System-Level Design and Verification Concepts for Hydrogen-fueled Vehicles: Fireworthiness

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ABSTRACT:

Safety is inherently a systems-level engineering challenge. The system design determines the placement of the storage system, the plumbing and pressure regulation, the pressure relief device(s), and the electronic controls.

Vehicle crashes are common and must be accommodated in the design. It is anticipated by all that there will be a top-level vehicle Crashworthiness standard for hydrogen vehicles similar to the U.S. Federal Motor Vehicle Safety Standard (FMVSS) 301 for gasoline or FMVSS 303 for Natural Gas (NG). These standards limit the amount of fuel leakage after a crash and thus contribute to fire safety.

The hydrogen fuel system (and fuel cell) can also be attacked by fire. A fire could result from an ignited hydrogen leak, a gasoline pool fire from an impacting vehicle, or from a fire in the passenger compartment started from an electrical, match, cigarette, or other ignition source. A vehicle-level, performance-based Fireworthiness Standard is proposed.

KEYWORDS : *Fireworthiness, Bonfire Tests, Pressure Relief Devices, Active PRD, Remote Defueling*

INTRODUCTION

Vehicle Crashworthiness standards such as FMVSS 208 (frontal impact) and FMVSS 214 (side impact) are conducted at the vehicle-level (pre-production or production vehicles). Survivability of the vehicle occupants is measured by performance-based injury measurements on instrumented crash dummies.

Vehicles can also be attacked by fire – with or without a crash. Sometimes this fire is from an external source such as from a burning building or an impacting vehicle. In other cases the fire originates in the vehicle – the majority of cases starting under the hood (Refs. 1-3). Crash-induced fires are the most dangerous because the occupants may be injured or entrapped.

Post-crash survival standards are in the FMVSS 300 series of standards in the U.S. FMVSS 301 (for gasoline and diesel) and FMVSS 303 (for NG) subject the entire vehicle to frontal, side, and rear impacts and limit the amount of fuel leakage.

FMVSS 302 is the only standard which addresses the flammability of the materials used in the vehicle. It is clearly NOT a vehicle-level test and it does not assess the survivability of the occupants. Further it only applies to certain materials in the passenger compartment and was originated to combat interior fires caused by matches or cigarettes.

It is proposed that we adopt a vehicle-level, performance-based test based on the ECE-R34 Annex 5 test procedure applied to plastic fuel tanks in Europe. This is being proposed in the context of hydrogen vehicles, but the same test protocol could also be applied to conventionally-fueled vehicles.

VEHICLE BONFIRE TEST

ECE R-34 Annex 5 (Ref. 4) was developed when plastic fuel tanks were being introduced. Cars sold in Europe must pass this test. It calls for a vehicle (or vehicle “buck”) to be exposed to a specified underbody gasoline pool fire. The region containing the plastic fuel tank is exposed for 2-minutes, and the test is passed if the tank does not leak. The test is conducted with the tank nearly full with real fuel. See Figure 1.

Figure 1. ECE R-34 Bonfire Test

The author has suggested applying a similar test to hydrogen vehicles (Refs. 5-6). It is suggested that the test duration be extended (to perhaps as much as 20 minutes) to increase time available for rescue. The actual exposure to the external bonfire could remain two minutes as currently used in ECE – R34. For a hydrogen vehicle the fuel should either remain contained or it should safely vent. Safe venting can occur with or without an ignited jet. In either case, the venting should not contribute to the fire spread into the passenger compartment.

In this paper the author suggests actually measuring passenger compartment tenability – with a goal of 20-minute survival time. This could be simply assessed by measuring temperature at eye-level between the front seats and CO concentration at the same place. Pass criteria would be temperature less than 200C and CO less than one percent. These criteria (and others) were used by GM in their full-scale burn tests done at Factory Mutual (Refs. 7-8). Temperature and CO are adequate survivability measures.

Another new suggestion is to use the crashed vehicles from FMVSS 301 or 303 for these tests. The vehicles which have been subjected to frontal or rear crashes will have real world deformations and open seams which will influence the fire paths into the passenger compartment and thus tenability. Also since these vehicles have to be crashed anyway, no additional vehicles would have to be crashed. After the leak tests are performed for FMVSS 301 or 303, the same vehicles could be exposed to the bonfire test. For the rear impact vehicle the bonfire could be performed similar to ECE R-34. For the front impact vehicle, the fire source could either be a pool fire under the front of the vehicle, or a representative fire initiated under the front hood. These could be similar to the ignition scenarios used by GM in their full-scale tests (Ref. 7). One might also want to subject the side impact vehicle (from FMVSS 301 or 303) to an external fire. The goal should be 20-minutes of survival time for the front seat occupants of the vehicle.

