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It is requested that a copy of this letter be inserted into any open dockets for FMVSS 301 through 305 and any dockets for future rulemaking on hydrogen-fueled vehicles or for improved fire safety of conventionally-fueled vehicles. If there are no appropriate fire safety dockets open, then please open one or more new dockets for these recommendations.

Subject: Improving Automotive Fire Safety: Recommendations from the Motor Vehicle Fire Research Institute.

BACKGROUND

On March 7, 1995, the U.S. Department of Transportation (DOT) and General Motors Corporation (GM) entered into an administrative agreement, which settled an investigation that was being conducted by the National Highway Traffic Safety Administration (NHTSA) regarding an alleged defect related to fires in GM C/K pickup trucks [NHTSA 1994, NHTSA 2001].

Under the GM/DOT Settlement Agreement, GM agreed to provide support to NHTSA's effort to enhance the current Federal Motor Vehicle Safety Standard (FMVSS) 301, regarding fuel system integrity, through a public rulemaking process. GM also agreed to expend $51.355 million over a five-year period to support projects and activities that would further vehicle and highway safety. Approximately ten million dollars of the funding was devoted to fire safety research [NHTSA 2001].

Subsequent to the GM/DOT Settlement, GM agreed to fund an additional $4.1 million in research related to impact induced fires. This latter research project was included under the terms of a judicial settlement. The fire safety project objectives are defined by the White, Monson and Cashiola vs. General Motors Agreement dated June 27, 1996 [Agreement 1996]. All research under the project has been made public for use by the safety community.

The Motor Vehicle Research Institute (MVFRI) was formed to administer and conduct this research. The work started in late 2001 and was completed in 2009. The purpose of this letter is to inform NHTSA of our major results and provide suggestions whereby the fire safety of autos can be improved. There is a unique opportunity now to take advantage of the results of some $14 M worth of fire safety research to advance the cause of improved fire safety. The MVFRI and GM/DOT reports are all available at: www.mvfri.org

INTRODUCTION

There are about 290,000 vehicle fires per year and about 520 fire fatalities per year [Ahrens 2008]. Many of these fires are non-crash fires which initiate in the engine compartment and can spread to the passenger compartment. Recent FARS data indicates that there are about 400 fatalities per year in crashes with fire coded as the most harmful event (MHE). However, there is substantial evidence that fires are underreported in FARS [Fell 2007 and 2009]. According to NASS data, over 3/4 of the crash related fires start under the front hood and more than half also propagate into the passenger compartment [Digges 2005a]. Fires in these crashes are particularly hazardous if the occupants are injured or entrapped.

FARS data shows that 60% of the fatalities with fire as the most harmful event (MHE) occur in vehicles with frontal damage [Digges 2009c]. Vehicle rollover is present in 28% of the fatalities with fire as the MHE. NASS data shows that for the major crash related fires that enter the occupant compartment, over 60% originate under-hood. For frontal crashes, 85% originate under-hood [Digges 2008]. For rollovers, the under-hood origin accounts for 50% of the major fires [Digges 2007c, 2007e, 2009c]. These statistical studies indicate opportunities for fire safety improvements in preventing or controlling the spread of under-hood fires resulting from frontal crashes and rollovers.

It is recognized that fire safety competes for resources with other safety initiatives. However, there are a number of inexpensive initiatives that can be immediately undertaken to improve fire safety. Our investigation of on-the-road vehicles has shown that extensive fire safety technology has been incorporated in some vehicles, but not others. These results suggest that the lack of attention to fire safety rather than the cost of countermeasures is an impediment to safety improvements. The incorporation of a fire safety rating within NCAP offers an immediate opportunity for encouraging improvements in the fleet. In addition, there are regulatory initiatives that offer opportunities for safety improvements during the near term. In the sections to follow, the highest priority initiatives are those that indicate a need for immediate attention.

