorless (see Table 5). The only indication of a gaseous hydrogen leak may be a whistling noise similar to escape of other high-pressure gases. A liquid hydrogen leak may be accompanied by an area of fog surrounding the leaking hydrogen and/or the formation of frost on the tank or lines in the vicinity of the leak, because the super cold hydrogen cools the surrounding air and causes water vapor to condense.[10]

9 The actual area/volume in which a flammable mixture will exist will depend on the rate and size of the leak and on ambient conditions.

10 This fog and frost may not appear in locations with very low humidity.

Table 5. Leak Profiles of Gaseous Hydrogen, Liquid Hydrogen, and Diesel Fuel

Leak Profile	Gaseous Hydrogen	Liquid Hydrogen	Diesel Fuel
			
Location	Gas quickly rises	May be liquid puddle – gas rises as it evaporates	Liquid puddle on ground and some vapors low to ground
Size	Very vertical and localized	Puddle will not spread far – gas may spread horizontally as it rises	Puddle can spread on ground
Duration	Quickly dissipates in open, *but may collect at ceiling in buildings*	Liquid evaporates quickly and gas dissipates in open, *but gas may collect at ceiling in buildings*	Liquid evaporates slowly
Visual Detection?	No	Maybe- potential fog and frost in area of leak	Yes
Odor?	None	None	Yes
Flammability	Very easily ignited	Very easily ignited	Easily ignited
Flames	Invisible in daylight	Invisible in daylight	Visible and smoky

2.3.2 Fires and Explosion

Hydrogen has higher energy content (per pound) than diesel fuel and is very reactive, which results in a very vigorous fire. However, the buoyancy of gaseous hydrogen means that it rises rapidly and diffuses quickly, resulting in a very vertical and localized flame. Hydrogen fires also tend to burn out fairly quickly. By contrast, diesel fuel and gasoline fires tend to burn longer and spread over a much larger area, as the liquid fuel puddle expands.

There is virtually no risk of a thermal "explosion" of hydrogen stored in a closed tank unless oxygen has been allowed to enter the tank during fueling operations, which is virtually impossible if the fueling system has been designed properly. Hydrogen gas that leaks into an enclosed space, whether on a vehicle or in a building, can create an explosive mixture, depending on the volume of hydrogen relative to the volume of air in the space.

Diesel fuel is not very volatile, and the risk that accumulated vapors will result in an explosion is small, even for large leaks. Gasoline, however, is very volatile and vapors from leaks can create the risk of an explosion if they collect in an enclosed space on the vehicle or in a building.

2.4 HYDROGEN SAFETY PRINCIPLES

The most important safety principle in any situation is education—making anyone who will come into contact with a vehicle aware of a potential hazard. For hydrogen and other alternative-fueled vehicles, this is done with appropriate labeling, to let users, emergency responders and the public know that hydrogen is present.

As with other motor fuels, fire and explosion are the most significant everyday hazards associated with hydrogen. Also as with other fuels, a hydrogen leak from a vehicle's fuel or engine system, or from a fueling station, provides the starting point for all fire and explosion hazards.

Safe design for using hydrogen therefore requires attention to these safety principles:

- Properly label all vehicles that use hydrogen fuel. Avoid fire and explosion by: Avoiding leaks through proper design and maintenance, Providing leak detection systems to detect leaks and, if a leak is detected, shut off the fuel system as soon as possible,
- Removing ignition sources from areas where leaked hydrogen might be present, and
- Properly ventilating all enclosed spaces where leaked hydrogen might accumulate.

These are essentially the same principles that apply to the use of any gaseous fuel (e.g., natural gas), but their application may be slightly different based on the properties of hydrogen. Each of these principles, as applied to hydrogen, is discussed further below.

2.4.1 Labeling

As with other alternative-fueled vehicles, all commercial vehicles that store hydrogen fuel onboard should carry a label that identifies the type of fuel used in order to alert emergency response personnel to the types of hazards they might face if the vehicle is involved in an accident. These labels should conform with SAE J2578, a fuel cell safety recommended practice developed by the Society for Automotive Engineers (SAE, 2002).

This practice recommends a diamond-shaped label with a blue background and white lettering (see Figure 16). It also specifically recommends that the words "Compressed Hydrogen" or "Liquid Hydrogen" be contained in the blue diamond, depending on the form in which the hydrogen is stored on the vehicle.

SAE J2578 does not specify the location of the hydrogen label on the vehicle. For hydrogen-fueled cars, the manufacturer usually affixes the label to the rear of the vehicle, as shown in Figure 16. For commercial tractor-trailer units, a label on the rear of the power unit would likely be obscured by the trailer. For that reason, all commercial vehicles should include the hydrogen label on the rear of the vehicle and on each side of the power unit cab, below the DOT numbers mandated by 49 CFR 390.21. As with these DOT numbers, the hydrogen labels should be legible from fifty feet in daylight.

Figure 16. Hydrogen Vehicle Label in Accordance with SAE J2578

Any commercial trailer unit that will store hydrogen (for example, to fuel a transportation refrigeration unit) should also have SAE J2578-compliant hydrogen labels affixed. These labels should be located on the rear of the trailer and on each side of the trailer, in the vicinity of where the hydrogen fuel tank is located.

2.4.2 Avoiding Fire and Explosion

As shown in Figure 17, a fire or explosion requires three things:

- Fuel (i.e., a hydrogen leak),
- An ignition source, and
- Oxygen (from the air).

Safe design for use of any gaseous fuel, including hydrogen, involves paying attention to all three legs of the "fire triangle."

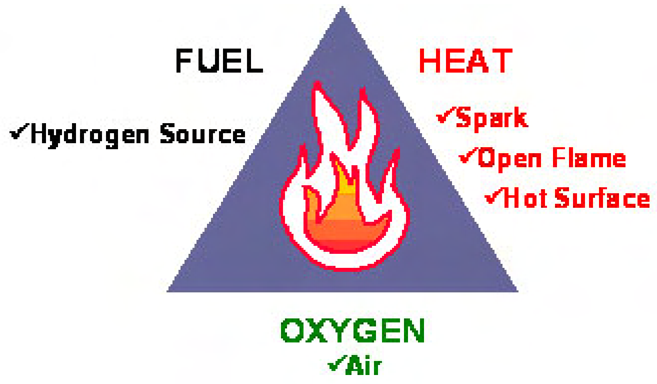


Figure 17. Fire Triangle

2.4.2.1 Removing the Fuel Source—Avoiding and Detecting Leaks

Good design for a fuel system involves two major principles:

- Avoiding leaks of hydrogen fuel
- Detecting leaks of hydrogen fuel

The most likely locations for a hydrogen leak are at joints and connections in the high-pressure hydrogen fuel system. Hydrogen gas is the smallest of all molecules and can, therefore, move more easily through joints than other gases. However, most hydrogen leaks can be avoided by designing hydrogen systems using appropriate materials and minimizing connections.

Proper maintenance practices, in accordance with the manufacturer's instructions, are also critical. This includes the use of the proper tools when making and breaking connections, tightening to the correct torque as specified by the manufacturer, and use of only approved replacement parts.

In a properly designed and maintained hydrogen fuel system, the most likely location for a hydrogen release will be through the PRD/TRD. If the PRD/TRD is properly oriented, a release will pose little danger to the vehicle, the operator, or the public. Hydrogen-fueled vehicles should enter only buildings designed to handle hydrogen.

All vehicles that use hydrogen fuel should also be equipped with one or more sensors to detect hydrogen leaks.

These sensors should be linked to the vehicle control system. If hydrogen levels approaching the lower limit of flammability are detected, the system will automatically shut down the vehicle and close valves to isolate the hydrogen within the high-pressure tank. In most cases, this will stop the source of the leak and remove any hazard. Some vehicles may include an "override" switch that will allow the vehicle to operate for a short time, even after a hydrogen leak has been detected. This switch should only be used in case of extreme emergency, for example, to move the vehicle out of high speed traffic or off of a railroad track.

Buildings used to store or maintain hydrogen-fueled vehicles should also generally be equipped with hydrogen sensors.

These sensors will be hooked into a building alarm system, as well as the building's ventilation system. If hydrogen levels approaching the lower limit of flammability are detected, the system will sound an alarm to warn people in the area to evacuate and will increase the ventilation rate in the building to help remove any accumulated hydrogen. Some buildings designed for hydrogen vehicles may also be equipped with ultraviolet flame detectors to detect hydrogen fires. If so, they will also be hooked to the building alarm system.

2.4.2.2 Removing Ignition Sources

Hydrogen is very easily ignited. A spark from static electricity, a vehicle tailpipe, electrical device, or even a hot surface can all ignite a mixture of air and leaked hydrogen within its flammable range.

It is important to minimize potential ignition sources in areas where hydrogen might leak and collect.

On a vehicle, static electricity is removed by proper grounding and bonding of electrical components. Fuel tanks, lines, and connections should be deliberately placed so that they avoid surfaces that might be hot or a source of ignition. In a building that will be used to house or maintain hydrogen fueled vehicles, any leaked hydrogen will quickly rise. The only area in which it is likely to collect in flammable concentrations is within a few feet of the ceiling. Electrical lines and equipment and heating equipment should not be located in this area near the ceiling. If electrical equipment must be located near the ceiling, it should be sealed so that it is "explosion proof" or intrinsically safe.

2.4.2.3 Ventilating Enclosed Spaces

Hydrogen leaking into open air poses very little danger to anyone—it will quickly dissipate to nonflammable levels. Hydrogen that leaks into an enclosed space potentially presents a much greater hazard. When designing a hydrogen fueled vehicle, it is important to minimize all potential for hydrogen to leak into the passenger compartment, trunk, cargo space, wheel wells, and other enclosed spaces. This is done through careful placement of fuel tanks, lines, and connections. It may also be advisable to provide ventilation openings in locations that might not otherwise require them, specifically to vent any leaked hydrogen.

Another important consideration is placement of the outlet for any PRDs/TRDs. These outlets should be at the top surface of the vehicle and pointed away from the passenger or cargo compartment.

Buildings that will be used to house or maintain hydrogen-fueled vehicles should be designed so that there are no dead pockets at the ceiling where leaked hydrogen might collect and not be swept in by the building's ventilation system.

3. GUIDELINES FOR DESIGN AND OPERATION OF HYDROGEN SYSTEMS ON VEHICLES

Safe use of hydrogen as an alternative fuel requires that vehicles be designed and operated with the physical and chemical properties of hydrogen in mind. These properties are discussed in chapter 2. In most aspects, commercial vehicles powered by hydrogen will be quite similar to those powered by diesel fuel, but the propulsion system will be significantly different and some hydrogen-specific design elements are required. Likewise, operation of these vehicles will be similar to operation of diesel-fueled vehicles, with a few specific exceptions.

This chapter briefly discusses the most important hydrogen-specific aspects of vehicle design and operation. The issues discussed are of necessity generalized and are based on current codes and standards and best practices (see Appendix B). Each vehicle manufacturer will develop their own specific designs, which are likely to vary significantly in their details, while adhering to the same over-all design principles.

The information in this chapter is intended to familiarize commercial vehicle operators with the types of safety systems they are likely to see on hydrogen-fueled vehicles and the general operating principles they will need to use with them. Vehicle operators should look to the manuals provided by the manufacturer with each hydrogen-fueled vehicle for specific operating and maintenance instructions.

3.1 GASEOUS HYDROGEN SYSTEMS

The most common method of storing hydrogen fuel on a vehicle is storage as a high-pressure gas, at pressures of 5,000–10,000 psi. This section discusses onboard gaseous hydrogen storage systems.

3.1.1 Design

The exterior of the vehicle should be marked with diamond-shaped labels that say “Compressed Hydrogen” in white letters on a blue background (see Figure 16). For commercial vehicles, one label should be located on the rear of the power unit and one label should be located on each side of the power unit cab below the DOT numbers. The hydrogen labels should be legible from fifty feet in day light.

The hydrogen fuel system will likely include two pressure regulators, which reduce the gas pressure in stages from the fuel storage cylinders to a fuel cell or hydrogen ICE. The three stages are:

- The fuel storage system at up to 5,000 psi,
- The motive pressure circuit at up to approximately 175 psi, and
- The low pressure circuit at approximately 15 psi.

Each stage will include pressure relief devices, isolation valves, and other valves to regulate the flow of gas under all conditions. All components should be designed to withstand at least three times their expected maximum working pressure (NFPA, 2005).

Storage cylinders used to hold compressed hydrogen gas must be tested and certified by the manufacturer to withstand the normal forces expected during vehicle operation (such as working pressure, pressure shocks from fueling, and vibration) over a 15-year life, as well as certain extreme events such as would be encountered in a vehicle crash. These cylinders should be permanently marked "hydrogen," securely mounted to the vehicle with the certification label visible, and protected from damage by road debris (i.e., if mounted between the frame rails, they should be protected by a cover).

All hydrogen storage cylinders must have a PRD or TRD installed. The outlets from each PRD/TRD should be connected to a common manifold that exits at or above the top surface of the vehicle, with outlet flow directed away from vehicle occupants and pedestrians.

Each hydrogen storage cylinder should have a manual shut-off valve installed that will allow that cylinder to be isolated from the rest of the fuel system for maintenance.