This vehicle-level, performance-based test is equally applicable to any form of hydrogen storage – compressed gas, liquid, or one of the many forms of hydride storage.

HYDROGEN STORAGE SAFETY

The hydrogen storage tank needs to be protected from both crash forces and from an assault by fire. In many, but not all, cases the hydrogen will be stored in a pressure vessel. This is certainly the case for compressed hydrogen storage at 5,000 to 10,000 psi (350 to 700 bar), and some hydride containers operate at up to 1,500 psi (100 bar). Most of these pressurized systems use carbon fiber windings held together with cured resins. These resins are flammable and the tank will burst if exposed to fire for a sufficient duration.

FMVSS 304 (and the CSA standard NGV2) contains several tests to ensure the survival of these pressure vessels. The above standards apply to natural gas, but many people expect that there will be a similar test for hydrogen-fueled containers. In this test a bare tank is subjected to a specified bonfire, and the tank is expected to survive for 20 minutes or safely vent. Tanks will rarely survive exposure for 20 minutes, so venting is normally required.

The Japanese Automobile Research Institute (JARI) has studied the bare tank bonfire test and found problems related to the size (fire power) of the fire and the design of the PRD shield. They have also conducted full-scale vehicle burn tests and compared them with the bare tank bonfire test. They conclude (Ref. 9) that “the currently specified flame exposure test will not always represent a real vehicle fire.” They further state “evaluation of safety through a flame exposure test on the actual vehicle is recommended to improve reliability.”

The consequence of a tank burst is very severe (See Figure 2, below). The mechanical energy of a high-pressure tank is tremendous. MVFRI sponsored a test at SwRI (Refs. 10-11) where a tank was tested without a Pressure Relief Device (PRD) to determine the survival time and the consequences of a burst. The tank burst after 6.5 minutes of exposure. Large pieces of the tank were ejected up to 80 meters, and overpressures of 6 psi (41 kPa) were recorded at 21 feet (6.5 m) away. The temperature and pressure of the hydrogen inside that tank did not increase very much – so a pressure-actuated PRD will not work. That is why temperature-actuated PRDs are used.

Figure 2. Hydrogen Tank Burst in FMVSS 304-Like Test

PRESSURE RELIEF DEVICES

The thermally-actuated PRD is the most important fire safety device on the vehicle. It must open when exposed to fire to protect the hydrogen storage tank. PRDs are tested at the component level (the Natural Gas PRD standard is called PRD1 and is issued by CSA) (Ref.12). A hydrogen PRD standard is currently under development. One of the tests is the "benchtop test" where the device is exposed to temperature and its ability to open is verified. This test is performed at 100% and 25% of the full tank pressure.

Many PRD designs require pressure in order to open properly. So the device must also be tested at the lowest pressure at which it is acceptable to let the tank burst. The author suggests that this is about 100 psi (7 bar) based on keeping the overpressure low and reducing the amount of chemical energy which is released into an intruding fire. It is suggested that the 25% test be replaced with an opening test at 100 psi (7 bar).

ACTIVE PRESSURE RELIEF DEVICES AND REMOTE DEFUELING

An active PRD uses an electrical signal to activate venting of any high pressure storage devices. It can be implemented using a normally-closed pyrotechnic valve. It should be used in parallel with a traditional passive PRD. Its advantage is that it can be activated by a wide variety of sensors (such as crash, leak, hydrogen, thermal, etc.) and initiate venting earlier and without having to wait for the fire to attack the tank and PRD. It is also a good solution to a localized fire that may attack the tank but not activate the thermally-actuated PRD.

If an active PRD is used, then it can also be used to provide a remote defueling capability. Remote defueling is extremely important to protect emergency responders who might be hesitant to approach a vehicle with a tank which may be damaged by crash forces and/or fire. (See Ref. 13 for the point of view of a fire brigade). The remote defueling can be initiated by using an IR or RF remote controller using a secure code unique to that particular vehicle.

HYDROGEN RELEASES INSIDE BUILDINGS

Hydrogen releases inside buildings such as residential or public parking structures can be very dangerous because of the explosion hazard. In some situations hydrogen can even detonate – which greatly increases the overpressures and the resulting damage.

The California Fuel Cell Partnership (CaFCP) sponsored a study by Parsons-Brinkerhoff (Ref. 14-15) of hydrogen leaks in 4 types of buildings. A steering committee recommended a medium size leak scenario of 20 CFM as representative of a leak in the intermediate or low-pressure parts of a hydrogen vehicle. They also assume wheel well sensors which would shut off the flow after a short time. The study concluded that these assumed leaks in these buildings were safe without having to increase the ventilation rates.

However, they did not consider the failure of the PRD in which it inadvertently opens and vents the contents of an entire vehicle (or possibly only one tank) of hydrogen in a few minutes (say, 3 minutes). Such high flow rates would not be handled by normal ventilation systems and could result in a very hazardous situation. Thus the PRD represents a single point failure with potentially severe consequences.

