The International Consortium
for Fire Safety, Health & The Environment
www.clean-and-safe.org
info@clean-and-safe.org

US Office P.O. Box 14270 Washington, DC 20004-4270 USA European Office Box 857 SE-501 15 Borås Sweden

Safety issues regarding fuel cell vehicles and hydrogen fueled vehicles

I. Introduction

The current discussion on dependence on foreign oil imports and the President's "Freedom Car" initiative has brought alternatively fueled vehicles and hydrogen to the attention of the public. Even though all current fuel cell and hydrogen vehicles are experimental and only being tested in low numbers on public roadways, several states have mandated zero emission vehicles to be introduced (ZEV) in the near future.

As new technologies, fuel cells and hydrogen have some associated safety concerns that have to be addressed. Although some of the concerns raised are similar to those encountered with substances such as compressed or liquid natural gas (CNG or LNG) and technologies such as electrically powered vehicles, the combination of different technologies in new vehicles and the addition of new and unproven technology warrant special attention. First responders should be informed of the potential risks of newly developed vehicles before they are commercialized, and measures should be put in place to minimize the hazards to the general population.

II. Properties of Hydrogen

Hydrogen has several properties that differ strongly from natural gas or methane. Hydrogen is being used experimentally as a vehicle fuel, not only because it oxidizes to harmless water, but also because it has a higher energy density per unit of weight than CNG or methane. One of the other positive characteristics of hydrogen is that it disperses very quickly, meaning that hydrogen concentrations under normal pressure dissolve to incombustible levels very quickly. This also means that under ambient air pressure hydrogen has very little energy density per unit of volume compared to other vehicle fuels. Hydrogen also rises very quickly and therefore is less of a threat outdoors.

While hydrogen has a high burn/explosive velocity, it has less explosive power than other fuel-air mixes. Except in extremely high concentrations, hydrogen is not toxic to humans. Hydrogen is odorless and tasteless. While the flame of burning hydrogen is visible under daylight conditions, it is a lot less so than flames from other fuels due to the lack of soot. A hydrogen flame can be most easily identified by the mirage-like effect on the air over and around the flame, as it otherwise does not produce significant heat radiation.

Hydrogen also has many characteristics that warrant its being handled with great care. Hydrogen-air mixtures can ignite or explode at both lower and higher concentrations of the gas in the air than CNG or methane. Hydrogen is more easily ignited than other fuels. The impact of this is negligible, however, as most other fuels can already be ignited by small amounts of static electricity.

To store hydrogen in liquid form, it has to be cooled down dramatically. Hydrogen has a boiling temperature of only 20° Kelvin or -435° F. This causes the fuel to boil off very quickly when spilled, creating only a narrow window for ignition. On the other hand, the intensely cold fuel can cause serious cold burn damage to people and embrittle and break metal equipment in particular. In enclosed locations with normal temperatures, spilled liquid hydrogen will create enormous gas pressures, tearing apart vessels without safety valves.

III. Areas of Concern

The two prime dangers from fuel cell and hydrogen-powered vehicles are the danger of electrical shock and the flammability of the fuel.

Fuel cells power vehicles by electro-chemically combining hydrogen gas (H_2) and oxygen (O_2) from the surrounding air into water (H_20) and electrical energy. The electrical energy is then used to power both the locomotion of the vehicle through electrical motors and the current electrical usage devices such as the radio, lights and air-conditioning. A notable difference between current and new-technology vehicles is that the voltage needed to power the electric motors is much higher in new vehicles than can be accommodated by the current standard voltage of a 14V system; the automobile industry is in the process of moving to a new standard of a 42V system. The 42V system was chosen as an industry standard in part for safety reasons: anything greater than 50 volts can stop a human heart. On the other hand, some fuel cell vehicle motors run on voltages exceeding 350V. With such high currents, the danger of electric shock is great.

The second area of concern lies in the fuels used to power this future generation of vehicles. Even though hydrogen remains the main focus of future fuel cell vehicles, it is neither the only possible fuel for them (other fuels used to power fuel cells directly include methanol, ethanol and methane), nor is hydrogen used only for this purpose. In addition, the hydrogen used to power a vehicle does not necessarily have to be stored on the vehicle as hydrogen. Reforming different hydrogen sources, such as alcohols, methane, propane and even regular gasoline, can create gaseous hydrogen in the vehicle itself. Hydrogen stored as such in a vehicle or reformed in it can also be used to power a 'classic' internal combustion engine. Besides reforming hydrogen in the vehicle itself, there are several ways of storing hydrogen in a vehicle. Each has its own set of flammability issues.