The fuel system should include one or more electrically activated valves that will isolate the hydrogen storage cylinders, individually or as a group, from the rest of the system when closed. These valve(s) should "fail safely" so that they will close if the control signal is lost due to a system fault.

All hydrogen fuel lines should be securely mounted to the vehicle and routed away from heat sources. To the extent possible, fuel line connections should be minimized since leaks are most likely at joints. Fuel lines should not be routed through the passenger compartment.

All components of the fuel system, including cylinders, lines, valves, and sealing materials should be constructed of materials that have been tested to be compatible with hydrogen and not subject to hydrogen embrittlement.

All components of the fuel system and engine system that will carry or contain hydrogen should be electrically grounded and bonded to the vehicle chassis to preclude the build up of static electricity.

Any compartment into which hydrogen could leak (from a fuel line connection or valve or from the fuel cell stack) should be ventilated such that hydrogen cannot collect in concentrations greater than 25 percent of hydrogen's lower flammable limit. Hydrogen carrying components should not be located such that hydrogen can leak into the passenger compartment under any circumstance. Because fuel cell stacks can develop internal leaks over time, they will likely be installed in their own enclosure, which will have both ventilation holes and a ventilation fan to force air through the enclosure to flush out any leaked hydrogen so that it can not collect.

One or more hydrogen sensors should be installed on the vehicle. The number and location of these sensors will depend on the hydrogen fuel and engine system design. These hydrogen sensor(s) should be connected to the vehicle control system to provide an alarm and automatic system shutdown if a hydrogen concentration greater than a preset threshold is detected. This threshold could be anywhere from 25 percent to 50 percent of the lower flammable limit for hydrogen (1–2 percent hydrogen concentration).

The fuel system may also have an excess flow valve installed that is designed to close off fuel flow and trigger an automatic system shutdown when flow in excess of a set threshold is detected. The threshold is set to be greater than the maximum flow that could be used by the fuel cell or hydrogen ICE at full power. Flows greater than this amount indicate that there is probably a leak in the system.

The vehicle may also have an inertial crash sensor installed, which can automatically trigger a vehicle shutdown when a crash is detected.

The vehicle control system should be configured so that automatic system shutdown can be triggered by detection of leaked hydrogen, excess fuel flow, a vehicle crash, or other system fault. Automatic system shutdown should include closing valve(s) to isolate hydrogen in the hydrogen storage cylinders, disconnecting traction power, and de-energizing high-voltage equipment. During system shutdown, hydrogen should be vented from all other fuel and engine system components. Some vehicles may include a switch to override automatic shutdown and allow the vehicle to continue to operate for a short time. This switch should only be used in case of extreme emergency, for example, to move the vehicle out of high-speed traffic or off of a railroad track.

The control system should also include a single main on/off switch that allows the vehicle operator to shut down the fuel cell system, disconnect traction power, de-energize high-voltage equipment, and shut off hydrogen fuel supply (isolating all hydrogen in the hydrogen storage cylinders). This switch should be located in the operator’s cab easily accessible to the operator, similar to a conventional ignition switch. Some vehicles may also have one or more secondary means of shutting down the system, for example, by opening a battery disconnect switch accessible from outside the vehicle.

The vehicle control system should include an interlock to the vehicle fueling port such that fueling cannot begin unless the fuel cell system is shutdown and the vehicle traction system is de-energized so that the vehicle cannot move.

The onboard fuel filling receptacle must be electrically bonded to the vehicle chassis, and some method must be provided to electrically connect the vehicle chassis to the fuel station ground during fueling. This can be done through the fueling nozzle (preferred) or with a separate ground strap.

A dust cap permanently mounted to the vehicle should be provided for the onboard fuel filling receptacle, to keep out dirt and debris when the vehicle is not being fueled.

The vehicle fuel system should include fittings and other provisions necessary to de-fuel safely from the hydrogen storage cylinders and purge the cylinders with nitrogen, as required for maintenance.

After system shutdown, hydrogen will typically be vented from the low-pressure sections of vehicle’s fuel system and fuel cell stack. The outlet for this venting hydrogen should be at or above the top surface of the vehicle. If, under normal operations, venting hydrogen will achieve concentrations greater than 25 percent of the lower flammable limit (1.0 percent hydrogen concentration), the hydrogen should vent through a hydrogen diffuser. The hydrogen diffuser should be designed to mix the exiting hydrogen gas with enough air that under normal operations the resultant flow will have a hydrogen concentration less than 25 percent of the lower flammable limit.

3.1.2 Operation and Maintenance

Anyone who will operate or maintain hydrogen-fueled vehicles should receive hydrogen safety training. At a minimum, this training should cover the characteristics of hydrogen, operation of onboard safety systems, hydrogen fueling operations, and actions to take in an emergency.

During maintenance, never substitute fuel system replacement parts that have not been specifically tested and certified for use with hydrogen (for example, lines, valves, and regulators designed for use with natural gas). While they may look and function the same, they may be subject to hydrogen embrittlement. In addition, compressed natural gas fuel systems typically operate at lower pressures (maximum 3,600 psi) than hydrogen fuel systems.

Periodically check all connections in the hydrogen fuel system for leaks using procedures outlined in the manufacturer's service manual. Tighten or repair all leaking joints, no matter how small the leak. Leak checks should also be conducted after repair or replacement of any fuel system lines or valves.

Never loosen any joint in the fuel system while the connected components are under pressure. Shut down the system and isolate and vent components as directed in the manufacturer's service manual. Torque all joints to the levels specified in the service manual. *Do not over tighten*. Overtorquing can cause leaks.

Air must never be allowed to enter the hydrogen fuel system. If exposed to the atmosphere, some components, particularly hydrogen fuel cylinders, must be **purged with nitrogen** before being refilled with hydrogen. See the manufacturer's service manual for specific purging procedures.

Periodically check the exterior surface of hydrogen fuel cylinders for nicks, dents, and cuts that could weaken the structure. See the manufacturer's service manual for information on the allowable level of wear and damage before cylinders need to be replaced. The Federal Motor Vehicle Safety Standards applicable to natural gas fuel cylinders (FMVSS 304, 49 CFR 571.304) specify that a visual inspection by a "qualified container inspector"[11] must be conducted "at least every 36 months or 36,000 miles or at the time of re-installation." The inspection procedures for damage assessment are outlined in pamphlet C-6[12] from the Compressed Gas Association. While standards specifically applicable to hydrogen cylinders have not yet been developed, at a minimum, the requirements applicable to natural gas fuel cylinders should be followed. Local laws and regulations may require more frequent cylinder inspections, for example, in conjunction with

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11 "CSA America is the only known standards development organization in the United States that provides testing and certification for qualified compressed natural gas (CNG) cylinder inspections and maintains a National Registry of Certified Inspectors. To qualify for a new certification or to renew an existing certification, candidates must successfully pass a certification exam. To maintain their status without re-examination, certified CNG Inspectors must perform and submit reports on 10 vehicle or 50 cylinder inspections per year."

12 Compressed Gas Association, Inc., Pamphlet C-6: Standards for Visual Inspection of Compressed Gas Cylinders, 1984.

annual registration safety inspections. The fuel system, including the high-pressure storage tanks, should also be visually inspected after any accident, and be retested or replaced as required.

Periodically check and calibrate hydrogen sensors in accordance with the schedule and procedures in the manufacturer's service manual.

Periodically check operation of the fan in the hydrogen diffuser and any ventilation fans in accordance with the schedule and procedures in the manufacturer's service manual.

The fuel system will likely include a coalescing filter to remove any oil that might carry over into the hydrogen fuel from the fuel station compressor. Check and empty or replace this filter periodically in accordance with the schedule and procedures in the manufacturer's service manual.

Do not ignore warning lights or alarms. Do not attempt to override automatic system shutdown unless absolutely necessary (e.g., to move vehicle off of railroad tracks).

Always make sure that the main switch is off before servicing the vehicle. Before working on the fuel cell system or gaseous hydrogen storage system, also disconnect the vehicle's 12/24-VDC battery and close the manual fuel valves to isolate hydrogen in the storage cylinders.

Do not try to repair damaged fuel lines—replace them.

Do not walk on hydrogen fuel cylinders or expose them to damage from impact or abrasion. Do not allow strong chemicals, such as battery acid or metal cleaning solvents, to contact the hydrogen fuel cylinders.

Always electrically ground and bond the vehicle when fueling and defueling. Connect the ground strap or cable at the fuel station if one is provided.

Before fueling, check that the onboard fuel port is free of dirt and debris. Always replace the fuel port dust cover after fueling.

Do not smoke or use a cell phone when servicing or fueling the vehicle.

If the vehicle must be defueled for servicing of the hydrogen fuel system, the rate of fuel release must be carefully controlled. Follow the instructions in the manufacturer's service manual. Unless the hydrogen storage tanks will be removed, always leave a small amount of pressure in the tanks so that the internal pressure is a few psi above atmospheric pressure. Any time tank pressure falls below atmospheric, it is possible for air to enter, and the tank must be purged with nitrogen before refilling with hydrogen.

3.2 LIQUID HYDROGEN SYSTEMS

Liquid hydrogen storage on vehicles is much less common than high-pressure compressed hydrogen storage. If your vehicle does store liquid hydrogen onboard, many of the design and operating considerations listed in Section 3.1 will apply, but since liquid hydrogen is stored at very low temperatures, the additional considerations listed below will also apply.

3.2.1 Design

The exterior of the vehicle should be marked with diamond-shaped labels that say “Liquid Hydrogen” in white letters on a blue background (see Figure 16). For commercial vehicles, one label should be located on the rear of the power unit and one label should be located on each side of the power unit cab, below the DOT numbers. The hydrogen labels should be legible from fifty feet in day light.

All cryotanks used to hold liquid hydrogen must be permanently marked “hydrogen,” securely mounted to the vehicle, and protected from damage by road debris.

All liquid hydrogen cryotanks must have a safety pressure relief valve installed. The outlet(s) from the valve(s) should empty into a hydrogen diffuser, whose outlet is located at or above the top surface of the vehicle. The hydrogen diffuser should be designed to mix the exiting hydrogen gas with enough air that under normal operations, the resultant flow will have a hydrogen concentration less than 25 percent of the lower flammable limit.

Each liquid hydrogen cryotank should have a manual shutoff valve installed that will allow that cylinder to be isolated from the rest of the fuel system for maintenance.

Each liquid hydrogen cryotank should be equipped with a liquid level gauge that can be read from the vehicle cab and a pressure gauge that can be read locally on or near the tank.

While certification standards for on-vehicle liquid hydrogen tanks have not yet been finalized, at a minimum, tanks should be tested/certified in the same way that current liquefied natural gas (LNG) tanks are tested. For each tank design, this includes a 10-foot and a 30-foot drop test of a full tank to ensure that the tank will not leak even if subjected to a severe crash, and a 20-minute flame test to ensure that the tank will not immediately vent even if impacted by a fire (SAE, 1997).

The fuel system should include one or more electrically activated valves that will isolate the hydrogen cryotank(s), individually or as a group, from the rest of the system when closed. These valve(s) should “fail safely” so that they will close if the control signal is lost due to a system fault.

All liquid and gaseous hydrogen fuel lines should be securely mounted to the vehicle and routed away from heat sources. To the extent possible, fuel line connections should be minimized since leaks are most likely at joints. Fuel lines should not be routed through the passenger compartment.

All components of the fuel system that will come into contact with liquid hydrogen, including cryotank(s), fill lines, valves, and sealing materials should be constructed of materials that have been tested to be compatible with the low temperatures of liquid hydrogen. All gaseous hydrogen fuel lines and valves (downstream of the cryotank heat exchanger) shall be constructed of materials that have been tested to be compatible with hydrogen and not subject to hydrogen embrittlement.

All components of the fuel system and engine system that will carry or contain liquid or gaseous hydrogen should be electrically grounded and bonded to the vehicle chassis to preclude the buildup of static electricity.

All components of the fuel system that will carry or contain liquid hydrogen must be well-insulated, labeled, and be located to prevent casual contact by vehicle operators or maintenance personnel. The outer insulating layer must be vapor sealed to prevent air infiltration. Any fuel line that may be isolated between two closed valves with residual liquid hydrogen still inside (i.e., a fill line) must contain a pressure relief valve to vent hydrogen that vaporizes as the line heats up. These valve(s) should vent to a common plenum, with the pressure relief valve(s) on the liquid hydrogen cryotank(s).

Any compartment into which hydrogen could leak (from a fuel line connection or valve or from the fuel cell stack) should be ventilated such that gaseous hydrogen cannot collect in concentrations greater than 25 percent of hydrogen's lower flammable limit. Hydrogen carrying components should not be located such that hydrogen can leak into the passenger compartment under any circumstance. Because fuel cell stacks can develop internal leaks over time, they will likely be installed in their own enclosure, which will have both ventilation holes and a ventilation fan to force air through the enclosure to flush out any leaked hydrogen so that it can not collect.

