HYDROGEN VEHICLE FUEL SYSTEMS – LOCALIZED FIRE PROTECTION CONSIDERATIONS

Milestone 1

HYDROGEN VEHICLE FIRE SAFETY RESEARCH REPORT

Submitted To:

Transport Canada
Road Safety

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1.0 Objective

Review existing research being performed elsewhere on vehicle fire safety issue involving hydrogen.

2.0 Introduction

The design of compressed hydrogen fuel systems for hydrogen vehicles has been largely based on the compressed natural gas (CNG) vehicle experience. As a result, the test procedures used to qualify on-board hydrogen fuel systems for service use the test protocol developed for the CNG industry. For example, evaluation of fire performance of the fuel system is limited to fire testing of individual components, i.e. the hydrogen fuel tank itself. Similarly, vehicle OEMs perform fire tests of gasoline tanks according to a standard procedure, but they are not required by regulation to perform fire tests of complete vehicles.

Vehicle OEMs do not consider hydrogen-fuelled vehicles any differently than petroleum-fuelled vehicles. Since fire tests of complete vehicles are not required by regulation for vehicles fuelled by petroleum products, CNG, LPG, etc., then OEM's suggest that such a test is not necessary as a regulatory requirement for hydrogen vehicles. As stated by the Japan Automobile Manufacturers Association, "…in vehicle fire testing, all fuel cell vehicles, gasoline vehicles and natural gas vehicles ought to be tested and evaluated under identical conditions"[1], meaning that if hydrogen vehicles are subjected to some special fire test condition, then it should be applied to all vehicle types.

While vehicle OEMs resist any regulatory imposition of fire testing involving vehicles, they do perform a certain amount of in-house fire testing. Essentially all major OEMs involved in the development of fuel cell vehicles have performed fire testing involving complete hydrogen vehicles. This testing has remained confidential to each OEM and is not available to the public.

3.0 Hydrogen Vehicle Fire Testing – Public Domain

3.1 The University of Miami

The first public investigation of hydrogen vehicle fires was conducted by Michael Swain, of the University of Miami, in 2001[2]. The purpose of the study was to produce a "…video comparing

[1] Japan Automobile Manufacturers Association ("JAMA") response to Docket No. NHTSA-2004-18039: NHTSA's Four-Year Plan for Hydrogen Fuel Cell, Fuel Cell and Alternative Fuel Vehicle Safety Research, (www.jama.org/library/technical_comment_2004-10-08.html), dated October 8, 2004

[2] EV World, "Hydrogen Car Fire Surprise" (http://evworld.com/article.cfm?storyid=482), January 18, 2003.

the severity of a hydrogen and gasoline fuel leak and ignition"[3]. Swain ignited hydrogen leaking from a fuelling receptacle on a vehicle, and compared it to the ignition of gasoline leaking from a fuel line. The hydrogen burned away after about 100 seconds, with no heat damage to the vehicle.

3.2 Japan Automobile Research Institute

JARI conducted a series of fire tests at Powertech Labs to evaluate the fire safety of vehicles that use compressed hydrogen as fuel[4,5]. The fire tests were conducted on vehicles that used compressed hydrogen and on vehicles that used compressed natural gas and gasoline and compared temperatures around the vehicle and tank, internal pressure of the tank, irradiant heat around the vehicle, sound pressure levels when the pressure relief device was activated, and damage to the vehicle and surrounding flammable objects.

For the hydrogen vehicle fires, 2 tanks of 24.8 MPa working pressure (and about 65 L water volume each) were installed separately in the trunk compartment of each vehicle, along with high pressure stainless steel lines running to the engine compartment of the vehicle, to simulate the tubing that might exist to supply fuel cell engines. The tanks were protected using thermally-activated pressure relief devices (TPRDs) of VTI glass bulb design, intended for use on CNG tanks. The TPRDs were either provided with vent tubes out of the vehicle, or without any vent tubes to allow the escaping hydrogen to vent into the vehicle. The fires were initiated in the passenger compartment, or a pool fire under the vehicle, and burned until the TPRDs activated.

One purpose of the tests was to identify whether the bonfire test to be required for land vehicle fuel tanks (ISO/CD 15869) applies to vehicle fires. It was found that the internal pressure and the tank surface temperature were different before the TPRDs were activated, compared to the bonfire test. Furthermore, a fireball was formed if the hydrogen gas was vented in the trunk in a gasoline pool fire situation. As a result, JARI concluded that it would be necessary to identify the strength of tanks after the fire test, and to determine a safe way of venting the hydrogen from a vehicle[5].

Another conclusion by JARI was that vehicles equipped with compressed hydrogen gas tanks were no more dangerous than CNG or gasoline vehicles in the event of a vehicle fire[4].