Both the electrical current and the flammability concern of the fuel translate into the design needs for the vehicle itself as well as the requirements for structures intended for the storage, refueling and repair of these vehicles.

A. The Vehicle Itself

Fuel cell vehicles currently being tested include public transportation and personal mobility vehicles. According to the US Department of Energy (DOE), there were nine different hydrogen vehicle-testing projects underway in the US as of March 2003. The safety issues regarding the vehicle can be divided into two separate categories. One category encompasses issues with normal vehicle operations; the other category contains issues with vehicle accidents.

As stated above, the main issues with fuel cells and hydrogen-powered vehicles stem from electrical shock and the flammability of the fuel.

1. Electric current

The fact that over 350V are needed for the drive train of fuel cell vehicles presents both an electrocution hazard and an ignition source for fuel contained in the vehicle or outside materials. Since a significant amount of the material used in vehicular construction is metal, with some degree of electrical conductivity, there is a high potential for electrical faults. This can pose a threat both in normal operations of the vehicle and especially in accidents. Even though most designs contain failsafe switches for the electrical system, these switches may be short-circuited if the vehicle is involved in an accident.

In addition to the electric current generated by the fuel cell during its operation, most prototype vehicles have an electrical storage component for acceleration and start up, much like today's hybrid vehicles. Most fuel cell vehicle store and draw on this additional electricity in form of batteries. Batteries can also represent the additional danger brought on by the presence of acids, to both the electrical system and the fuel system. More exotic and less researched forms of energy storage are ultra capacitors and mechanical flywheels. Ultra capacitors store electrical energy under high voltages for rapid release. While this is positive for vehicle operation, it also holds the risk of very strong unintentional electrical discharges. Flywheels store energy as movement energy of a rapidly revolving weighted object in an electromagnetic enclosure that acts as an electrical motor and generator. If flywheels are unbalanced or their enclosures broken by an accident, they can release massive amounts of physical energy on their surroundings.

2. Electrical Drive System

The electrification of the drive system can also cause the vehicle to be a source of new dangers. Electrical or computer faults can cause the vehicle to engage the motor by itself, reverse the direction or engage the brakes. It remains to be seen if these dangers are greater than those posed by current mechanical drive systems, but new technology generally needs some time to find and address some technical quirks.

B. Fuel-Specific Problems

Fuel cell vehicles can be fueled in a variety of different ways. Regardless of the source of the fuel, the hydrogen, methane, methanol, or ethanol has to be stored and transported to the fuel cell or engine.

1. Internal fuel transmission and consumption

Methanol and ethanol are both liquids and thus even though they are more flammable than regular gasoline or diesel oil, they are more manageable than gaseous substances. Current experience with conventional engines fueled with these two alcohols should be applicable to fuel cells using them. Methanol has the added problem of being toxic.

Methane is the main component of natural gas (70%). The difference in the use of methane by the fuel cell, as opposed to hydrogen, is that methane can produce carbon monoxide, which besides being able to ‘poison’ the fuel cell can also poison occupants of the vehicle. Methane fuel cells are in early stages of development with no current model uses in vehicles. Experience with natural gas should be otherwise very much applicable to methane.

Thus, the main fuel-related issues for fuel cell safety regard the use of hydrogen. While being a very clean and energy-dense fuel, hydrogen has the tendency to disperse quickly under normal pressure. This causes the need for higher pressure of hydrogen in the fuel transport system than for natural gas. Additionally, hydrogen molecules are so small that they can easily escape through miniature holes and can even enter the molecular structure of some steels, making them brittle over time. Also, the use of very fine membranes in Proton Exchange Membrane (PEM) fuel cells can lead to direct combustion of hydrogen with oxygen. In normal operation of the vehicle, slowly escaping hydrogen that collects to form a flammable or even explosive mixture with air is the main matter of concern. An accumulation of gaseous hydrogen is seen as particularly dangerous in the enclosed passenger or storage compartments of any hydrogen-fueled vehicle.

2. Fuel Storage

Storage of methanol and ethanol will be similar to that of today’s liquid fuels. Methane storage can be virtually copied from natural gas storage either in compressed or liquid form. Hydrogen storage again poses the main problem for fuel cell and hydrogen-using vehicles.

At normal pressure, hydrogen takes up a huge volume per unit of energy. This can be addressed by creating hydrogen in the vehicle itself by reforming different hydrogen sources, such as alcohols, methane, propane and even regular gasoline. Even though all these sources of hydrogen have their own issues concerning fuel storage, there are established methods for storing them. The reforming process, however, has its own risks, as it combines pressure and temperature differences in an environment of moving volatile substances. There are numerous approaches to reforming the different hydrogen-carrying substances. Most of these reforming processes are still too energy intensive, hot or voluminous to be included in vehicles, particularly in passenger cars. As reforming works around the most of the problems of hydrogen storage, it has enormous potential.