One or more hydrogen sensors should be installed on the vehicle. The number and location of these sensors will depend on the hydrogen fuel and engine system design. These hydrogen sensor(s) should be connected to the vehicle control system to provide an alarm and automatic system shutdown if a hydrogen concentration greater than a preset threshold is detected. This threshold could be anywhere from 25 percent to 50 percent of the lower flammable limit for hydrogen (1–2 percent hydrogen concentration).

The fuel system may also have an excess flow valve installed that is designed to close off fuel flow and trigger an automatic system shutdown when flow in excess of a set threshold is detected. The threshold is set to be greater than the maximum flow that could be used by the fuel cell or hydrogen ICE at full power. Flows greater than this amount indicate that there is probably a leak in the system.

The vehicle may also have an inertial crash sensor installed that can automatically trigger a vehicle shutdown when a crash is detected. Some vehicles may include a switch to override automatic shutdown and allow the vehicle to continue to operate for a short time. This switch should only be used in case of extreme emergency, for example, to move the vehicle out of high-speed traffic or off of a railroad track.

The vehicle control system should be configured so that automatic system shutdown can be triggered by detection of leaked hydrogen, excess fuel flow, a vehicle crash, or other system fault. Automatic system shutdown should include closing valve(s) to isolate hydrogen in the hydrogen storage cylinders, disconnecting traction power, and de-energizing high voltage equipment. During system shutdown, hydrogen should be vented from all other fuel and engine system components.

The control system should include a single main on/off switch that allows the vehicle operator to shut down the fuel cell system, disconnect traction power, de-energize high voltage equipment, and shut off the hydrogen fuel supply (isolating all hydrogen in the liquid hydrogen cryotank(s)). This switch should be located in the passenger cab easily accessible to the operator, similar to a conventional ignition switch.

The vehicle control system should include an interlock to the vehicle fueling port such that fueling cannot begin unless the fuel cell system is shutdown and the vehicle traction system is de-energized so that the vehicle cannot move.

The onboard liquid hydrogen filling receptacle must be electrically bonded to the vehicle chassis, and some method must be provided to electrically connect the vehicle chassis to the fuel station ground during fueling. This can be done through the fueling nozzle (preferred) or with a separate ground strap.

A dust cap permanently mounted to the vehicle should be provided for the onboard fuel filling port, to keep out dirt and debris when the vehicle is not being fueled.

The vehicle fuel system should include fittings and other provisions necessary to safely remove hydrogen fuel from the liquid hydrogen cryotank(s) and purge them with nitrogen or helium as required for maintenance.

After system shutdown, hydrogen will typically be vented from the vehicle's low-pressure gaseous fuel system and fuel cell stack. The outlet for this venting hydrogen should be at or above the top surface of the vehicle. If, under normal operations, venting hydrogen will achieve concentrations greater than 25 percent of the lower flammable limit (1 percent hydrogen concentration), the hydrogen should vent through a hydrogen diffuser. The same hydrogen diffuser can be used for both this function and to diffuse hydrogen released through the fuel system pressure relief valve(s).

3.2.2 Operation and Maintenance

Anyone who will operate or maintain liquid hydrogen-fueled vehicles should receive hydrogen safety training. At a minimum, this training should cover the characteristics of hydrogen and liquid hydrogen, operation of onboard safety systems, liquid hydrogen fueling operations, and actions to take in an emergency.

During maintenance, never substitute fuel system replacement parts that have not been specifically tested and certified for use with liquid hydrogen. Lines that will carry liquid hydrogen must be well-insulated with the outer layer of insulation vapor sealed. O-rings or other seals used in connections between liquid hydrogen lines must be made of special materials that can withstand liquid hydrogen temperatures without breaking. Substituting seals made of different materials can result in liquid hydrogen leaks.

When working on the liquid hydrogen fuel system, always wear personal protective equipment, including safety glasses and a full face shield, loose fitting insulated or leather gloves, leather boots ankle height or higher, a long-sleeved shirt, and long pants without cuffs. Pant legs should be worn outside of the boots.

Never loosen any joint in the hydrogen fuel system while the connected components are under pressure (gaseous hydrogen lines) or contain liquid hydrogen. Never disturb the insulation on liquid hydrogen lines or cryotanks while they contain liquid hydrogen. Shut down the system, isolate and vent components as directed in the manufacturer's service manual. Torque all joints to the levels specified in the manufacturer's service manual. Do not over tighten. Overtorquing can cause leaks.

Air must never be allowed to enter the hydrogen fuel system. If exposed to the atmosphere, any component that will carry liquid hydrogen (including cryotanks and lines) must be purged with helium before being refilled with liquid hydrogen. Nitrogen must not be used because the residual nitrogen in the lines could liquefy and freeze when exposed to liquid hydrogen. This could potentially plug pressure relief valves and other system valves. Alternatively, components can be purged of air with nitrogen and the nitrogen can be purged with gaseous hydrogen before refilling with liquid hydrogen. See the manufacturer's service manual for specific purging procedures.

Periodically check all connections in the hydrogen fuel system for leaks using procedures outlined in the manufacturer's service manual. Tighten or repair all leaking joints, no matter how small the leak. Leak checks should also be conducted after repair or replacement of any fuel system lines or valves.

Periodically check the exterior surface of liquid hydrogen cryotanks and fuel lines for cuts or damage to the exterior insulation layer. All damage that breeches the vapor barrier must be repaired.

Periodically check and calibrate hydrogen sensors in accordance with the schedule and procedures in the manufacturer's service manual.

Periodically check operation of the fan in the hydrogen diffuser and any ventilation fans, in accordance with the schedule and procedures in the manufacturer's service manual.

Do not ignore warning lights or alarms. Do not attempt to override automatic system shutdown unless absolutely necessary (e.g., to move vehicle off railroad tracks).

Always make sure that the main switch is off before servicing the vehicle. Before working on the fuel cell system or liquid hydrogen storage system also disconnect the vehicle's 12/24-VDC battery.

Do not walk on liquid hydrogen cryotanks or expose them to damage from impact or abrasion.

Always electrically ground and bond the vehicle when fueling. Connect the ground strap or cable at the fuel station if one is provided.

Before fueling, check that the onboard fuel port is free of dirt and debris. Always replace the fuel port dust cover after fueling.

Do not smoke or use a cell phone when servicing or fueling the vehicle.

The manufacturer of the liquid hydrogen cryotank will specify a minimum ullage[13] space required in each tank. During fueling, this ullage space must be maintained and tanks should not be overfilled.

3.3 HIGH VOLTAGE SYSTEMS

Any voltage greater than 30 VAC or 60 VDC can harm humans through electric shock and is considered "hazardous voltage" (SAE, 2002).

Hydrogen fuel cells produce electricity at nominal voltages of 300 to 600 VDC, which is used to power an electric drive system that operates at similar voltages (often after conversion to alternating current). The drive system may be designed with a hybrid-electric configuration. If so, there will also be a high-voltage battery pack installed on the vehicle.

Hydrogen fueled ICEs do not produce electricity directly, but hydrogen ICE vehicles may also be designed with a hybrid-electric drive configuration. If so, they will also include a high-voltage battery pack and other high-voltage electrical components.

3.3.1 Design

All electrical cables that carry greater than 30 VAC or 60 VDC should be considered high-voltage cables and should be permanently identified with orange covering material, and be located to preclude casual contact by vehicle operators and maintenance personnel. No high voltage cables should be routed through the passenger compartment.

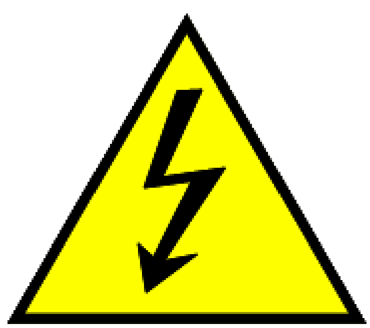

Figure 18. Hazardous Voltage Symbol

Any part or connector energized with high voltage during normal operations should be located behind a cover or in an enclosure labeled with the hazardous voltage symbol. See Figure 18. Removal of the cover should require removal of special fasteners and/or should trigger an

13 *Ullage space is the free vapor space available above the liquid level in a filled tank.*

interlock system that de-energizes the high-voltage components. If the cover or enclosure is made of conductive material, it should be grounded to the vehicle chassis.

The electrical system should include an automatic disconnect function that isolates both poles of any high-voltage source (fuel cell stack and/or high voltage battery pack) from other system components. The connectors used should be "fail safe" so that they will open if the control signal is lost due to a system fault. This automatic disconnect function should be triggered by the following:

- Turning off the main switch
- By automatic system shutdown (due to a hydrogen sensor detecting a leak, or other system fault that shuts off the hydrogen fuel supply)

All high-voltage components should be designed with adequate electrical isolation to prevent "current leakage" between them and other electrical components or the chassis. The vehicle control system should include a ground fault monitoring system that can detect leakage current and set a warning light and/or take other action (up to automatic system shutdown) when a current above a set threshold is detected.

3.3.2 Operation and Maintenance

When working on high-voltage systems, always ensure that the main switch is in the "off" position and tag it and/or lock it in that position so that no one else can turn the vehicle on.

Always assume that high-voltage electrical components are live, even when the vehicle main switch is in the off position. Use a volt meter to check before touching any electrical component.

Always use appropriate personal protective equipment, such as high-voltage gloves, when working on high-voltage systems. Follow the safety recommendations in the manufacturer's service manual.

Never wear jewelry when working around high-voltage systems.

Always reinstall high-voltage covers and barriers. Reapply high-voltage labels if they are removed or damaged.

Do not ignore warnings from the ground fault monitoring system. Follow instructions in the service manual to isolate and repair the source of the fault. Unrepaired ground faults can cause shocks or electrocution to vehicle occupants or service technicians.

High-voltage electrical cables are designed with special shielding and insulation, and the exterior cover should be made from orange colored material. Always replace high-voltage wiring and harnesses with parts as specified by the manufacturer. Do not manufacture your own high-voltage harnesses or substitute non-approved parts.

Remember that high voltage will always be present inside a traction battery or ultracapacitor pack (if vehicle has a hybrid-electric drive system) even when the main switch is off or automatic shutdown has occurred. Special tools and procedures are required to work safely inside the battery/ultracapacitor pack. Do not open the battery/ultracapacitor pack cover unless you have been trained to work safely with live high voltage.

3.4 LIQUID FUEL REFORMERS

A fuel reformer produces a hydrogen-rich gas onboard the vehicle from a liquid fuel, such as diesel fuel, gasoline, or methanol. This gas, called reformate, is 45–75 percent hydrogen and is used to feed a hydrogen fuel cell. See Section 1.4, Reforming of Liquid Fuels. The use of a fuel reformer eliminates the need to carry gaseous or liquid hydrogen on the vehicle since the fuel for the fuel cell is created on demand in the reformer. When the system is shut down, any residual reformate in the reformer and fuel cell stacks is usually vented, and there is virtually no hydrogen gas present on the vehicle.

3.4.1 Design

The exterior of the vehicle should be marked with diamond-shaped labels that say “Hydrogen” in white letters on a blue background (see Figure 16). For commercial vehicles, one label should be located on the rear of the power unit and one label should be located on each side of the power unit cab, below the DOT numbers. The hydrogen labels should be legible from fifty feet in daylight.

The working fluids inside a fuel reformer can be anywhere from 200–1500 °F while it is operating. All of the hot components should be packaged together and shielded to preclude casual contact by vehicle operators or maintenance personnel. These components should also be packaged on the vehicle to minimize the possibility that reformate leaking from the fuel cell stack will be able to contact any hot surfaces and ignite.

The control system should include a single main switch that allows the vehicle operator to shut down the fuel cell system, disconnect traction or APU power, de-energize all high voltage equipment, and remove power from the reformer’s liquid fuel pump. This switch should be located in the passenger cab easily accessible to the operator, similar to a conventional ignition switch or APU on/off switch.

A fuel cell vehicle with an onboard liquid fuel reformer has significantly less free hydrogen onboard than a fuel cell vehicle that carries compressed hydrogen gas or liquid hydrogen onboard. The reformate produced by fuel processors used with PEM fuel cells will contain hydrogen, carbon dioxide, nitrogen, and water. For SOFC APUs, the reformate produced by the fuel processor may also contain up to 30 percent carbon monoxide. Therefore, it is advisable to include one or more hydrogen sensors when a PEM fuel cell is used, or combustible gas sensors that can detect both hydrogen and carbon monoxide when an SOFC is being used, on the vehicle to detect leaks of reformate from the fuel cell stack while it is operating. These sensor(s) should be connected to the vehicle control system to provide an alarm and automatic system shutdown if a hydrogen or carbon monoxide concentration greater than a preset threshold is detected. Automatic system shutdown should include de-energizing the liquid fuel pump to shut off the flow of liquid fuel to the fuel reformer. During system shutdown, reformate should be vented from the reformer and fuel cell stack.

3.4.2 Operation and Maintenance

Anyone who will operate or maintain vehicles with liquid fuel reformers should receive hydrogen safety training. At a minimum, this training should cover the characteristics of hydrogen, operation of onboard safety systems, and actions to take in an emergency.

Always assume that any fluid leaking from a fuel reformer is hot enough to cause injury.

