CRASH-INDUCED FIRE SAFETY ISSUES
WITH
HYDROGEN-FUELED VEHICLES

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1. Introduction

The Motor Vehicle Fire Research Institute (MVFRI) is charged with conducting research related to crash-induced fire safety in automobiles and light trucks (vans, SUVs, and pickup trucks). The next section will describe MVFRI in more detail. All the research that has been initiated to date has to do with existing, gasoline-fueled vehicles.

The author has been conducting a "problem definition" of fire safety issues for hydrogen-fueled vehicles. His preliminary thoughts and ideas are contained in this paper. They are being presented at the National Hydrogen Association meeting to help evoke discussion and feedback. After this feedback, the research ideas will be finalized, and we will decide what research, if any, we might fund over the next two years.

Previous work on hydrogen safety has been reviewed. DTI did a major report in 1997 for Ford and DOE [1]. It is very comprehensive but has limited results relative to crashworthiness. Sandia did a report in 1994 [2], and there is an informative video on hydrogen safety issues [3].

There are about 42,000 occupant fatalities in traffic accidents per year (2001) [4], including 328 fatalities where fire is reported as the "most harmful event." Thus fire deaths are less than one percent of traffic deaths. Between 1991 and 2000 the number of fire-related fatalities has remained relatively constant.

The National Highway Traffic Safety Administration (NHTSA) usually regulates vehicle safety based on accident data. Therefore, regulation frequently does not occur until there are many vehicles on the road, and problems start showing up.

MVFRI is interested in anticipating problems before they occur. We can possibly conduct research, and encourage NHTSA to set standards for H_2-fueled vehicles which will ensure their safety from the beginning.

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2. Motor Vehicle Fire Research Institute (MVFRI)

MVFRI is a non-profit organization incorporated in the State of Virginia. You can learn more about it, and our currently funded projects, on our website (www.mvfri.org).

Our charter is to perform crash-induced fire research on automobiles and light trucks. Our focus is on the future, but we do study vehicles on the road up to 5-years old to identify good and bad engineering practices.

MVFRI is funded from a court settlement between GM and the owners of their C/K pickup trucks for certain model years. The funding is about $4M spread over three years. We are now entering year two. Our work can also be thought of as a follow-on to about $10M in fire research that was conducted and funded by GM under a settlement between GM and DOT over the same C/K vehicles. Most of the considerable body of research reports are available on the NHTSA website (www.nhtsa.gov) or organized by subject at the MVFRI website. Look for docket number 3588 in the NHTSA Docket Management System. However, none of those reports deal with hydrogen safety.

3. Scope

The number of advanced vehicle technology options is potentially very large. Energy carriers include gasoline, methanol, natural gas, and hydrogen. Fuel storage could be compressed gas, liquefied gas, and hydrides of various types. There may or may not be a reformer on board. There may or may not be an electrical energy storage device (such as a battery or ultracapacitor) for hybrid operation. And the conversion scheme could be a conventional Internal Combustion (IC) engine or a Fuel Cell (FC). The above yields at least 96 possible combinations. Many of the technology developers are exploring several options at this time. That is wise.

A comparison of several of these technology options and fuels has been done by Heywood et al [5]. They compare the life cycle energy use and greenhouse gas emissions. From this it is clear that hydrogen made from natural gas is a transitional strategy, and that the country will ultimately need a renewable source of hydrogen.

There are others [6] who have challenged the hydrogen economy and instead advocate methanol or other liquid fuels for transportation.

I will down-select to one reference option. For the purpose of this paper I wish to emphasize using hydrogen as the fuel. Liquefied H_2 has challenges because of boil-off, and the hydrides are still much too heavy. So I will pick compressed gas for the balance of the paper. It also seems to be the general consensus that the early vehicle prototypes will mainly be compressed gas – and that it is the most straight-forward to implement. In this option, there is no reformer on board.

Since fuel cells are still very expensive, it makes sense to use on-board storage of energy. I will choose a battery hybrid. This allows the fuel cell to be sized for average power instead of peak, and allows regenerative braking to improve the overall efficiency.

So my reference vehicle is assumed to be: compressed hydrogen, fuel cell, and hybrid battery. I also assume there will be a conventional 14-volt (or 42-volt) electrical system for non-propulsive loads. From a propulsion point of view, it is basically an electric vehicle.