JARI has also conducted in-house studies to understand the impact of a hydrogen-jet flame when the TPRD is activated, on fire-fighting and rescue activities[6]. They investigated a vehicle-fire

[3] M. Swain, University of Miami, EV World, "Fuel Leak Simulation" (2003), http://evworld.com/library/swainh2vgasvideo.pdf), March 25, 2003

[4] J. Suzuki, et al, "Fire Safety Evaluation of a Vehicle Equipped with Hydrogen Fuel Cylinders: Comparison with Gasoline and CNG Vehicles", SAE 2006 World Congress & Exhibition, April 2006, Detroit, MI, USA, Session: Fire Safety (Part 1 of 6): Hydrogen Vehicle Safety (Part 1)

[5] Y. Tamura et al, "Evaulation of the High-Pressure Hydrogen Gas Cylinders in Simulated FCEV Fires", JARI Research Journal, Vol. 24, No. 10.

[6] Y. Tamura, et al, "Evaluating the Thermal Hazard of Hydrogen-Jet Flames in Vehicle Fires Using a Thermal Manikin", JARI Research Journal, Vol 28, No. 7

situation with an upward hydrogen-jet flame from a high-pressure (70 MPa) tank and the resulting skin-burn injuries on a thermal mannequin dressed in fireproof clothing. The results indicated that in the event of a vehicle fire, the upward hydrogen-jet flame was no more dangerous than gasoline.

5.4.3 Motor Vehicle Fire Research Institute

The Motor Vehicle Fire Research Institute has sponsored one fire test of a vehicle equipped with a Type 3 hydrogen tank of 34.5 MPa service pressure, but without a pressure relief device[7]. The purpose of the test was to determine "how far away is safe for rescue and bystanders if the PRD valve does not release".

The vehicle's gasoline fuel tank was removed and replaced with the hydrogen tank, and the vehicle exposed to a propane bonfire in order to simulate the occurrence of a gasoline pool fire on the underside of the vehicle. Measurements included temperature and carbon monoxide concentration inside the passenger compartment of the vehicle to evaluate tenability. Measurements on the exterior of the vehicle included blast wave pressures. Documentation included standard, infrared, and high-speed video. The interior of the vehicle became untenable due to high temperature and carbon monoxide concentration just after 4 minutes into the test. However, this was a result of the bonfire source, not the hydrogen tank. Catastrophic failure occurred in approximately 12 minutes, severely damaging the remains of the burnt vehicle well after its interior had become untenable[8].

To examine the safety of hydrogen-fuelled vehicles, K.H. Digges[9] asked the following questions:

(1) What are the surface temperature and internal pressure responses of hydrogen tanks when exposed to bonfire tests and how do these responses influence the design of the pressure relief device?
(2) What are the failure characteristics of different hydrogen tank designs?
(3) What is an appropriate burn test for hydrogen fuel tanks?
(4) What is the extent of the risk of major vehicle fires (occupant compartment entry) from the hydrogen leakage permitted by a broken fuel line?
(5) What is the influence on the location of the leakage on the risk of a major fire or explosion?
(6) What are the characteristics of the most significant threats associated with hydrogen leakage?
(7) What is an appropriate test to assure the safety of hydrogen fuel lines?
(8) What is the nature of the most significant threats associated with hydrogen fuel tanks and fuel lines subjected to crash induced fires?

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[7] K. Digges & R. Stephenson, "Recent MVFRI Research in Crash-Induced Vehicle Fire Safety, SAE 2007-01-0880, April, 2007.
[8] N. Weyandt, "Intentional Failure of a 5000 psig Hydrogen Cylinder Installed in an SUV Without Standard Required Safety Devices" SAE Document No. 2007-01-0431.
[9] MVFRI Research Summary, Kennerly H. Digges, Research In Fire Safety For Hydrogen-Fueled Vehicles Based On Contracts With: Southwest Research Institute and FIREXPLO.

Figure 1: Hydrogen Tank Bonfire Test Apparatus

In a bonfire test (see Figure 1) that Digges conducted without a TPRD, the composite resin on the surface of the tank ignited after approximately 45 seconds. After 6 minutes and 27 seconds, the tank failed catastrophically through the bottom, launching the 14.0 kg main portion 82 m from the test location. Blast pressures were 300 KPa at 190 cm. The internal temperature and pressure of the hydrogen at the time of failure was 39°C and 35.7 MPa, respectively. The pressure inside the tank did not rise sufficiently so that a pressure-activated pressure relief device would have activated to prevent rupture. The temperature inside the tank also did not climb sufficiently to activate a thermally-activated pressure relief device if it used the *internal* temperature as the temperature source. Digges concluded that it was necessary to locate TPRD's such that they would at least experience the same fire as the tank would.