In general, most fuel reformer/processors will be designed to be "line replaceable units" and the vehicle operator or mechanic will have no reason to open up the "hot box." Defective units will be removed from the vehicle and sent to the manufacturer for trouble-shooting and repair of internal components. If you have reason to open up a fuel processor enclosure, allow time after system shutdown for the internal components and the working fluids to cool down. In some cases, these components may stay hot for hours or days. See the manufacturer's service manual for working temperatures and cool down periods.

Periodically check any external connections from the fuel reformer to other vehicle systems (i.e., fuel line) for signs of leaks using the procedures outlined in the manufacturer's service manual. Tighten or repair all leaking joints, no matter how small the leak.

Periodically check electrical connections from the fuel processor/SOFC APU to other vehicle systems for signs of corrosion or electrical arcing.

The fuel processor may have air and/or fuel filters, as well as fuel desulfurization traps, that must be replaced periodically. See the manufacturer's service manual for replacement intervals and procedures.

3.5 HYDROGEN INJECTION SYSTEMS

Hydrogen injection systems create small amounts of hydrogen and oxygen through electrolysis, to supplement the diesel fuel in a standard diesel engine. See Sections 1.2.3 and 1.5.

A hydrogen injection system for a diesel engine produces and uses significantly less hydrogen than a hydrogen fuel cell or hydrogen ICE, and does not require that compressed or liquid hydrogen be carried on the vehicle. The system is designed to produce hydrogen only when required, in response to driver throttle commands. When the system is shut off, no hydrogen should be present on the vehicle.

3.5.1 Design

The exterior of the vehicle should be marked with diamond-shaped labels that say "Hydrogen" in white letters on a blue background (see Figure 16). For commercial vehicles, one label should be located on the rear of the power unit and one label should be located on each side of the power unit cab, below the DOT numbers. The hydrogen labels should be legible from fifty feet in daylight.

The electrolyzer used to create hydrogen and oxygen should include an automatic disconnect function that isolates both poles of its power source (engine alternator or 12/24-VDC battery).

The connectors used should "fail safely" so that they will open if the control signal is lost due to a system fault. This automatic disconnect function should be triggered both by turning off the vehicle's ignition switch and by any electrolyzer system fault.

All hydrogen and oxygen lines from the electrolyzer to the engine air intake should be securely mounted to the vehicle and routed away from heat sources. These lines should not be routed through the passenger compartment or in any area that would allow hydrogen or oxygen to leak into the passenger compartment under any circumstance.

The hydrogen lines from the electrolyzer to the engine's air intake should be constructed of materials that have been tested to be compatible with hydrogen and not subject to hydrogen embrittlement.

The electrolyzer and the hydrogen and oxygen lines from the electrolyzer to the engine's air intake should be electrically grounded and bonded to the vehicle chassis to preclude the buildup of static electricity.

Any compartment into which hydrogen could leak from the hydrogen lines should be ventilated such that hydrogen cannot collect in concentrations greater than 25 percent of hydrogen's lower flammable limit.

3.5.2 Operation and Maintenance

Anyone who will operate or maintain vehicles with hydrogen injection systems should receive hydrogen safety training. At a minimum, this training should cover the characteristics of hydrogen, operation of onboard safety systems, and actions to take in an emergency.

During maintenance, never substitute for the hydrogen lines replacement parts that have not been specifically tested and certified for use with hydrogen (for example lines, valves, and regulators designed for use with natural gas). While they may look and function the same, they may be subject to hydrogen embrittlement.

Periodically check all connections from the electrolyzer to the engine's air intake for leaks, using procedures outlined in the manufacturer's service manual. Tighten or repair all leaking joints, no matter how small the leak.

Never loosen any joint in the hydrogen injection system while the system is operating. Before servicing, turn off the ignition and wait for the hydrogen injection system to vent, as directed in the manufacturer's service manual. Torque all joints to the levels specified in the manufacturer's service manual. Do not over tighten. Overtorquing can cause leaks.

4. GUIDELINES FOR DESIGN AND OPERATION OF HYDROGEN FUELING FACILITIES

Safe fueling of hydrogen vehicles requires that hydrogen fueling facilities be designed and operated with the physical and chemical properties of hydrogen in mind. These properties are discussed in chapter 2. In addition to the general safety principles that apply to all fuel stations, there are some hydrogen-specific design elements and safety procedures that are required at hydrogen fuel stations.

This chapter briefly discusses the most important aspects of hydrogen fuel station design and operation, with an emphasis on safety. The issues discussed are of necessity generalized, and are based on current codes and standards and best practices. Each fuel station manufacturer and operator will develop its own specific designs and operating procedures, which are likely to vary significantly in their details, while adhering to the same over-all safety principles.

The information in this chapter is intended to familiarize commercial vehicle operators with the general safety aspects of hydrogen fueling. Vehicle operators should always follow specific instructions issued by each hydrogen fueling station they use.

4.1 COMPRESSED HYDROGEN FUELING

A compressed hydrogen fuel dispenser is very similar to a compressed natural gas fuel dispenser, and the entire fuel station is often also very similar. Both will include a high-pressure compressor station to raise the pressure of the gas (hydrogen or natural gas) to fuel the vehicles. The major difference between a natural gas and hydrogen station is the source of the gas that will be compressed. Natural gas fuel stations are supplied with gas from a utility pipeline. Some hydrogen pipelines do exist in this country, but they are not widely available in most cities.

Sometimes hydrogen is trucked to a fueling site from a hydrogen production facility in a tube trailer that stores the hydrogen at high pressure, and vehicles are fueled directly from these tubes (see Figure 19).

Figure 19. Hydrogen Tube Trailer

Photo courtesy of Sunline Transit.

Hydrogen can also be trucked to the fuel station and stored on-site as liquid hydrogen. If so, the fuel station will have a large liquid hydrogen cryotank and a vaporizer. A vaporizer is a large heat exchanger that is used to boil off the liquid hydrogen and raise the temperature of the resulting hydrogen gas. After it is vaporized, the hydrogen gas is then compressed into high-pressure tanks for delivery to vehicles (see Figure 20).

Figure 20. Liquid Hydrogen Storage Tank and Vaporizer

Photo courtesy of Santa Clara Valley Transportation Authority.

Hydrogen can also be produced on-site at the fueling station by electrolyzing water, by reforming natural gas, or both (see Sections 1.4 and 1.5). If the hydrogen is produced by reforming natural gas, the natural gas will be supplied by a utility pipeline. The reformer used will be similar to onboard fuel reformers as described in Section 1.4, but will be much larger and will include an additional processing step to separate the hydrogen from the other components of the reformate (carbon dioxide and nitrogen). See Figure 21.

Figure 21. Natural Gas Reformer

Photo courtesy of Sunline Transit.

Hydrogen dispensers look very much like gasoline or diesel dispensers, but the fueling nozzle is different (see Figure 22). The high-pressure fueling nozzle used with hydrogen is similar to those used with natural gas. A female coupling on the fueling nozzle mates with a male coupling on the vehicle, and the attendant turns a lever to lock the two together. Fueling can then begin (see Figure 23). The nozzle is likely to also include an electrical connection to establish communication between the fuel station controller and the vehicle system controller, as well as a bonding path to bond the vehicle to the fuel station so that static electricity cannot build up and cause a spark while fueling.

Figure 22. Compressed Hydrogen Dispenser

Photo courtesy of Santa Clara Valley Transportation Authority.

Figure 23. Compressed Hydrogen Fuel Nozzle
Photo courtesy of Santa Clara Valley Transportation Authority.

4.1.1 Design

It is generally recommended that all components of a hydrogen fuel station be located outdoors in open air. The facility should not be located under overhead wires, roadways, or overhanging buildings. If the fueling dispenser is located within a building, it must be a separate building with no uses other than for vehicle fueling and must be equipped with adequate ventilation and safety systems. See chapter 5 for design requirements for buildings that will house hydrogen fueling operations.

If the fueling dispenser is covered by a rain canopy, it must be designed so that any hydrogen that leaks from the dispenser or vehicle being fueled cannot collect under the canopy. See Figure 24, which shows upwardly sloping canopies with smooth undersides over hydrogen fuel dispensers so that hydrogen cannot collect.

Figure 24. Hydrogen Fueling Station
Photo courtesy of Alameda Contra-Costa Transit District.

All components of the fuel station should be protected from damage by vehicles.

Public access to all components except the fuel dispensers should be restricted.

The minimum distance from any hydrogen equipment to other buildings or public roadways should be ten feet (NFPA, 2005).

The hydrogen fuel dispenser should be designed with a "breakaway" device that shuts off fuel flow in case a vehicle moves away with the hose connected. A one-quarter turn manual isolation valve should be installed just upstream of the breakaway connection.

All electrical equipment at the fuel station that might be exposed to hydrogen must be designed so that it cannot produce a spark. This is often done by sealing all openings in the equipment.

All electrical equipment and any equipment that will hold or carry hydrogen, including the dispenser and fueling hose, must be electrically grounded and bonded to the facility. The vehicle being fueled must also be bonded to the facility. This can be done through the fueling nozzle connection or with a separate ground strap.

If heat is provided at the fuel station, it must be provided using forced hot air, steam, or hot water. Open flame heaters should never be used.

Fueling will likely be automated. Once the nozzle is locked securely in place, fueling will start and will automatically stop when the maximum rated fuel pressure is reached on the vehicle (i.e., 5,000 psig). Fuel should not flow unless a positive connection is made between the fuel nozzle and the receptacle on the vehicle. Fuel systems automatically adjust for temperature to ensure a full fill. Fueling in hot weather may result in a final pressure above the rated pressure; fueling in cold weather may result in a lower final pressure. The system should also be designed so that filling will not start when the pressure in the vehicle fuel tanks is less than atmosphere pressure (15 psia). Pressures lower than atmospheric indicate that air might have entered the tank, which could cause a significant fire and explosion hazard. The system should also be designed to automatically shut down if any fuel station fault is detected. Automatic shutdown should interrupt all electrical power to the fuel station equipment, including the compressors.

The fuel station may include provisions for defueling a vehicle through the fueling nozzle or through a separate hose connection to the vehicle fueling port. Hydrogen leaving a vehicle during defueling may be routed to the suction side of the hydrogen compressor or may be vented to open air. If hydrogen is vented, the vent outlet should be higher than any surrounding buildings or structures and should include a hydrogen diffuser or flame arrestor.

Any high-pressure hydrogen storage tank at the fuel station must be equipped with a PRD/TRD. The outlets from each PRD/TRD should be connected to a common vent stack. The top of the vent stack should be higher than surrounding buildings.

If the hydrogen fuel station stores liquid hydrogen on-site, the liquid hydrogen cryotank must be equipped with a pressure relief valve. Any liquid hydrogen line that could be isolated between two closed valves with liquid hydrogen inside must also be equipped with a pressure relief valve. The outlets from these pressure relief valves should be connected to a common vent stack. The top of the vent stack should be higher than any surrounding buildings and should be equipped with a hydrogen diffuser or flame arrestor.

The fueling facility should include well-marked emergency stop buttons at each fuel dispenser and at each exit from the fueling area. Pushing an emergency stop button should interrupt all non-essential electrical power to the fuel station equipment.

The station should include one or more hydrogen sensors and one or more ultraviolet flame sensors located to sense hydrogen leaks or flames in the vicinity of the fuel dispenser(s). These should be linked to the fuel station's automatic shutdown system so that all electrical power to station equipment will be interrupted if a flame is detected or if hydrogen levels greater than 25 percent of the lower flammable limit are detected.

Dry powder fire extinguishers should be located at the fuel station.

Signs in place at the fuel station should include, at a minimum:

- No smoking.
- No cell phones.
- Before fueling, vehicle ignition must be off, and vehicle must be grounded and bonded.
- Hydrogen gas is odorless.
- Location of emergency stop buttons.
- Location of manual shut-off valves.
- Location of fire extinguishers.

4.1.2 Operation and Maintenance

Anyone who will operate a compressed hydrogen fueling station should receive training on fueling operations and hydrogen safety. At a minimum, this training should cover the characteristics of hydrogen, fueling procedures, operation of fuel station safety systems, and actions to take in an emergency.

Smoking and the use of cell phones should never be allowed at the hydrogen fueling station. Other activities that could cause a spark or flame, such as welding and cutting or using jumper cables, should never be allowed at the hydrogen fueling station. Vehicle maintenance should not be done at the hydrogen fuel station.

Before fueling a vehicle, turn off the ignition, set the parking brake, and electrically ground/bond the vehicle to the fuel station. Grounding/bonding may be done automatically through the fuel nozzle connection, but do not assume that it will. Check for a separate ground bond strap at the fuel dispenser and, if provided, follow instructions for its use.

Do not fuel a vehicle with a known hydrogen fuel leak.

When working on or around the hydrogen fuel station, use only nonsparking tools.

The hydrogen sensors, flame sensors, and other emergency equipment at the fuel station should be maintained, calibrated, and checked at least annually in accordance with the manufacturer's instructions (NFPA, 2005).