4. Crash-induced Safety Issues and Some Countermeasures

All vehicles have to be designed to be safe in a crash environment. Not only do the vehicles have to meet all the applicable Federal Motor Vehicle Safety Standards (FMVSS's), but there are special standards which apply to electric vehicles (FMVSS 305) and for Compressed Natural Gas Vehicles (FMVSS 303 and 304). The fuel cell car is basically an electric vehicle with battery pack voltages likely to be in the 300-volt range. The natural gas vehicle standards (NGV-2) are being updated and extended to cover hydrogen-fueled vehicles, and hopefully will be harmonized with all the various codes and standards activities in the US and overseas.

The FMVSS's are considered to be minimum performance standards, and most manufacturers test their vehicles to more stringent standards than the minimum required by the government (NHTSA).

SAE has recently released a Recommended Practice for General Fuel Cell Vehicle Safety [7]. It doesn't cover much with respect to crashworthiness.

It is also important for a new technology vehicle such as the H_2/FC vehicle to exhibit exemplary safety features. People are wary of hydrogen, and know that it is potentially explosive. Compressed gas also contains a great deal of stored mechanical energy (at 5,000 or 10,000 psi) which can do serious damage if a tank bursts. A single spectacular fire ball or explosion seen on the evening news involving a hydrogen vehicle could seriously set back the program of introduction of such vehicles – even though such fire balls (called a "BLEVE" – Boiling Liquid Expanding Vapor Explosion) do occur with gasoline-fueled vehicles. It may not be fair, but the standard of safety for these new vehicles will have to be higher than that of the vehicles we currently drive.

Humans seem to have an innate fear of fire, and we frequently shudder when we hear of someone dying in a fire. Many of us view it as the worst way to die. That perhaps explains why the fire safety of conventional gasoline-fueled vehicles has continued to improve over the past 25 years.

There are an infinite number of crash scenarios that occur in real-world crashes. There are single and multiple vehicle crashes. Cars can be exposed to gasoline pool fires from another vehicle. The Europeans have a test for plastic fuel tanks where the tank is exposed to an intense pool fire (ECE-R34 test). For conventional vehicles, the fuel systems are becoming better protected, and as a result nearly 2/3 of the post-crash fires are caused by frontal collisions rather than rear. Rear impact fires are more severe, however, so there are still more fire fatalities in rear impact crashes.

I would now like to focus on some non-fire safety issues with H_2/FC vehicles. As stated above, the mechanical energy stored in the compressed gas is very high, and could cause a great deal of damage, independent of any fire, if the tank bursts. Also, the tank is very strong and could become dislodged by the crash forces and perhaps intrude into the passenger compartment and become sort of a battering ram. The same is possible with other vehicle components which are dense and strong. Examples include the battery pack, the fuel cell itself, the reformer, and the hydride storage unit if there is one. There are also hazards of electrical shock and electrolyte spillage (covered by FMVSS 305), and coming into contact with hot surfaces (for some system concepts).

Electrical fire issues

There are many fire-safety issues to consider. First I will discuss electrical fires since the H_2/FC vehicle is fundamentally an electric vehicle. Studies have shown that 85% of crash-related fires are electrical in origin [1, 8]. This figure is for electrical systems which operate at 14-volts (14-volts is the charging voltage - the battery is at 12-volts when discharging). The industry is planning a transition to 42-volt electrical systems over the next several years. At that voltage there are increased fire safety concerns due to carbon tracking phenomena which can “grow” a short across an insulator, and due to sustained arcing which puts out a tremendous amount of energy if not detected and shut off quickly. MVFRI and USCAR are jointly sponsoring some work at UL in this area. Electric vehicles with several hundred volt systems (say 300-volts), as well as a lower voltage (14 or 42-volt) supply for other loads, are obviously a fire-safety concern. There is no reason to assume that the incidence of electrical fires will be any less in the H_2/FC vehicle. Thus ignition sources are potentially present in many, but not all, parts of the vehicle. If hydrogen is released, there is a good chance it will ignite. In some cases it may be preferable for the hydrogen to ignite quickly rather than accumulate and give rise to a deflagration.

There are many countermeasures for electrical fires. The location and protection of the batteries are important. Current cars frequently have the battery in the front of the engine compartment, and it is vulnerable to crushing and shorting in a frontal crash. There are up to 7 flammable fluids (not counting gasoline, but including coolant and windshield washer fluid which can splash on the battery and other wiring) under the hood of current vehicles. It is possible that the H_2/FC vehicles will have fewer flammable fluids to be exposed to such an ignition source. Some current vehicles, BWM is an example, have the battery in the trunk. They also have a battery disconnect (circuit breaker) which is activated by the crash sensors on the car. Certainly the H_2/FC vehicles will have that feature on at least the high voltage sources, and perhaps also on the lower voltage (14 or 42-volts) for the other loads.