Hydrogen can be stored in four main ways: compressed, as a liquid, in hydride form bound to metals, or on the surface of solid porous materials or carbon nano-tubes. The forms of storage that are currently being tested are compressed hydrogen and liquid hydrogen.

Compressed hydrogen is stored at 3,600 psig, 5,000 psig or 10,000 psig. The first two of these pressures are currently being tested. In contrast with compressed natural gas (CNG), compressed hydrogen cannot be stored in steel tanks, as the hydrogen molecules would embrittle the metal. Also the pressure in these tanks is much higher than in tanks for CNG. Even though these tanks were and are being designed with extreme care, the possibility of a leak still exists. This again might lead to the accumulation of flammable or even explosive hydrogen air mixtures. The rupture of the pressure tank can cause very high concentrations of hydrogen to form in the vicinity of the vehicle, as the turbulent flow rate of hydrogen is extremely high. Even though hydrogen disperses very quickly, this emission will cause a combustible mix to form for a short period in the open. Enclosed areas could accumulate enough hydrogen-air mixture for a large explosion.

Liquid hydrogen (LH_2) has to be stored at temperatures lower than 20° Kelvin or -435° F. Even well-insulated storage tanks cannot maintain this low a temperature without relying on outside cooling, which is prohibitive for passenger vehicles from an energy-needs standpoint. The result of this is the expected leakage of 1%-3% of the hydrogen contained in the LH_2 tank per day, depending on the use and build of the vehicle. This controlled emission of hydrogen over time is not considered overly dangerous, as controlled oxidization by catalysts or dispersion is possible. Catastrophic ruptures of the LH_2 tank can not only endanger people due to the extreme temperature of the liquid, but can also lead to very high hydrogen concentrations in the surrounding air, especially in confined places such as tunnels.

One of the safest methods of storing hydrogen in vehicles is by binding it with metal hydrides. For this method of storage hydrogen, is bound to different metal alloys in porous and sometimes loose form by applying moderate pressure and heat. The application of heat and the reduction of the pressure are later used to extract the hydrogen gas from the metal. The greatest drawback of this method is the weight of the metal hydride needed to contain sufficient fuel for sustained vehicle operations (>200 mi). The weight of some alloys can go up to 1250 kg to store 15 kg of hydrogen, thereby greatly increasing the weight and also decreasing the vehicle's energy efficiency. Another potential problem with metal hydrides is the flammability of some of the alloys used, such as magnesium in MgNi alloys, which have much better metal-to-hydrogen rates than the example above.

Solid porous materials and carbon nano-tubes are still in the early stages of development. While their properties appear to be close to metal hydride storage, they have other problems related to the porous material, the high volume and weight of the material per weight of hydrogen carried which are still unsolved. The carbon nano-tubes are now still prohibitively expensive and also have the potential problem of flammability.

C. The Fueling and Maintenance of the Vehicle

Aside from being operated normally on public roads, fuel cell and hydrogen vehicles also need to be parked, fueled and maintained. As most of the current hydrogen studies are being conducted on a very low number of vehicles, their infrastructure is mostly located in a very controlled environment. When these tests expand to 'normal' consumer trials, these vehicles need a more public infrastructure available to them. This raises some associated safety concerns with both new infrastructure for fueling and maintenance as well as private and public parking.

In a U.S. electric code from the 1930s, hydrogen was given a very high flammability class that corresponds to high requirements for electric appliances in the vicinity of hydrogen. A review of this rather extreme classification of hydrogen is under way.

1. Fueling

Both fuel cell vehicles requiring other types of fuel and hydrogen-powered vehicles will need a specialized infrastructure to maintain their operations. As for the issues for the vehicle fuel system, this paper focuses on hydrogen, since the other potential fuels are already being distributed for fleets of vehicles or are similar to current fuels. Hydrogen today is transported as a liquid in insulated trailers similar to fuel trucks. Future sources hydrogen for fueling stations can be gaseous hydrogen pipelines or reforming hydrogen on-site from the source-fuels described above. Aside from an injection fueling mechanism for the vehicles, there are issues with the storage of hydrogen at the fueling sites and the detection of hydrogen leaks. Especially with fuel cell vehicles, there is a great potential for problem with the electric circuitry in the vicinity of flammable gases.