4.2 LIQUID HYDROGEN FUELING

If liquid hydrogen is carried on your vehicle, it must be fueled at a liquid hydrogen fuel station. The station will include one or more large liquid hydrogen cryotanks, and one or more dispensers with a liquid hydrogen fueling nozzle. Compressors and pumps are not used with liquid hydrogen. To get liquid hydrogen to flow from the cryotank, heat is added to the tank via a small heater. As the heat is absorbed, some liquid hydrogen vaporizes, raising the pressure in the tank, which pushes out liquid hydrogen. See Figure 25 for a photo of a liquid hydrogen storage tank and dispenser.

The fuel nozzles used with liquid hydrogen look something like compressed hydrogen nozzles, but are more complicated (see Figure 26). A male coupling on the fueling nozzle mates with a female coupling on the vehicle, and the attendant turns a lever to lock the two together. Fueling can then begin.

Figure 25. Liquid Hydrogen Storage Station

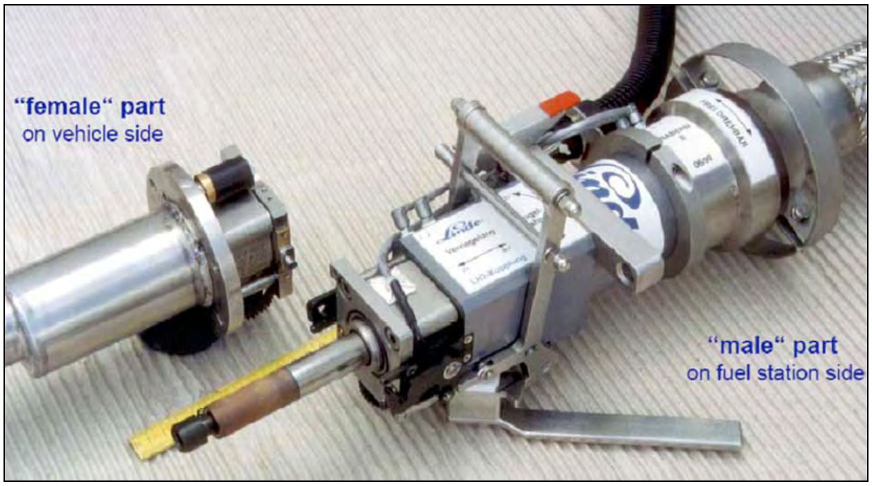

Figure 26. Liquid Hydrogen Fueling Nozzle and Vehicle Fuel Port

Photo courtesy of Air Products and Chemicals.

4.2.1 Design

All components of a liquid hydrogen fuel station should be located outdoors in open air. The facility should not be located under overhead wires, roadways, or overhanging buildings. Applicable codes prohibit liquid hydrogen cryotanks larger than 600 gallons and any liquid hydrogen fueling dispenser from being located inside a building (NFPA, 2005). These codes also specify minimum set-back distances between liquid hydrogen storage tanks and any occupied buildings or public roadways. These distances range from ten to seventy five feet, depending on the size of the liquid hydrogen storage tank(s). Any liquid hydrogen transfer point (i.e., liquid hydrogen dispenser) must be located at least twenty-five feet from the nearest building.

If the fueling dispenser is covered by a rain canopy, it must be designed so that any liquid hydrogen that leaks from the dispenser or vehicle being fueled cannot collect under the canopy as it vaporizes and rises. See Figure 24, which shows upwardly sloping canopies with smooth undersides over hydrogen fuel dispensers so that hydrogen gas cannot collect.

All components of the fuel station should be protected from damage by vehicles. The liquid hydrogen cryotanks and all facility piping other than the fueling hose should be located behind a barrier that will deflect any leaking liquid hydrogen away from personnel fueling vehicles.

Public access to all components except the fuel dispensers should be restricted.

All site drains and entrances to cellars and other underground facilities must be located far enough from the liquid hydrogen fuel station so that any leaked or spilled liquid hydrogen will vaporize before reaching the drain or opening. Depressions or dikes should be considered around the liquid hydrogen cryotank(s), as well as the dispensers to limit the spread of any spill. Liquid hydrogen that enters an underground space will create a significant fire and explosion hazard as it vaporizes.

All components of the fuel station that will carry liquid hydrogen should be well-insulated with the exterior surface of the insulation vapor sealed. They should be protected from casual contact with station personnel and vehicle operators.

The liquid hydrogen storage tanks, lines, and dispensers should be mounted on a concrete pad. They should not be located over asphalt or any other combustible material. Leaking liquid hydrogen can condense (liquefy) surrounding air. Liquefied air is oxygen enhanced and will create a severe fire hazard if it drips onto combustible material.

The hydrogen fuel dispenser should be designed with a “breakaway” device that will shut off liquid hydrogen flow in case a vehicle drives away with the hose connected. A manual, one-quarter turn isolation valve should be installed just upstream of the breakaway connection.

All electrical equipment at the fuel station that might be exposed to hydrogen must be designed so that it cannot produce a spark. This is often done by sealing all openings in the equipment.

All electrical equipment and any equipment that will hold or carry liquid hydrogen, including the dispenser and fueling hose, must be electrically grounded and bonded to the facility. The vehicle being fueled must also be grounded and bonded to the facility. This can be done through the fueling nozzle connection or with a separate ground strap.

If heat is provided at the fuel station, it must be provided using forced hot air, steam, or hot water. Open flame heaters should never be used.

The liquid hydrogen cryotank(s) must be equipped with manual shut-off valves and electrically or pneumatically activated automatic shut-off valves. These valve(s) should “fail safely” so that they will close if the control signal is lost due to a system fault.

The system should be designed to automatically shut down if any fuel station fault is detected. Automatic shutdown should interrupt all electrical power to the fuel station equipment and close the automatic shut-off valves at the liquid hydrogen storage tanks.

The fueling facility should include well-marked emergency stop buttons within ten feet of each fuel dispenser and at each exit from the fueling area. Pushing an emergency stop button should interrupt all non-essential electrical power to the fuel station equipment and close the automatic shut-off valves at the liquid hydrogen storage tanks.

The station should include one or more hydrogen sensors and one or more ultraviolet flame sensors located to sense hydrogen leaks or flames in the vicinity of the fuel dispenser(s). These should be linked to the fuel station’s automatic shutdown system so that all non-essential electrical power to station equipment will be interrupted, and the automatic shut-off valves at the liquid hydrogen storage tanks will be closed if a flame is detected or if hydrogen levels greater than 25 percent of the lower flammable limit are detected.

The liquid hydrogen cryotank(s) must be equipped with pressure relief valves. Any liquid hydrogen line that could be isolated between two closed valves with liquid hydrogen inside must also be equipped with a pressure relief valve. The outlets from these pressure relief valves should be connected to a common vent stack. The top of the vent stack should be higher than any surrounding buildings and should be equipped with a hydrogen diffuser or flame arrestor.

A high-pressure air, nitrogen, or helium supply should be located at the liquid hydrogen fuel dispenser to clean ice and frost from the fueling nozzle as required.

The fueling nozzles should be designed so that fuel can not flow until there is a positive lock between the nozzle and the fuel port on the vehicle. They should also have a self-closing end or an automatic shutdown device that will close off the flow of liquid hydrogen if the nozzle is disconnected from the vehicle.

Dry-powder fire extinguishers should be located at the fuel station.

Signs in place at the fuel station should include, at a minimum:

- NO Smoking.
- No cell phones.
- Before fueling, vehicle ignition must be off and vehicle must be grounded.
- Hydrogen gas does not have a distinct odor.
- Location of emergency stop buttons.
- Location of manual shut-off valves.
- Location of fire extinguishers.

4.2.2 Operation and Maintenance

Anyone who will operate a liquid hydrogen fueling station should receive training on fueling operations and hydrogen safety. At a minimum, this training should cover the characteristics of gaseous and liquid hydrogen, fueling procedures, operation of fuel station safety systems, and actions to take in an emergency.

Smoking and the use of cell phones should never be allowed at the liquid hydrogen fueling station. Other activities that could cause a spark or flame, such as welding and cutting or using jumper cables, should never be allowed at the hydrogen fueling station. Vehicle maintenance should not be done at the hydrogen fuel station.

Before fueling a vehicle, turn off the ignition, set the parking brake, and electrically ground and bond the vehicle to the fuel station. Grounding and bonding may be done automatically through the fuel nozzle connection, but do not assume that it will. Check for a separate ground and bond strap at the fuel dispenser and, if provided, follow instructions for its use.

Because of the extremely low temperature of liquid hydrogen, spills can cause serious frostbite to exposed skin. Fueling attendants who connect and disconnect the liquid hydrogen nozzle from the vehicle should wear safety glasses and a full face shield, loose fitting insulated or leather gloves, leather boots ankle height or higher, a long-sleeved shirt, and long pants without cuffs. Pant legs should be worn outside of the boots.

In the past, some fueling couplings used with liquid hydrogen required heating and rinsing to separate the two parts and to disconnect them from the vehicle after fueling. Newer designs have improved the safety and speed of fueling operations through the use of a special coaxial "cold withdrawal coupling." This allows the operator to disconnect immediately from the vehicle after refueling has stopped and to refuel rapidly multiple vehicles without waiting for the coupling to warm up in between. Nonetheless, ice and frost may occasionally form on the nozzle. Before connecting to the vehicle, the attendant should check the mating surfaces on both the dispenser nozzle and the vehicle fuel receptacle to ensure they are free of solid particles. If necessary, the attendant can use the high-pressure air, nitrogen, or helium at the dispenser to remove ice and frost from the nozzle before connecting.

Do not fuel a vehicle with a known hydrogen fuel leak.

When working on or around the liquid hydrogen fuel station, use only nonsparking tools.

The hydrogen sensors, flame sensors, and other emergency equipment at the fuel station, should be maintained, calibrated, and checked at least every six months, in accordance with the manufacturer's instructions (NFPA, 2005).

5. GUIDELINES FOR DESIGN AND OPERATION OF VEHICLE MAINTENANCE FACILITIES

Indoor facilities that will be used to store or maintain hydrogen-fueled vehicles must be designed and operated with the physical and chemical properties of hydrogen in mind. These properties are discussed in chapter 2. Building design principles generally used to accommodate hydrogen are similar to those used to accommodate other gaseous fuels such as natural gas, but they differ significantly from design principles generally used when only diesel fuel must be accommodated inside the facility.

This chapter briefly discusses the most important aspects of building design and operation to accommodate hydrogen use. The information in this chapter is intended to familiarize commercial vehicle operators with the general safety aspects of using hydrogen vehicles inside buildings. Building designers and owners must always follow the specific requirements of current local building codes and directives of public safety officials.

The issues discussed here are, out of necessity, generalized and are based on current codes and standards and best practices. Given that there are so few hydrogen vehicles on the road, these codes and practices are not well-developed at this time. In the past, facilities designed for experimental hydrogen vehicles have been designed with elaborate safety systems that were costly to implement.

A recent facility design study commissioned by the California Fuel Cell Partnership recommended that no changes were required to current standard design practices to accommodate hydrogen vehicles when building public parking structures, private garages, or vehicle maintenance shops (Parsons Brinckerhoff, 2004). The analysis showed that the leak scenarios investigated would not result in a flammable mixture of hydrogen inside any of these facility types. The recommendations of this study have not been universally adopted, and local officials may impose more stringent requirements that do require modifications to these types of facilities to accommodate hydrogen vehicles.

In addition, this study looked only at small vehicles (5-passenger sedans) carrying relatively small amounts of hydrogen onboard (13 lbs.), limited the analysis to a single vehicle at a time inside any facility, and specifically excluded consideration of what would happen if a PRD/TRD released while the vehicle was inside.

Commercial fleet vehicles are likely to carry significantly more hydrogen onboard and to have more vehicles concentrated at a single facility. It is also probably not prudent to rule out completely the possibility of a PRD/TRD release inside a maintenance facility for commercial vehicles. Based on experience with natural gas vehicles, the most likely time for a PRD/TRD release is during or shortly after fueling, due to an increase in internal tank temperatures during fueling. However, a PRD/TRD release during maintenance could never be ruled out unless the vehicle's hydrogen tanks were emptied[14] before bringing the vehicle inside the maintenance bay.

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14 *See Section 3.1.2 for a discussion of hydrogen tank defueling, including requirements for subsequent purging with nitrogen before refilling.*

The discussion below takes into account the larger quantities of hydrogen that will typically be carried on hydrogen-fueled commercial vehicles compared to passenger vehicles and specifically addresses the possibility of a PRD/TRD release inside a facility. The discussion applies to indoor hydrogen fueling facilities and buildings that will be used for overnight or long-term storage or for maintenance of vehicles that carry compressed or liquid hydrogen onboard. Fuel cell vehicles that use an onboard liquid fuel reformer or diesel vehicles with a hydrogen injection system can be stored and maintained in any facility since they do not have any hydrogen onboard when the reformer or injection system is not operating.

The below design guidelines are based on the following major principles:

- Detect hydrogen leaks as soon as possible by providing a leak detection system inside the building,
- Remove ignition sources from areas of the building where leaked hydrogen might accumulate,
- Properly ventilate all enclosed spaces where leaked hydrogen might accumulate in the building, and
- Provide warning to building employees and activate automatic safety systems in the event of a leak. These automatic safety systems may include rolling up bay doors automatically, increasing ventilation, and shutting down non-essential power systems and equipment (see Section 2.4).