In a second test in 2006, Digges et al. conducted a bonfire test of a Type 3 (aluminum liner with carbon fibre composite reinforcement) hydrogen fuel tank installed in a "popular" SUV. Again, the test was performed on a tank without a TPRD, so it is only relevant as far as measuring fire temperatures and tank temperature and pressure prior to rupture are concerned, as opposed to testing how an actual system would react to a motor vehicle fire.

The initializing fire was a propane burner (265 kW) that burned until the hydrogen tank burst. The burner pan size was approximately one inch larger that the tank in each dimension.

The fire was initiated and portions of the vehicle became involved (plastic body panels, tires, and then the interior). The temperatures on the underside of the tank quickly rose in excess of 650^{o}C. Measurements inside the vehicle showed that the driver's position space became untenable (CO > 1% and temperature > 200^{o}C) in about 4 minutes. The internal tank pressure remained fairly constant during the first 9 minutes, at which time the pressure transducer failed. The fire continued and grew and the hydrogen tank burst after 12 minutes. Digges concluded, based on analysis of the video and thermocouple data, that is was "very likely" that a TPRD mounted at either end of the tank in this test could have been thermally actuated and prevented the tank from bursting.

Next, Digges examined the effects of hydrogen leaking from broken fuel lines. These tests showed that while there is a high risk associated with tank rupture, a hydrogen fire is a lot less damaging than a gasoline fire.

Similar to the GM tests on gasoline pool and engine compartment fire tests, Digges simulated hydrogen leaks and ignition in passenger vehicles, measuring temperature and heat flux. Underside and engine compartment tests were done, some allowing the hydrogen to accumulate prior to ignition.

In other tests, hydrogen jet-fires impinged directly on the underside of the hood of the engine compartment (see Figure 2). The thermocouple in the direct path of the jet-fire recorded a temperature above 1204°C in each test, but temperatures on the underside of the vehicle did not increase appreciably.

Figure 2: Fuel Line Leakage with Hood Open

Digges[10] observed that only minor overpressures (less than 0.25 psig) were measured from releases on the underbody of the vehicle, and for the low flow rate (24-g/min) releases in the engine compartment. These pressures are not typically considered high enough to cause bodily harm or window breakage. Overpressures nearest the underbody release remained relatively constant with increased duration due to the lack of confinement areas for hydrogen accumulation. At longer durations, the overpressure on the interior of the engine compartment did increase for the underbody releases, although not enough to cause any apparent damage to the vehicle (see Figure 3).

[10] MVFRI Research Summary, Kennerly H. Digges, Research In Fire Safety For Hydrogen-Fueled Vehicles Based On Contracts With: Southwest Research Institute and FIREXPLO.

Figure 3: Fuel Line Leakage with Hood Closed

In fact, in Digges's test damage to the vehicle was minimal for the majority of tests and consisted mainly of burnt plastic components. Temperatures for short-duration delayed-ignition tests were higher in the location of the release, whether on the underside of the vehicle or in the engine compartment. Temperatures for longer duration delayed-ignition tests, however, were consistently higher in the engine compartment, where more hydrogen could accumulate. Heat flux data followed the same trend as temperature data.

High temperatures were evident in the areas of the hydrogen release, and in areas such as the engine compartment, in which the hydrogen could collect. However, these temperatures were brief in the delayed ignition tests, insufficient to ignite surrounding exterior components. In the jet-fire tests, temperatures and heat fluxes were obviously of a magnitude and duration that could cause severe burns or ignite most plastic components. The extent of a jet-fire hazard would ultimately depend on the size, location, and direction of leak. At no time, however, was there a significant rise of temperature in the passenger compartment of the test vehicle.

This is in contrast to what GM discovered when it conducted similar tests with gasoline as the fire's fuel. It is possible that once the problem of hydrogen tank rupture is solved (or at least the risk factor significantly reduced), a hydrogen fuelled vehicle may be considered safer than one fuelled with gasoline.

4.0 Hydrogen Vehicle Fire Testing – OEM Domain

OEM fire testing of hydrogen vehicles has focused on using a point source of fire, i.e. either initiating a fire within the passenger compartment, or using a pool fire beneath the vehicle. One OEM has investigated the effects of a tire fire on an installed hydrogen tank.

The consensus of the OEMs appears to support the idea that the fire testing of a complete vehicle is an expensive proposition, and the results will be highly dependent on how a fire is initiated in or around the vehicle. For example, would the fire commence in the engine compartment, the passenger compartment, from an external liquid fuel source that engulfs the underside of the vehicle, from cargo carried on-board the vehicle, or from a leak in the vehicle fuel system that ignites? It is thus more cost effective to test fuel systems mounted in a simulated installation package.

Many tests have been concerned with the ignition of hydrogen mixtures either leaking into the vehicle, or leaking out of the tailpipe. These tests are not concerned directly with the fire safety of the fuel system, but the consequences of fuel leakage.