2. Maintenance

The main problem for maintenance localities for fuel cell and hydrogen-fueled vehicles is the electric code mentioned above. Especially in connection with the high voltage and complete electrification of these vehicles, this will definitely pose a problem. Aside from this, there are the general problems of stationing a vehicle in an enclosed space because of the possibility of a buildup of gaseous hydrogen.

a) Parking of the vehicle

Parking a hydrogen vehicle or other gas-fueled vehicle in an enclosed structure is a serious safety concern as it can lead to a buildup of the gas. Hydrogen’s tendency to rise and disperse rapidly makes this the only situation in which small leaks can create extremely dangerous situations.

b) Emission

As noted above, liquid hydrogen tanks always emit small quantities of hydrogen if it is not oxidized or burned off in a controlled manner. All hydrogen-containing fuel systems have a great propensity for at least small leaks due to the pressure of the gaseous hydrogen and the small size of the individual molecules. Because of the high dispersion rate of hydrogen, small leaks would likely pose a problem only in small individual garages. Safety concerns in larger private or public parking garages will be more of an issue if and when the number of hydrogen-fueled vehicles rises dramatically. Without major changes to parking structures or installation of continuous ventilation even in private, individual garages, hydrogen detectors will be essential to protecting all enclosed environments in which hydrogen will be present.

3. Detection

The high probability of at least trickling emissions of hydrogen and the lower flammability level of about 6% (hydrogen under normal pressure) leads to the necessity of early detection of even very low concentrations of hydrogen. Sensors to detect concentration of hydrogen below the lower flammability level are currently still very expensive. Odorants that are added to natural gas cannot be easily added to hydrogen or methane used in fuel cells as the larger molecules and especially the sulfur content of current odorants would poison fuel cells. Research is being conducted into the possibility of removing these odorants before the fuel enters the fuel cell. This would leave the fuel cell itself and molecular-sized leaks in the fuel transport system as the only sources of odor-free hydrogen. Odorants are still difficult for detectors to pick up, but they are less expensive than hydrogen detectors.

IV. Current Status of Regulation / Model Codes

In the US, the Bush Administration's fuel cell and hydrogen initiative and increasing testing of fuel cell vehicles has spurred diverse regulatory activity. The DOE Energy Efficiency and Renewable Energy Office's Hydrogen, Fuel Cells & Infrastructure Technologies Program is trying to coordinate much of this development.

- The National Fire Protection Association (NFPA) is currently reviewing its standards for hydrogen vehicle fueling and maintenance stations (NFPA 50A and NFPA 50B).

- The Society of Automotive Engineers (SAE) is in the process of drafting guidelines for hydrogen fueled and fuel cell vehicles.

- Also involved are the International Code Council (ICC), which is reviewing its building codes; the American Society of Mechanical Engineers (ASME) and the American Society for Nondestructive Testing (ASNT) on the safety and testing of the fuel tanks; and several other hydrogen, gas and testing institutions.

Internationally, the World Forum for the Harmonization of Vehicle Regulations, WP.29 of the United Nations' Economic Commission for Europe, has formed an informal group to develop safety regulations for hydrogen-fueled vehicles. In March 2003, at a meeting of the Forum, Jeffrey W. Runge, M.D., administrator of the National Highway Transportation Safety Administration of the US Department of Transportation, addressed the safety of hydrogen-fueled vehicles in the following way:

"[I]n our exuberance about the advantages for our environment and consumption of fossil fuels, we must not be caught off guard with the potential impact on safety. It will be challenging to find the appropriate balance between ensuring a continuing energy supply, protecting the environment, and ensuring safety. Only then can we move forward with confidence, and in turn, build consumer confidence in these advanced technologies.
Many countries around the world have been conducting research to promote hydrogen vehicle technologies. Just last month, President Bush, in his annual 'State of the Union' address to America, announced his intentions to focus U.S. efforts on developing, testing and deploying hydrogen-fueled vehicles. The industry worldwide has made tremendous progress in researching and building prototypes of these vehicles. I have personally driven hydrogen fuel cell vehicles in Europe, Japan and the U.S., and I find them to be

promising technology. However, thus far, our safety evaluation of these vehicles is limited. While the industry has been working diligently to develop harmonized industry standards, governments are only beginning to assess these technologies from a regulatory perspective. Much research and testing is still needed in order to evaluate their safety impact and develop a performance-oriented regulation that will not limit technological innovation."

V. Non-vehicular developments

Outside the use of fuel cells in vehicles, there is an increasing trend especially in the mobile computing and consumer electronics field to substitute fuel cells for batteries. This is especially true for power-hungry devices such as notebook computers and video cameras. Some prototypes for laptops already exist, and regulations for carrying hydrogen on airplanes are being discussed. Even though the amounts of hydrogen used in these applications is very small, this development seems to warrant some attention.

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