5.1 DESIGN

All facilities should have positive ventilation. Ventilation inlets should be at floor level and outlets should be at ceiling level. Typically at least five air changes per hour should be provided in maintenance facilities, while vehicle storage areas can have lower rates (local codes may vary).

Facilities should have one or more hydrogen detectors located at ceiling level in the areas where vehicles will be fueled, maintained, or stored (see Figure 27).

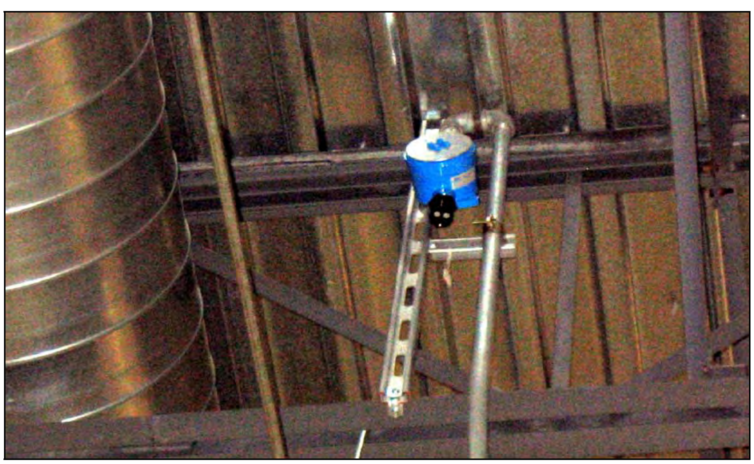

Figure 27. Hydrogen Detector Located at Ceiling Level
Photo courtesy of California Fuel Cell Partnership.

These hydrogen detectors should be linked to an alarm system that will provide two levels of automatic alarm and action:

Level 1 (typically when hydrogen is detected at 25 percent of lower flammable limit):

- Shut off all hydrogen gas supplies (for fueling areas).
- Sound an audible alarm heard in the area of the detector.
- Flash red light(s) in the area of the detector.
- Open maintenance bay doors.
- Increase building ventilation rate to at least double the base rate.

Level 2 (typically when hydrogen is detected at 50 percent of lower flammable limit):

- Sound the fire alarm for building evacuation.
- Automatically notify emergency or safety coordinator for the facility.
- Disconnect all electrical power other than for alarms and ventilation fans.

The structural system for the building's roof/ceiling should not create pockets where leaked hydrogen gas can collect without being swept by the ventilation system.

Electrical equipment, including lights, conduit, and wiring should not be located within eighteen inches of the ceiling. If equipment must be located in this zone (e.g., hydrogen detectors and ventilation fans), it must be sealed so that it is "explosion proof" (see Figure 28).

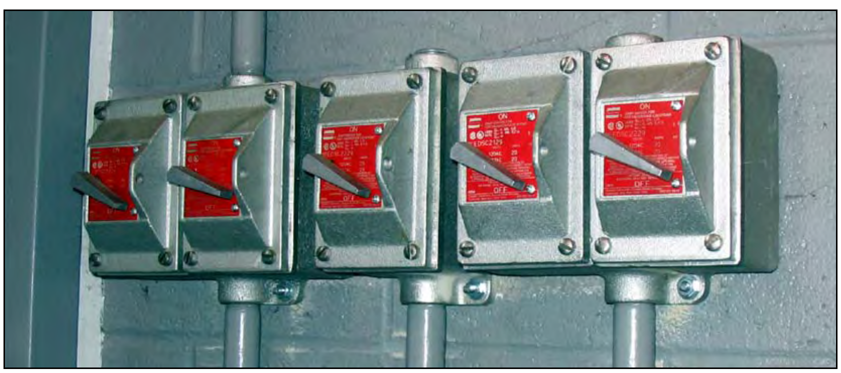

Figure 28. Explosion Proof Switches

Photo courtesy of Santa Clara Valley Transportation Authority.

Building heating should be provided by forced hot air, hot water, steam, or other indirect methods. Air intakes should be properly located to avoid the intake of ventilated gas. Open flame heaters should not be located in the building.

The building fire alarm system should include UV detectors to detect a hydrogen flame.

If vehicles that store liquid hydrogen onboard will be maintained or stored in the facility, each maintenance bay or parking location should have a dedicated vent that can cover the outlet from a vehicle's pressure relief valves. These vents should be manifolded to a building stack vent. The top of the building stack should be higher than surrounding buildings and should vent into an open area with no overhanging wires or structures. The building stack should be equipped with a diffuser/flame arrester.

5.2 OPERATION AND MAINTENANCE

Never bring a vehicle with a known hydrogen fuel leak into any building.

Check and calibrate hydrogen sensors and UV flame sensors in accordance with the manufacturer's service schedule.

Regularly check the operation of the building's hydrogen alarm system to ensure that the system automatically triggers the correct actions at each level of alarm.

Train all employees on hydrogen safety in accordance with the Facility Safety Plan, and conduct regular fire/hydrogen alarm drills.

PEM fuel cell engines and SOFC APUs that include a fuel reformer and which operate on liquid hydrocarbon fuels (i.e., methanol or diesel fuel) will emit carbon dioxide in their exhaust. The volume of exhaust and the amount of carbon dioxide emitted will be significantly less than the amount produced by a commercial vehicle's main diesel engine while idling. Nonetheless, these devices should not be operated inside a closed building unless the exhaust outlet is connected to a system that vents the exhaust to the outside of the building. Carbon dioxide emitted into a poorly ventilated space can displace oxygen and result in asphyxiation.

5.3 FACILITY SAFETY PLAN

For each building that will maintain or house hydrogen-fueled vehicles, the organization should develop a written Facility Safety Plan. This plan should include, at a minimum:

- Schedule and procedures for calibration of the hydrogen detection/alarm system
- Schedule and procedures for conducting a test of the hydrogen detection/alarm system
- Schedule and procedures for conducting fire/hydrogen alarm drills for all building employees, and re-training whenever new equipment or new hazards are present
- Instructions for what each employee should do in the event of a hydrogen alarm at each level of detection.
- Rules regarding employee conduct, for example:
  - No smoking in the facility
  - Only specially trained employees should work on hydrogen fuel systems
  - No vehicles with known fuel leaks should be brought into the building unless defueled

- Maintenance practices related to hydrogen systems, for example:
  - Vehicles should be defueled before bringing them into the building for work on the hydrogen fuel system
  - Procedures to protect hydrogen components during welding and cutting
  - Vehicles with onboard liquid hydrogen should have pressure relief valves connected to the building vent at all times when in the building
- Schedule and curriculum of hydrogen safety training for new employees and ongoing refresher training for existing employees. Provide training or re-training whenever a new hazard or new equipment posing a new hazard is introduced.

All facility employees should be given initial and refresher training on hydrogen safety. Topics should include at a minimum:

- General overview of hydrogen properties
- Description of hydrogen detection/alarm system
- Actions to take in the event of a hydrogen alarm

6. EMERGENCY RESPONSE FOR PERSONNEL ASSIGNED TO VEHICLES CARRYING HYDROGEN

As discussed in chapter 2, hydrogen has significantly different physical and chemical properties from other motor fuels, such as diesel fuel and gasoline. Based on these characteristics, the response to an incident with a hydrogen-fueled vehicle or at a hydrogen fuel station will be different from the response to incidents involving other fuels. This chapter briefly describes issues relevant for response to hydrogen vehicle and fuel station incidents.

6.1 RESPONDING TO AN INCIDENT

The vehicle operator may receive a visual and audible indication of a leak from the onboard hydrogen gas detection system, or he or she may smell or see smoke, indicating a potential fire.

If the operator suspects a hydrogen gas leak or a fire of any kind, the operator should, if possible, stop the vehicle in a safe place away from potential ignition sources, such as elevated train tracks, and away from any overpasses where leaking gas might collect. The operator should shut off the vehicle and evacuate all passengers before calling for assistance.

In response to an on-road incident with a hydrogen-fueled vehicle or at a hydrogen fueling station, always maneuver responding vehicles and keep personnel upwind of the incident. Any leaking hydrogen gas may be moved by the wind, especially if the vehicle or fuel station is carrying or storing liquid hydrogen.

Commercial vehicles carrying hydrogen fuel can be identified by a blue diamond label on the rear and on either side of the power unit cab that will say either “Hydrogen,” “Compressed Hydrogen,” or “Liquid Hydrogen” (see Figure 16). Commercial trailers carrying hydrogen fuel (for example, to power a transportation refrigeration unit) should also be labeled with the blue diamond label on the rear and on either side in the vicinity of the hydrogen storage tanks.

Look for signs of a hydrogen leak or fire. A large high-pressure hydrogen gas leak will likely produce a whistling sound, while leaking liquid hydrogen will likely be accompanied by an area of fog in the surrounding air and frost on equipment and lines in the vicinity of the leak.

A hydrogen fire has a virtually invisible flame in daylight, but the heat given off may create a shimmer in surrounding air due to changes in air density or may ignite other nearby materials that will have a visible, smoky flame. A UV optical sensor, if available, can be used to search for signs of a hydrogen fire.

Locate the vehicle’s PRD/TRD venting location (for compressed hydrogen) or the pressure relief valve venting location (for liquid hydrogen). These should be at vehicle roof level. Also locate the hydrogen storage tanks. These may be between the frame rails of the vehicle, in an enclosure behind the vehicle cab, or on the roof of the vehicle under a cowling. The hydrogen storage tanks and PRD/TRD location are the most likely locations for a hydrogen leak or fire.

If one must approach the vehicle, do so perpendicular to the hydrogen tanks, not directly in front of the ends of the tanks. If a compressed hydrogen cylinder was to fail, it would fail at the dome ends. If there is any question that there might be an undetected hydrogen fire, one can approach the vehicle with a corn straw broom extended and moving slowly back and forth. Any hydrogen fire will ignite the broom's bristles.

If safe to do so, shut down the vehicle by turning the ignition key. In all cases, this should close valves that will isolate the hydrogen in the storage tanks, shutting off the flow of hydrogen to any leaks in the fuel cell engine or hydrogen supply lines. Commercial vehicles may also have an emergency shutdown switch in the driver's compartment and/or a battery disconnect switch accessible through a marked compartment door on the side of the vehicle. If so, turning either of these switches off should also isolate hydrogen in the hydrogen storage tanks.

Even with the vehicle shut off, it is still possible for hydrogen to vent from a PRD/TRD (compressed hydrogen) or from a pressure relief valve (liquid hydrogen). It is impossible to stop the flow from a PRD/TRD once it has started; one must just wait for all of the hydrogen in the tanks to vent. Flow from a liquid hydrogen tank pressure relief valve will stop once the pressure inside the tank falls below a set value, but may start again if the tank pressure begins to rise (for example, if the tank is impacted by burning of adjacent materials, which will cause the tank temperature to rise).

Hydrogen fuel cell vehicles are electric vehicles and high voltage (nominal 300–600 VDC) will always be present when the fuel cell is operating. High-voltage lines can be identified with orange coverings or markings. Some commercial fuel cell vehicles will be designed with a hybrid-electric drive configuration, in which case, a high-voltage battery or ultracapacitor pack will also be present on the vehicle. Shutting off the ignition switch and/or activating the emergency shutdown switch or throwing the battery disconnect switch should de-energize the fuel cell engine and all high-voltage lines. However, high voltage will always be present inside the battery or ultracapacitor pack (if included).

Even if the system is off, one should never cut any hydrogen fuel line or high-voltage cable. One should never under any circumstances cut into a hydrogen storage tank or high-voltage battery pack.

Commercial vehicles with a hydrogen-fueled ICE engine may also be designed with a hybrid-electric drive configuration, in which case, a high-voltage battery or ultracapacitor pack and high-voltage lines will be present. As with fuel cell vehicles, shutting of the ignition switch on these vehicles should isolate hydrogen in the hydrogen storage tanks and isolate high voltage in the battery or ultracapacitor pack.

6.2 DETECTING HYDROGEN LEAKS

Hydrogen is naturally odorless and colorless. The sulfur-based odorants typically used with natural gas and propane to aid in leak detection are incompatible with fuel cells and are not currently used with hydrogen.

Large leaks of hydrogen gas will likely have an audible hiss, and leaking liquid hydrogen will likely be accompanied by fog in surrounding air and frost on equipment and lines in the vicinity of the leak.

Small hydrogen leaks can also be confirmed using a hand-held hydrogen sensor (see Figure 29). These devices use similar technology to the hydrogen sensors installed on fuel cell vehicles and at hydrogen fueling stations.

Figure 29. Hydrogen Leak Detector

Photo courtesy of B. Parsley.

6.3 HYDROGEN FIRES

A hydrogen fire should not be extinguished with water or chemicals. Static electricity generated across the leak orifice, or an adjacent hot surface, could explosively reignite the leaking hydrogen. The best way to deal with a hydrogen fire is to shut off the flow of hydrogen gas by closing supply valves, which will extinguish the flame. If a small flame must be extinguished in order to gain access to a hydrogen supply valve, a dry-powder extinguisher is recommended (Air Products, 2004).