POTENTIAL RULEMAKING CHANGES

1. FMVSS 301

    a. Immediately extend the current leakage requirements to all flammable fluids – not just to the fuel which powers the vehicle. Conduct all crash tests (including NCAP) with all electrical systems charged and connected, and with all under-hood fluids present. Set limits on the leakage of all flammable fluids at the same level as the motor fuel and require that the fuel pump and unfused electrical circuits be automatically disabled after the crash [Digges 2007d; 2009b]. In order to better understand the causes of crash induced fires, consider conducting the crash tests with engines hot and running.

    b. Immediately include a door opening requirement after the 301 crash tests [Digges 2009b]. The last time that 301 was revised the rulemaking decision was to drop a proposed door opening requirement because there was no test procedure. See Appendix A for a simple R&D plan to develop a door opening test.

c. Consider a lower fluid leakage limit for all flammable fluids. The original requirement was for a maximum of one ounce per minute of leakage (this was later changed to 28 grams per minute). The selection of this quantity of leak was not based on fire science considering the probability of ignition or flame propagation to other parts of the vehicle. It was principally based on the volume of a carburetor float chamber (carburetors are rarely used anymore since fuel injection has become nearly universal). A lower leak limit should be based on real ignition and fire propagation tests.

2. FMVSS 302

   a. Immediately regulate the flammability of under-hood liners. Measurements show that the heat release rate of under-hood liners varies by a factor of 100 between different vehicles [Fournier 2005]. Since these are attached to the underside of the hood, they are at the top of the compartment and are readily exposed to flames which can then spread horizontally. Using the best of currently used liner materials could reduce the rate of fire propagation and growth.

   b. The fire test procedures developed and validated under the GM/DoT Agreement offer the test technology required to regulate the fire properties of underhood materials. NASS shows that most motor vehicle fires start in the engine compartment and subsequently spread to the occupant compartment. FARS shows that frontal crashes are the most frequent crash mode when fire is the MHE and this harmful frontal crash condition is increasing with time. There are many solid materials under the hood that are flammable and can accelerate the spread of the fire into the passenger compartment. The amount of flammable plastics in the engine compartment has increased with time. In modern cars, plastic materials have surpassed motor fuel as the main fire load. A regulation of fire safety for under-hood materials should be initiated as either an extension of an upgraded FMVSS 302 or a new fire safety standard. See [SWRI 2003].

   c. Most of the fire experts who conducted research on our projects consider FMVSS 302 to be outdated. It was developed 40 years ago when a lighted cigarette was the most frequent threat to originate an occupant compartment fire. In response to the fire threat from an under-hood fire, the tenability time of materials that comply with 302 is less than 5 minutes [Digges 2005b]. Extensive research on alternative test methods has been conducted under NHTSA, GM/DOT, and the MVFRI projects. Consider requiring a better test method with more stringent acceptance criteria that will result in less flammable interior materials. See [Digges 2007a, SWRI 2003 and FM 2005] for more discussion.

3. FMVSS 303

   a. Upgrade the rear impact speed and barrier to match that of FMVSS 301.

4. FMVSS 304

   a. Consider replacing the tank-level bonfire test with a vehicle level-test. (See Appendix B for a proposed compressed gas vehicle burn test). Appendix B is written in a way that it can be applied to both compressed H2 and CNG vehicles.

b. If you decide not to require the vehicle-level test, consider adding a localized fire tank test which will simulate a tank exposed to a localized fire away from the location of the PRD.

c. The bonfire test fire should be standardized. You should specify the fuel (propane or LPG) and the heat release rate. We suggest using a flow rate that will provide 300 kW of fire power [Zalosh 2005, Tamura 2006]. Standardizing these parameters will make the test more repeatable from test-to-test and from test facility to test facility. Steps should also be implemented to shield the tank test area from wind. These improvements should reduce the standard deviation of the exposure heat input.

d. If you decide to keep a bare tank bonfire test similar to FMVSS 304, then consider performing an additional tank bonfire test without a PRD to establish the baseline tank burst time. This gives information about the tank. This information will allow you to establish a time margin between the beginning of fire exposure and the time of tank burst. (See Appendix C for more details)

5. FMVSS 305

   a. Upgrade the rear impact speed and barrier to match that of FMVSS 301. (A current NPRM proposes to do this.)

   b. Add a requirement that there be “no fire” after the vehicle crash tests. This will address the possibility of a fire starting in or around the high-energy traction battery.