Another important factor is the flammability of materials which can be exposed to electrical ignition sources. GM did a lot of work in this field [9] and NHTSA is currently doing some additional work at SwRI using the cone-calorimeter flammability tester. MVFRI is augmenting this work by funding the collection of toxic gas emissions from the burning plastic samples.

An analysis of the results from the GM reports [10] show a wide range of variations in the fire resistance of automotive polymers. For example, the following ranges were found: 1) decomposition or vaporization temperature range - 240 to 527 ^{o}C; 2) thermal response parameter range - 70 to 490 kW-s$^{1/2}$/m^2 (higher values represent higher ignition resistance); 3) release rates range (at 50 kW/m^2 external heat flux) - a) heat - 100 to 1300 kW/m^2; CO - 0.5 to 8 g/m^2-s and smoke - 0.4 to 8 g/m^2-s; 3) fire propagation index range - 7 to 28 (m/s$^{1/2}$)/(kW/m)$^{2/3}$ (there will be no fire propagation for values ≤ 6). Thus it is desirable for materials with increased fire resistance be used around the electrical (and hydrogen) components.

Hydrogen release issues

Any of the H_2/FC components can potentially result in a release of hydrogen. This section will also include a few comments about components which are not part of the reference vehicle.

First I will discuss the compressed hydrogen tank. To have any reasonable mass fraction, the tank will undoubtedly will be a Type 3 (aluminum liner) or Type 4 (plastic liner) carbon fiber wrapped tank. Typical pressures can be 5,000 to 10,000 psi. That sounds scary to some people. Actually the tank is very strong – just because it has to withstand that much pressure - and is unlikely to burst in a crash. Interestingly enough, the tank is probably most vulnerable at low pressures when the tank wall is less stiff [11].

Several regulator suppliers make a regulator which goes at least partially inside the tank. That provides considerable protection to the regulator, and makes it unlikely that it will be torn off in a crash - which would result in a very rapid emptying of the entire contents of the tank. Since there are likely to be ignition sources, that hydrogen could easily ignite. So it is extremely important to avoid any high pressure hydrogen releases.

A countermeasure here is to have an in-tank solenoid operated shut-off valve that will isolate the high pressure hydrogen. There may also be designs where an "excess flow valve" is a good addition to the fuel system

Another tank safety issue is that the tank may get exposed to a gasoline pool fire from another vehicle. The fiber composite tank is a pretty good insulator, so the temperature and pressure rise of the hydrogen may not be great. A partially filled tank may never exceed its normal operating pressure. However, the fire will gradually weaken the carbon fibers themselves and eventually the tank will burst if the hydrogen is not vented out. This is usually done by a thermally-actuated Pressure Relief Device (PRD). This is a good solution *if* the relief valve sees the same fire as the tank. SwRI had a bad experience with a steel core composite natural gas tank that burst when being subjected to the DOT FMVSS 304 bonfire test [12]. The test specifies the dimensions of the pool fire, which was shorter than the length of the tank. As a result, the tank saw the high temperature and the relief valve did not – hence the burst which blew out a steel wall, broke railroad ties, and bent some very heavy steel I-beams. For configurations where the PRD may see a different heat flux from the tank, it would be desirable to have a redundant PRD in another location. The use of *both* a thermally-actuated and a pressure-actuated PRD should also be considered.

There is a lot of mechanical energy stored in the compressed gas tank. A simple calculation shows that if a tank ruptures (and leaks, say, 5 kg), and produces a jet in a preferred direction, that the vehicle will get an impulse of ca 6000 Newton-seconds. This impulse would accelerate a 3000-pound car on a friction-free surface to a velocity of about 10 miles per hour. If that happened with a high-thrust release, it would give the occupants a noticeable jolt.

Another tank issue relates to aging tanks. All compressed gas tanks are required to have an expiration date to protect against fatigue and corrosion failures. Fifteen years is considered a long tank life. However, there are many passenger vehicles on the road which are older than 15 years. Is it realistic to expect the owner, who may be a low income person at this age of the vehicle, to replace an expensive tank system? Also those older tanks are presumably more vulnerable in a crash situation.