The flow of hydrogen through a leaking PRD/TRD cannot be stopped. The best approach in this situation is to let the fire burn until all of the hydrogen has been consumed, while protecting surrounding vehicles and structures. If safe to do so, move nearby vehicles away from the hydrogen fire. Water sprays could help to keep surrounding equipment and structures cool. Use normal procedures to extinguish secondary fires ignited by the burning hydrogen and to deal with gasoline or diesel fuel spilled from other vehicles involved in the incident.

Be aware of the PRD/TRD outlet locations from uninvolved hydrogen tanks. If a loud hissing is heard, move away.

See Figure 30, which shows a simulation of a fire in a hydrogen-fueled vehicle (SAE, 2006). In this test, a fire was intentionally started in the driver's ashtray, which spread through the vehicle cabin. After approximately 15 minutes, a PRD on one of two trunk-mounted compressed hydrogen storage cylinders activated due to an increase in the temperature in the trunk to above 230 °F. In the photo on the left, flames from ignited hydrogen released through the PRD can be seen rising above the vehicle. After approximately 15 seconds, virtually all of the hydrogen had vented from both storage cylinders, but the cabin fire was still burning (right photo). In this test, the maximum height of the hydrogen flames was higher than the maximum height of flames during a similar test of a gasoline-fueled vehicle, but the gasoline-fueled flames were wider and persisted longer (from growing to diminishing flame). Radiated heat levels around the vehicle were also lower for the hydrogen-fueled fire than for the gasoline-fueled fire, and total damage to the vehicle was less (though in both cases it was significant). This is only one of many vehicle fire scenarios, but is illustrative of the differences between hydrogen-fueled fires and those fueled by gasoline or diesel fuel.

Figure 30. Hydrogen Vehicle Fire Showing Ignited Hydrogen Released from PRD

6.4 LIQUID HYDROGEN

Leaking liquid hydrogen poses a severe frostbite hazard to exposed skin. As it warms, liquid hydrogen will vaporize and create a cloud of cold hydrogen gas above the liquid puddle. This cloud may move sideways before rising as the gas warms further, and may extend beyond the area of accompanying fog. This cold hydrogen gas also poses a frostbite hazard and all personnel should stay upwind of the leak site.

As with gaseous hydrogen, the best approach to dealing with leaked liquid hydrogen that has ignited is to shut off the source of the leak if possible, protect surrounding structures and equipment, and let it burn until all of the hydrogen has been consumed.

Never spray water onto a liquid hydrogen tank. If it is venting, the water could freeze and plug the tank's pressure relief valve, resulting in excessive pressure and possible rupture of the tank.

While leaked liquid hydrogen is unlikely to travel far before vaporizing, the liquid should not be allowed to enter a storm sewer or other underground structure. This could result in a severe fire and explosion hazard as the hydrogen vaporizes and mixes with air in the enclosed space.

APPENDIX A:
OPERATION OF A FUEL CELL

PEM FUEL CELL

A PEM fuel cell is generally constructed from a series of thin layers of different materials, each with a different function, that are stacked together. These include a metal or graphite flow plate on either side of the device, each covered with a layer of porous carbon fiber paper. Each flow plate has grooves cut into it to distribute either hydrogen or oxygen across the carbon fiber paper. Between the layers of carbon fiber paper is a thin plastic-like film, called a "proton exchange membrane," which is coated on both sides by a platinum-based catalyst (see Figure 31).

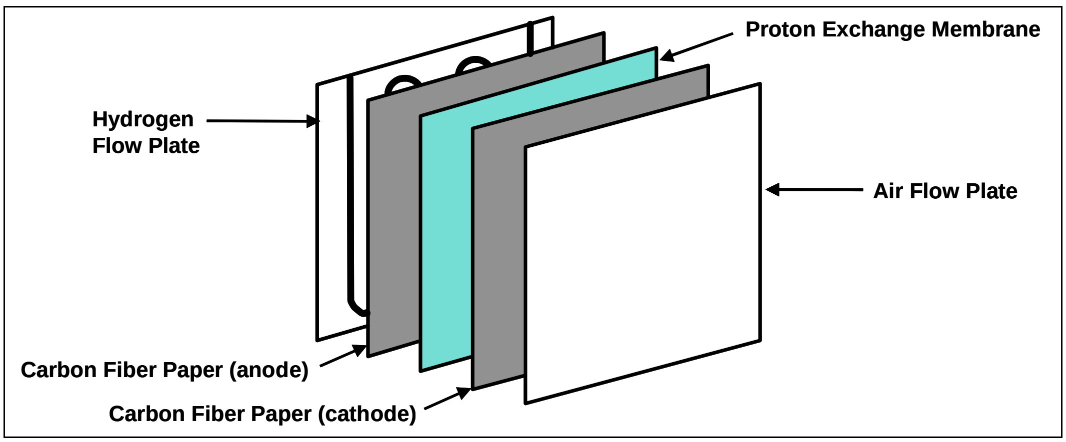

Figure 31. PEM Fuel Cell Construction

The hydrogen fuel flows through the flow plate on one side of the device, while air flows through the flow plate on the other side of the device. The two layers of carbon fiber paper act as the anode (hydrogen side) and cathode (air side) of the fuel cell. The anode and cathode are connected together electrically to form an electrical circuit. One or more electrical loads, such as an electric motor, are connected to this external circuit.

The proton exchange membrane acts as the electrolyte in the galvanic fuel cell. Because both the anode and the cathode are porous, they allow the hydrogen and air to contact either side of the proton exchange membrane, but the two gas streams do not mix.

At the surface of the membrane, the platinum catalyst causes the electron in each hydrogen atom that contacts it to separate from the atom's nucleus—leaving a proton, or hydrogen ion. While a hydrogen atom cannot pass through the membrane, a proton can. In fact, the protons are drawn through the proton exchange membrane to the cathode on the other side. In the meantime, the separated electrons flow along the anode and through the external electrical circuit. This flow of electrons is electricity, which is put to work by the devices connected to the circuit.

When two protons reach the cathode they combine, in the presence of the platinum catalyst, with one oxygen atom and two electrons flowing into the cathode from the electrical circuit, creating a molecule of water (H_2O). This water, along with the electricity flowing through the circuit and a small amount of heat, are the only by-products of the reaction. See Figure 1, which shows the operation of a PEM fuel cell.

For additional information, see the following websites that include both descriptions and animations of fuel cells in operation:

http://www.humboldt.edu/~serc/animation.html

http://www.howstuffworks.com/fuel-cell.htm

http://www.fuelcells.org/basics/how.html

SOFC FUEL CELL

Like PEM fuel cells, solid oxide fuel cells (SOFCs) are galvanic cells that directly produce electricity from hydrogen and oxygen through an electrochemical reaction. However, SOFCs are constructed of different materials and use a different chemical reaction from PEM fuel cells.

In an SOFC, the electrolyte is not a plastic-like material—it is a ceramic material made of a solid metal oxide, usually zirconium oxide. This electrolyte does not need to be coated with an expensive platinum catalyst as in a PEM cell. Rather than passing positively charged hydrogen ions (i.e., protons) across the electrolyte from the anode to the cathode, an SOFC passes negatively charged oxygen ions (O^{-2}) in the other direction, from the cathode to the anode. Electrons are still passed from the anode to the cathode through an external circuit, and the major by-product of the reaction is water, which collects at the anode (see Figure 6).

SOFCs are generally constructed differently than PEM cells as well. Rather than being built by stacking separate material layers, they are often built like computer chips by chemically depositing thin layers of the different materials required (College of the Desert, 2001c). They can be built either with a flat plate design or with a tubular design. In a tubular design, the zirconium oxide is deposited onto the outside of porous supporting tubes and the air is directed through the middle of the tubes, while the fuel is distributed around the outside of the tubes (see Figure 32).

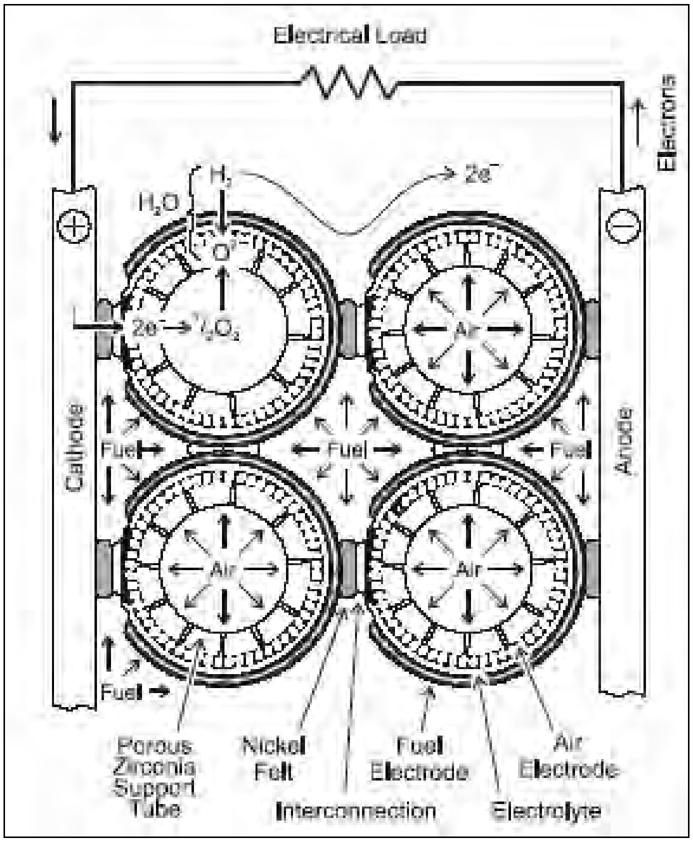

Figure 32. SOFC Construction Tubular Design

Source: College of the Desert, 2001c.

Unlike a PEM cell, an SOFC does not need to be fueled with pure hydrogen gas. Because SOFCs operate at such high temperatures and because oxygen ions are transferred through a solid oxide electrolyte material—not hydrogen ions—SOFCs support automatic "reforming" of gaseous hydrocarbon fuels, such as methane (natural gas), within the device. Reforming is the chemical process of separating the hydrogen from the carbon atoms in a hydrocarbon fuel. If combined with a relatively simple fuel reformer/processor, diesel fuel or gasoline can also be used to fuel an SOFC. The reformate produced by the fuel processor, which will include hydrogen, carbon dioxide, carbon monoxide, and nitrogen, is introduced as the fuel at the anode. In this case, the exhaust from the SOFC will include CO_2 and nitrogen, as well as water and heat.

SOFCs operate at much higher temperatures than PEM fuel cells—between 600 °F and 1,000 °F—so the waste heat created during operation is also at a higher temperature and can therefore more easily be put to use, for example, to heat the interior of a vehicle as is typical of the waste heat from an ICE.

APPENDIX B: CODES AND STANDARDS AND RECOMMENDED PRACTICES

Regulations are legal requirements established by relevant government agencies or oversight organizations. Codes are guidelines for the design of the built environment and are generally adopted by local jurisdictions. Standards are rules, guidelines, or characteristics for equipment, components, or processes often promulgated by industry organizations. Standards may be voluntary or may be enforced when referenced in codes or government regulations.

The precedent for establishing system safety programs for new technologies and operations has a long history in several industries (e.g., military, commercial aircraft, petrochemical, and public transit).

The commercial use of hydrogen in vehicle applications is in its infancy, and the development of applicable codes and standards is ongoing. Although currently there are few specific regulations or codes for design and operation of hydrogen fueled vehicles, there are a number of applicable standards, guidelines, and recommended practices developed by the National Fire Protection Association and the Society for Automotive Engineers. Some of these requirements have been included in state-level building codes. The remainder of this chapter discusses existing standards and codes applicable to hydrogen vehicles and facilities.

FEDERAL REGULATIONS

U.S. federal regulations associated with vehicles, systems, and equipment are contained in the Code of Federal Regulations (CFR). Depending on the type of vehicle, transportation mode, or subject, different federal agencies have responsibility to develop and oversee these regulations.

The following is a list of CFR regulations that pertain to different types of vehicles, as well as different aspects of hydrogen production and use, along with the agency responsible for them. In some cases, these regulations have requirements specific to hydrogen operations. In other cases, they are general regulations applicable to all vehicles, with no specific reference to or requirements associated with hydrogen use.

- Trucks
  It is important to note that hazardous materials carried on a vehicle for the purpose of supporting the operation or maintenance of that vehicle including its auxiliary equipment are exempt as "materials of trade" from the hazardous materials regulations (see 49 CFR 171.8 and 173.6). Examples of such hazardous materials include fuel for propulsion or auxiliary power units, electrolyte for batteries, and chemicals (e.g., urea) for selective catalytic reduction. Otherwise, hazardous materials carried as cargo on a vehicle are subject to the hazardous materials regulations at 49 CFR Parts 171-180. While not subject

to regulation by the Pipeline and Hazardous Materials Safety Administration, the U.S. Department of Transportation modal administrations (such as FMCSA) may subject to regulation the "materials of trade" as well as the vehicle systems that they support.