6. Future Hydrogen Fueled Vehicle Standards

   a. See Section 4 (a) above. We propose that you consider a full vehicle burn test for compressed gas vehicles. See Appendix B for recommendations.

   b. A hydrogen (H2) blue diamond sticker should be required on the back of the vehicle. This is for the benefit of emergency responders.

ADDITIONS TO THE NCAP TESTS

1. Immediately expand NCAP to include ratings for fire safety and ease of egress. Test the vehicle with all the electrical systems charged and connected, and under-hood fluids present. Prior to the crash test subject the vehicle to a spit rollover and determine the degree to which the fuel pump and the unfused electrical system have been isolated. Measure any fluid leakage during the spit rollover. Repair the electrical system as needed and conduct the crash test. Determine the functioning of the features for automatic electrical isolation after the crash. Measure all fluid leakage after the crash and during the subsequent rollover. Base fire safety ratings on the extent of containment of flammable fluids and electrical isolation. Measure the force required for door opening and the extent to which the seatback deformed or collapsed. Provide safety ratings based on the fire safety and ease of egress after a crash (See Appendix D and Digges letter to NHTSA Administrator dated April 3, 2007, Attachment 1).

2. For liquid-fueled vehicles, consider adding a vehicle burn test after the FMVSS 301 frontal crash (See Appendix D). Begin the burn under the hood. Monitor CO and temperature inside the passenger compartment in the vicinity of the driver's head. Record the time to untenability and base the "star rating" on the untenability time. Suggest 5 stars for 30 minutes of survival time.

3. For Compressed Natural Gas vehicles consider a burn test starting in the engine compartment and ensure that the NG tank(s) vents down to 20 bar before the tank bursts.

4. For Compressed Hydrogen vehicles consider a burn test starting in the passenger compartment to ensure that the H2 tank(s) vents down to 20 bar before the tank bursts (see Appendix B).

STATE PROGRAMS SUGGESTIONS

1. Develop a procedure in conjunction with the states to require high pressure compressed gas (H2 or CNG) tanks to be periodically inspected and also taken out of service at their end of certified lives (or to ensure that the tank has been recertified for additional life). The vehicle registration system can be used for this purpose – similar to that done for emission controls in several states. [Stephenson 2008]. Initiate activities to provide inspection agencies with the legal authority to remove an unsafe tank from service without the vehicle owner's permission.

NATIONAL CENTER FOR STATISTICS AND ANALYIS (NCSA) SUGGESTIONS

1. Immediately initiate programs to reduce the underreporting of fires and fires as most harmful event (MHE) in FARS. See [Griffin 1997 and Fell 2007, 2009]. Provide training for FARS technicians to assist in identifying fire cases through sources other than the PAR. Provide training in accurate coding of cases where fire is the MHE. Encourage all states to include "box" for coding for crash related fires in their Police Accident Report (PAR). The average fire rate for the states with this feature is 25% higher than the average rate in FARS [Fell 2009].

2. Initiate programs to improve the reporting of entrapment and rescue times in FARS. The state-to-state variation in entrapment is very large [Fell 2009]. The definition of entrapment in the PAR may vary from the FARS definition. It is important to distinguish between the arrival times of various emergency responders (police, fire, paramedic/ambulance, and the fire truck with the "jaws of life" for extrication).

3. Initiate programs to determine the effectiveness of the new 301 standard.

4. Perform a study (perhaps in conjunction with NFPA) to determine the relative frequency of electrical, hot surface ignition, or mechanical sparks as the ignition source in under-hood fires.