The high pressure regulator typically lowers the supply pressure to around 150 psi or so. Usually there will be another low pressure regulator which supplies H_2 at the pressure desired by the fuel cell (say 50-75 psi) or IC engine (0.5 to 50 psi). Most configurations will have several feet of tubing to move the intermediate and low pressure H_2 around the vehicle. A conservative assumption is that these lower pressure tubes will be severed in a crash. With ignition sources nearby, we should assume that this hydrogen will ignite. As a countermeasure here, it is important to keep the trapped volumes down so that the amount of energy release from this small fire is less than that required to ignite nearby materials. Material selection in the vicinity of the hydrogen tubes is important, as well as spacing.

It is also desirable to limit the flow rates (by use of orifices and tube sizing) of the various regulators and lines to be just slightly more than that required by the fuel cell at full power. An “excess flow valve” may also be useful here. Pressure measurements on the intermediate and low pressure lines can also detect a breach by a rapid decrease in pressure, and shut off the solenoid valve in the tank.

Another component, which might be on some vehicles, would be a hydride storage device of some kind. These will not be housed in a pressure vessel which could hold the full pressure if all the hydrogen were released from the hydride. Thus, there will have to be a pressure relief device, and all of the hydrogen could be driven out. This could happen if the hydride system were exposed to an electrical fire or gasoline pool fire. It is important for this scenario that the hydrogen be safely vented to where it will not burn, or where it will not cause secondary fires if it does burn.

The fuel cell itself does have a small inventory of hydrogen. In a crash, the fuel cell could easily be crushed and the hydrogen could cross the membrane. The fuel cell probably cannot be designed to contain the resulting pressure, so it will be necessary to safely vent any products.

Reformer systems will also have some inventory of flammable and hot gases which must be managed.

In summary, the most important countermeasures include:

1. The location and protection of major components and the routing of electrical wires and fuel lines;

2. The selection of low flammability materials which might be exposed to electrical or hydrogen fires. (And also might be exposed to gasoline pool fires from another vehicle); and

3. The rapid disconnect of electrical and hydrogen sources after detection by the vehicle crash sensors for crashes over a specified severity. The hydrogen can also be shut off due to a variety of system sensors such as low or high pressures or temperatures in various lines or components.

5. Potential Research Tasks

I will now describe some straw man research tasks which might be worth doing. As stated before, MVFRI would like feedback from any of you or your colleagues as to the value of such research, and whether similar tasks have been adequately done before. If they have been done, please send us a reference.

1. Vehicle buck ignition and flammability tests.

One could use an underbody buck of the whole or a portion of a vehicle prototype. The tank location and plumbing and surrounding materials should be realistic. One could then make controlled releases of hydrogen at the leak rate and position of a severed part of the intermediate or low pressure tubing. Ignition sources, probably electrical arcs, could be created at various distances from the leak.

Questions which could be investigated include: (1) how close does the ignition source have to be to the leak to get ignition? (2) Is ignition desirable over letting a hydrogen cloud build up and then perhaps cause a larger energy release or even explosion? (3) How quickly does the hydrogen shut-off and electrical disconnect have to work to avoid igniting secondary fires in nearby materials? (4) What is the best venting strategy for the tank, reformer, hydride, and FC? (5) vent locations; (6) active versus passive ventilation systems (if active, is the ventilation fan always on or is it triggered by a hydrogen sensor?); (7) materials selection; and many others.

One could also examine whether there are situations where a man-made ignition source is desirable to prevent a larger accumulation of hydrogen.

2. Develop a sled test for a bare compressed gas tank and regulator

A sled test has been developed by BMW to test plastic fuel tanks used for gasoline. Perhaps a sled test for the carbon fiber tanks could be developed. The tank (and all of the components which are exposed to high pressure) could be placed stationary up against a fixed barrier and hit with a moving barrier with an appropriate amount of momentum. A starting point might be a 3000-pound barrier moving at 50 mph. Such a test would be cheaper than full scale vehicle crashes, and might be more reproducible.

Issues include the amount of deformation of the two barriers. Should they be rigid or deformable? Perhaps the FMVSS 214 deformable barrier used in side impact could be utilized. Would it be desirable to also test with sharp sheet metal that could cut tank fibers?

One could study: (1) the orientation of the tank and regulator which is most vulnerable? (2) the pressure at which the tank is weakest; (3) the mechanical impulse if there is a rupture; etc.

3. Pool fire test

One could develop a pool fire test which uses a vehicle underbody buck. This could be similar to the ECE-R34 test for plastic fuel tanks for gasoline. This would be more realistic than the bare tank bonfire test because the tank would be in the intended location and integrated with the vehicle. The flame flow would be affected by the vehicle configuration which in turn would affect the heating of the tank, regulator, and the pressure relief device. The test should probably be done with hydrogen in the tank.