  - 49 USC 31136 and 31502(b), 49 CFR Subpart E (Safety standards for commercial motor vehicles fuel systems)
  - 42 USC 7521-7590, 40 CFR Parts 80, 85, 86 (EPA) (Control of air pollution from new and in-use motor vehicles and engines)
  - 49 USC 30101 et seq., 49 CFR Pts. 501-596, Working Part 29 (NHTSA) (Safety standards for all motor vehicles)
  - Responsible Oversight Agencies: EPA, FMCSA, NHTSA

- Buses
  It is important to note that hazardous materials carried on a vehicle for the purpose of supporting the operation or maintenance of that vehicle including its auxiliary equipment are exempt as "materials of trade" from the hazardous materials regulations (see 49 CFR 171.8 and 173.6). Examples of such hazardous materials include fuel for propulsion or auxiliary power units, electrolyte for batteries, and chemicals (e.g., urea) for selective catalytic reduction. Otherwise, hazardous materials carried as cargo on a vehicle are subject to the hazardous materials regulations at 49 CFR Parts 171-180. While not subject to regulation by the Pipeline and Hazardous Materials Safety Administration, the U.S. Department of Transportation modal administrations (such as FMCSA) may subject to regulation the "materials of trade" as well as the vehicle systems that they support.
  - 42 USC 7521-7590, 40 CFR Parts 80, 85, 86 and 88 (EPA) (Control of air pollution from new and in-use motor vehicles and engines)
  - 49 USC 5121, 49 USC 31136 and 31502(b), 49 CFR Subpart E (FMCSA) (Safety standards for commercial motor vehicles)
  - 49 USC 30101 et seq., 49 CFR Pts. 501-596, Working Part 29 (NHTSA) (Safety standards for all motor vehicles)
  - Responsible Oversight Agencies: EPA, FMCSA, NHTSA

- Fuel Cell Siting and Hydrogen Production, Distribution, Storage, Use, Dispensing, and Disposal
  - 49 USC 5101 et seq., 49 CFR Pts. 171-180 (PHMSA) (Hazmat transportation, packaging, and inspection)
  - Responsible Oversight Agencies: EPA, PHMSA

- Occupational Safety and Health Administration (OSHA)
  - 29 CFR §1910.38, Emergency action plans, provides for the content of an emergency action plan when an emergency action plan is required by another standard.
  - 29 CFR §1910.103, Hydrogen, contains requirements for hydrogen systems.
  - 29 CFR §1910.132(a), Personal protective equipment, requires that protective equipment, including personal protective equipment for eyes, face, head, and extremities, protective clothing, respiratory devices, and protective shields and barriers, shall be provided, used, and maintained in a sanitary and reliable condition wherever necessary.

– 29 CFR §1910.156, Fire brigades contains requirements for the organization, training, and personal protective equipment of fire brigades whenever they are established by an employer. The requirements under 1910.156 apply to fire brigades, industrial fire departments and private or contractual type fire departments. Personal protective equipment requirements contained in this section apply only to members of fire brigades performing interior structural firefighting.
– 29 CFR §1910.1200, Hazard communication requires that hazards associated with hydrogen must be conveyed to employees. In addition, the standard requires that the information be transmitted through a comprehensive hazard communication program, including, but not limited to, container labeling, material safety data sheets, and employee training on the hazards associated with handling hydrogen.
– Responsible Oversight Agencies: OSHA

NATIONAL FIRE PROTECTION ASSOCIATION STANDARDS

The National Fire Protection Association (NFPA), established in 1896, serves as the world's leading advocate of fire prevention and is an authoritative source on public safety. One of the activities of the NFPA is to develop codes and standards to enhance fire safety. The codes serve a wide range of applications, from general fire building codes to specific applications. The following is a list of NFPA codes that are applicable to hydrogen facilities:

- **NFPA 101 –** Life Safety Code (Applicable to maintenance facility design)
- **NFPA 70 –** National Electric Code (Applicable to maintenance facility design)
- **NFPA 30A –** Code for Motor Fuel Dispensing Facilities and Repair Garages (Applicable to maintenance and vehicle storage facility design)
- **NFPA 50A –** Gaseous Hydrogen Systems at Consumer Sites (Applicable to refueling and fuel storage facility design)
- **NFPA 50B –** Liquefied Hydrogen Systems at Consumer Sites (Applicable to refueling and fuel storage facility design)
- **NFPA 52 –** Vehicular Fuel Systems Code (Applicable to vehicle fuel systems in general, not specific for hydrogen)
- **NFPA 55 –** Compressed and Liquefied Gases in Portable Cylinders (includes NFPA 50A and 50B) (Applicable to refueling and fuel storage facility design)
- **NFPA 88 –** Standard for Parking Structures (Applicable to vehicle storage facility design)

COMPRESSED GAS ASSOCIATION

Since 1913, the Compressed Gas Association (CGA) has been dedicated to the development and promotion of safety standards and safe practices in the industrial gas industry. It is due to the efforts of the CGA that the industry has remained largely self-regulating throughout the twentieth century. More than 200-member companies worldwide work together through the committee system to create technical specifications, safety standards, and training and educational materials; to cooperate with governmental agencies in formulating responsible regulations and standards; and to promote compliance with these regulations and standards in the workplace. The following is a list of CGA standards applicable to hydrogen:

- **CGA G-5.4 –** Standard for Hydrogen Piping Systems at Consumer Locations Edition 3, February 18, 2005 (Applicable to refueling and storage facility design)
- **CGA G-5.5 –** Standard for Hydrogen Vent Systems Edition 2, April 20, 2004 (Applicable to refueling and storage facility design)
- **CGA G-5.6 –** Standard for Hydrogen Pipeline Systems Edition 1,May 12, 2005 (Applicable to refueling and storage facility design)
- **CGA H-2 –** Guidelines for the Classification and Labeling of Hydrogen Storage Systems with Hydrogen Absorbed in Reversible Metal Hydrides Edition 1, April 24, 2004 (Applicable to refueling and storage facility design)
- **CGA H-3 –** Standard for Cryogenic Hydrogen Storage Edition 1, March 14, 2006 (Applicable to refueling and storage facility design*)*
- **CGA C-6.4 –** Methods for External Visual Inspection of Natural Gas Vehicle (NGV) Fuel Containers & Their Installations (Applicable to refueling and storage facility design)

SOCIETY OF MECHANICAL ENGINEERS (ASME) STANDARDS

Founded in 1880 as the American Society of Mechanical Engineers, ASME sets internationally recognized industrial and manufacturing codes and standards that enhance public safety. The following is a list of ASME standards and guidelines applicable to hydrogen:

- ASME **–** Boiler and Pressure Vessel Code - 2007 Edition 2005 (Applicable to fuel storage system design*)*
- 2006 Design Factor Guidelines for High-Pressure Composite Hydrogen Tanks (Applicable to fuel storage system design*)*
- 2005 Hydrogen Standardization Interim Report for Tanks, Piping, and Pipelines (Applicable to fuel storage system design)

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE) STANDARDS

The Society of Automotive Engineers (SAE) develops standards and recommended practices for the design, operation, and maintenance of automotive systems and equipment. The following is a list of SAE publications that are applicable to hydrogen:

- **SAE J2574 –** Fuel Cell Vehicle Terminology
- **SAE J2600 –** Compressed Hydrogen Surface Vehicle Refueling Connection Devices

- **SAE J2760 –** Pressure Terminology Used in Fuel Cell and Other Hydrogen Vehicles
- **SAE J2594 –** Fuel Cell Recyclability Guidelines
- **SAE J 2578 –** Recommended Practice for General Fuel Cell Vehicle Safety
- **SAE J1766 –** Post Vehicle Collision Electrical Energy Storage Safety

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

The International Organization for Standardization (ISO) is the world's largest developer of standards. ISO is a network of the national standards institutes of 157 countries, on the basis of one member per country, with a Central Secretariat in Geneva, Switzerland, that coordinates the system. ISO standards are voluntary. As a nongovernmental organization, ISO has no legal authority to enforce their implementation. A certain percentage of ISO standards, mainly those concerned with health, safety, or the environment, has been adopted in some countries as part of their regulatory framework or is referred to in legislation for which it serves as the technical basis. ISO standards that pertain to hydrogen are:

- ISO Standard 13985, dated November 1, 2006 - Liquid hydrogen - Land vehicle fuel tanks (Applicable to fuel storage system design)
- ISO Standard 21012, dated November 15, 2006 - Cryogenic vessels – Hoses (Applicable to fuel storage system design)
- ISO Standard 15916, dated February 15, 2004 – Basic Considerations for the Safety of Hydrogen Systems (Applicable to hydrogen system safety)

GLOSSARY

Catalyst – A material that increases the rate of a chemical reaction without itself being consumed in the reaction. A proton exchange membrane fuel cell requires a platinum-based catalyst to drive the chemical reactions between hydrogen and oxygen in the cell.

Combustion – High-temperature oxidation of a fuel (i.e., burning) which releases heat and light.

Cryogenic Liquid – Any liquid whose temperature is below -100 °C.

Cryotank – A well-insulated container used to store a cryogenic liquid. Also called a "cryogenic vessel" or a "dewar."

Diffuser – A device designed to reduce the concentration of a gas (such as hydrogen) by mixing with air.

Electrolyzer – A galvanic cell composed of an anode and a cathode submerged in a water-based electrolyte, used to separate water into hydrogen gas and oxygen gas through the application of an electric current.

Fail Safe – Design in which a device or system will be put into the safest possible condition if the device or system fails. For example, an electrical switch that requires a signal voltage to stay closed; if the signal is lost due to a failure, the switch is designed to open and cut off the flow of electricity.

Fuel Cell – A galvanic cell that uses an electrochemical reaction to directly produce electricity from the oxidation of hydrogen. In a fuel cell, hydrogen is the anode material and oxygen is the cathode material (see Galvanic Cell).

Fuel Cell Engine – A device that combines one or more fuel cells with support systems to create a practical device for producing electrical power from hydrogen fuel. In addition to the fuel cells themselves, a fuel cell engine will typically require a fuel delivery system, an air system, a cooling system, and a water handling system.

Galvanic Cell – A device composed of an anode, a cathode, and an electrolyte. An electrochemical reaction between the anode and cathode materials causes electrical current to flow in a circuit connecting the anode and cathode. As part of the reaction, ions are transported across the electrolyte between the anode and cathode.

Green House Gas – Gaseous components of the earth's atmosphere that cause heat from the sun to be trapped, thus warming the earth. The most abundant man-made green house gas is carbon dioxide, produced during combustion of hydrocarbon fuels.

Ground (electrical) – A physical conductive connection between a device and a reference point (such as a vehicle chassis). The connection provides a path for electric current to flow, ensuring that the device will be at the same electrical potential as the reference, so that an electrical charge that might cause a spark cannot build up.

Hazardous Voltage – Any voltage that can harm a human through electric shock. Any voltage greater than 30 VAC or 60 VDC is considered a "hazardous voltage."

Hybrid-Electric Drive System – A hybrid electric drive system is one that uses two distinct power sources to provide propulsion power, for example, an internal combustion engine and a battery pack, or a fuel cell engine and a battery pack. In a hybrid-electric drive system, power from the battery pack supplements the engine when peak power is required (during acceleration) so the engine does not need to be as large as it would be in a conventional drive system. The battery can also be used to store power generated during braking for later use. In a conventional drive system, all braking energy is wasted. The use of a hybrid-electric drive system increases overall fuel efficiency, especially in stop-and-go driving.

Hydride – A compound of hydrogen with other elements. Both solid metal hydrides and chemical hydrides can be used to store hydrogen fuel for a fuel cell vehicle. In a solid metal hydride, the hydrogen is absorbed onto the surface or into the crystalline lattice of the metal. In a chemical hydride (for example, sodium borohydride), the hydrogen is chemically bound to other elements.

Hydrocarbon – A chemical compound that consists only of the elements hydrogen and carbon. Various hydrocarbons are the main components of all fossil fuels, including gasoline, diesel fuel, and natural gas.

Hydrogen Embrittlement – The process by which a metal becomes brittle and develops small cracks due to exposure to hydrogen.

Ion – An atom, normally electrically neutral, that gains an electrical charge by gaining or losing one or more electrons. A positive ion is an atom that has lost one or more electrons and a negative ion is one that has gained one or more electrons.

Lower Flammable Limit – The lowest concentration at which a mixture of a gas in air can burn. The lower flammable limit for hydrogen is 4 percent by volume at room temperature and atmospheric pressure. If less than four percent hydrogen is present, the mixture will not burn.

millijoule – One-thousandth of a joule. A joule is a unit of work or energy. One millijoule is the amount of energy required to lift up an object that weighs 1 gram to a height of 10 centimeters.

Proton Exchange Membrane Fuel Cell – A type of low-temperature hydrogen fuel cell that uses a proton exchange membrane electrolyte, which passes hydrogen ions from the anode to the cathode. PEM fuel cells must be fueled with pure hydrogen gas. PEM fuel cells are the most common type of fuel cell used to power vehicles.

Reforming – A chemical process that converts a liquid or gaseous hydrocarbon fuel, such as diesel fuel or natural gas, into a hydrogen-rich gas.

Reformate – The product of reforming a hydrocarbon fuel. Depending on the fuel and the process used, reformate will be anywhere from 40 to 75 percent hydrogen by volume, with the remainder carbon dioxide, nitrogen, and water vapor.

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