The only way to handle this is to set a very high reliability standard for this failure mode (a type-2 failure – when it opens when you don't want it to open). The author has proposed a reliability goal of 10^{-8} per year – which would result in about 2 such incidents per year in the US when there are 200 million hydrogen vehicles on the road. This level is sometimes called eight 9s of reliability. It would be extremely difficult (and costly) to demonstrate such a high reliability for the PRD.

The author suggests that one way to achieve such a high reliability would be to put two thermally-actuated PRDs in series. The combination of two PRDs with four 9's of reliability would yield the eight 9's overall goal. Note that in this arrangement the upstream PRD would have its outlet protected from contamination and water (which could freeze and cause damage). Also the downstream PRD would not be pressurized and would thus be expected to have a much lower failure rate. It would be desirable, however, to monitor the pressure between the two devices to be able to detect if the upstream device has failed.

Putting two devices in series would increase the probability of a type 1 failure (failure to open when it is exposed to fire - since both devices would have to open) – but this may be a good trade-off.

This building hazard is why the PRD must be the most reliable fire safety component on the hydrogen vehicle.

KEEP THE HIGH-PRESSURE HYDROGEN IN THE TANK

With current storage technologies, a hydrogen vehicle will commonly have several tanks in order to have adequate range. The plumbing configuration to interconnect these tanks is a challenge for the fuel system designer.

The tanks themselves are very strong because of the high pressures inside them. This makes them very crashworthy. However, piping and other components external to the tank are more vulnerable in a crash, and if they are damaged in a crash they may result in a high-pressure (i.e. high flow rate) leak.

Fortunately, several manufacturers now make an “in-tank regulator” which screws into the boss of the tank and only releases intermediate pressure (frequently around 150 psi (10 bar)) at the outlet. This configuration is inherently safer and is recommended as a “best engineering design practice.”

VEHICLE UNDERBODY HYDROGEN RELEASE EXPERIMENTS

MVFRI sponsored a series of hydrogen release experiments on a popular SUV at SwRI (Ref. 16). Hydrogen was released at two locations: the first was along the inside of the left frame rail about half way between the fuel tank (which was removed) and the engine compartment. The second location was at the point where the normal gasoline fuel line bends up to enter the engine compartment. Thus this hydrogen release was directly into the engine compartment.

A hydrogen release rate of about 20 CFM (48 g/min) was assumed based on the leak scenario assumed in the CaFCP/Parsons-Brinkerhoff study (Refs. 14-15). This would represent a “medium” size leak in the intermediate or low pressure parts of the fuel system.

The first two series of tests were delayed ignition. The hydrogen leak duration was one second and then the gas cloud was ignited using an “electric match.” The release duration was then successively doubled up to 64 seconds duration. Each ignition produced a loud bang, but did not cause ignition of any vehicle components. The blast was benign until the engine compartment release reached 64 seconds – when the metal hood was buckled from the overpressure. The test was stopped at that point.

Another series of tests was done with immediate ignition at the time of initiation of the hydrogen flow. This resulted in an ignited jet. Again we started with a one second jet and then successively doubled the time. These jets were remarkably benign and only long (16 second) jets resulted in any ignition of the underbody or underhood components.

JARI conducted gas leakage ignition tests at a lower flow rate but for longer durations (Ref. 17). They conclude that “If this hydrogen were ignited, there would be almost no impact on the vehicle itself or humans inside it.”

INCIDENT REPORTING

It is important for standards development organizations (SDOs) to have real-world feedback on how well their standards are working. To this end, there should be incident reporting systems at the SDO, National, and International levels. Any failures of components or vehicle systems should be reported. An international data base should at least include Europe, Japan, and North America.

CONCLUSIONS

1. A vehicle-level Fireworthiness test is proposed to be performed on front, rear, and maybe side crashed vehicles. Twenty-minute tenability in the passenger compartment will be monitored using temperature and CO measurements. If this is done, the bare-tank bonfire test could probably be eliminated – at least in terms of national or international regulations.

2. The thermally-actuated Pressure Relief Device is the most important fire safety device on the vehicle. It must be extremely reliable (ca 10^{-8} per year) to reduce the probability of dangerous releases in

enclosed spaces such as parking garages. It is suggested to put two PRDs in series in order to achieve this level of reliability.

3. An active PRD can provide an additional level of redundancy and can also provide a remote defueling capability to protect emergency responders.

4. A recommended "best engineering design practice" is to use an in-tank regulator on each pressure vessel and to keep the high pressure confined to the hydrogen storage device.

5. Underbody release experiments have shown that both ignited jets and delayed ignition bursts are rather benign.

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