One could study: (1) the proper operation of the pressure relief device(s). (2) tank venting and survivability at different initial pressures, etc.

4. Small and/or intermediate scale material flammability tests with a hydrogen flame.

Material flammability is done in the laboratory using one of several types of equipment: the FMVSS 302 Bunsen burner horizontal burn test; a cone-calorimeter test (ASTM E 1354); or the Factory Mutual Fire Apparatus (ASTM E 2058). The 302 test is very lenient and very out of date, and needs to be upgraded [13]. The cone calorimeter is now widely used for flammability tests. The sample is subjected to a radiant heat flux and the time to ignition, heat release rate, toxic gases, and other properties can be measured. GM performed a series of tests on *interior* materials at SwRI using the cone, and NHTSA is currently testing “exterior” materials with the same device.

The cone calorimeter and the FM apparatus both use radiant heat transfer to heat the sample. In the case of hydrogen it is known that very little radiation is given off by the flame due to the lack of carbon. To get a heat flux into the sample, the flame will actually have to impinge directly on the sample. This will mainly involve convective heat transfer. This can be calculated for simple geometries, but may have to be done experimentally for complex configurations and flame geometries such as under a vehicle. Such testing will also be valuable for validation of combustion and material ignition computer models.

Basic combustion principles show that only the heat flux matters for ignition, independent of whether the heat is transferred by convection or by radiation. Combustion and flame spread is affected by the flame of the burning materials rather than the hydrogen. Thus, a lot of information from previous tests can be used to select materials for use on hydrogen-fueled vehicles.

5. Self-ignition experiments

Venting hydrogen can sometimes self-ignite. One possible explanation is that particulate matter in the flow (from within the fuel system, or from external debris) can acquire a static charge and cause a spark. The low ignition energy of hydrogen (ca 20 micro joules) can then ignite the flow. This phenomenon is rare, and not very repeatable.

It might be desirable to conduct some purposeful venting events with known loads of particulate matter to see under what conditions self-ignition occurs. The plumbing could be configured to be typical for a vehicle application.

The results of this work could help with the design of vent systems and pressure relief devices, and help to set cleanliness requirements for the tanks and their fuel.

6. Development of reliable, low cost, hydrogen sensors for on-board application

Some developers may wish to enhance safety by having on-board hydrogen sensors. These could be used to alert the driver, turn on ventilation fans, and turn off the high pressure hydrogen supply. Note that a battery hybrid FC vehicle has the advantage that you could shut off the hydrogen and still operate the vehicle on the battery for a safe and controlled stop, or maybe even have enough range to get to a service station.

Current hydrogen sensors are fairly expensive, and some will also respond to gases other than hydrogen (catalytic combustion types).

7. Design of debris shields to protect tanks and other components

It is known that fuel tanks on conventional cars and light trucks are damaged by road debris. The same will be true for hydrogen tanks and perhaps other critical systems.

A debris shield can be designed to protect against rocks and materials with specified velocities. There may be disadvantages, however. The shield will change the heat transfer to and from the tank or component. That could be good or bad. If it protects the tank from a pool fire, that would be good. If it prevents the thermally actuated-pressure release device from working as intended, it would have a bad outcome.

Such designs will be highly vehicle-specific and are probably best left to the vehicle manufacturers.

6. Summary

Some potential crash-induced fire safety issues and possible countermeasures have been discussed. Those, in turn, led to a list of straw man research projects which might be worth doing.

I urge you to comment on these activities, and propose additional ones which I may have missed. If you think that any of the tasks have already been done, please tell us and provide a reference. Or if you think there is no need to do a particular task, I want to hear that also. If you have suggestions as to organizations that would be good candidates to perform the research, also let me know. Please send your comments by e-mail to: rodys@earthlink.net

MVFRI has not yet decided whether we will actually fund anything in the hydrogen area.

7. Curriculum Vita

R. Rhoads Stephenson has a PhD in Mechanical Engineering from Carnegie Mellon University. He spent 36 years at Caltech's JPL and worked in both the energy and space areas. He is now retired and a consultant to MVFRI. In the mid-70's he headed an assessment of advanced automotive power plants which was funded by a grant from Ford [14]. The study included an assessment of all kinds of heat engines as well as alternate fuels, electrics, hybrids, and fuel cells. He was head of R&D for the National Highway Traffic Safety Administration (NHTSA) from 1978 to 1981.

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