5. Develop statistical distributions of emergency response times. This can perhaps be done in cooperation with the automatic crash notification (ACN) companies. This can help set survival time goals for fire protection materials and systems.

6. Add a field to the NASS and FARS systems which uniquely identifies the primary fuel used by the vehicle (gasoline, diesel, E-10, E-85, bio-diesel, propane, natural gas, hydrogen, pure electric, plug-in electric, etc.)

7. It would be desirable to know the frequency of liquid fuel pool fires under vehicles. The fuel source can be from either the vehicle with fire induced injuries or an impacting vehicle without fire injuries. Consider adding a NASS field to include this observation.

RESEARCH AND DEVELOPMENT SUGGESTIONS

A. Compressed Hydrogen and Natural Gas fueled vehicles

Some of the items below may be mature enough for rulemaking. Others may require additional R&D to develop test procedures and to quantify benefits.

1. Develop a vehicle-level fire test (perhaps in conjunction with DOE)

   Rationale: The current tank-level bonfire test is a good pre-qualification or screening test, but it does not represent real world vehicle fires. We have had recent tank bursts with the Crown Victoria and Honda Civic CNG vehicles where a vehicle fire attacked a tank in a localized area and the PRD did not activate. Each vehicle model is a unique design, so rather than trying to develop a localized bare tank fire test, it will be much more representative to do a full-scale vehicle burn. We suggest the use one undamaged vehicle plus the vehicles crashed under the Fuel System Integrity test (the assumed H2 equivalent of the FMVSS 301 and 303 tests). See Appendix B for a suggested test.

2. Develop and test a localized fire test.

   The vehicle-level burn test is preferred, but some may prefer to develop a localized fire test. This will need additional R&D

3. Develop a new generation of PRDs which are sensitive to heat along a line rather than at a point.

   Rationale: Modern composite tanks are very good insulators and do not conduct heat well in the longitudinal direction. Current design PRDs are usually mounted at one end of the tank and may not get hot enough to activate. A linear-sensitive PRD could extend the entire length of the tank, and provide much better fire protection. See SwRI test reports and summaries in [Digges 2006; 2007b]. Appropriate rulemaking (not using the fully engulfed fire of FMVSS 304) may incentivize the development and use of linear-sensitive PRDs.

4. Develop and test a new furnace-based PRD activation test.

   Rationale: This is the only test which shows that the PRD actually activates when heated and, thus, works as designed. The new CSA HPRD1 standard has changed the PRD activation test from the old CNG “Chimney Test.” The new test needs to be specified more completely and validated. It can probably be performed in a commercially-available, temperature-controlled oven.

5. Validate the new PRD creep test.

   Rationale: It is important that a PRD not open when there is no fire. This would be very dangerous if it were to happen inside a building such as a parking garage. Creep of the eutectic materials used in most PRDs can allow this type of failure to happen. The new CSA HPRD1 standard requires a 500-hour accelerated creep test. This test needs to be validated with longer duration testing to make sure that the creep properties are linear and will prevent this type of failure for the lifetime of the PRD (which could be up to 25 years).

6. Continue numerical modeling of tank temperature distributions when exposed to fire.

   Rationale: DOT/RITA funded the first year of such an effort at the University of Missouri at Rolla. [Hu 2008]. It would be useful to extend this work to cover type 4 tanks. RITA has lost their funding for the extension of this work and it would be very useful if NHTSA and/or DOE could find a way to continue this work.

B. Conventionally Fueled Vehicles

1. Develop statistics and field experience to determine the relative frequency of under-hood fires caused by hot surface ignition, electrical shorts, and mechanical sparks. (See NCSA item 4, above).

2. Develop statistics on the benefit of battery disconnect devices in reducing the incidence of electrical fires. Several models of vehicles have pyrotechnic battery disconnect systems that are initiated with air bag deployment.

3. Develop the basis for a standard to delay the spread of fire from the engine compartment to the occupant compartment. Existing vehicles have a wide variation in the size of openings in the bulkhead [Digges 2007c]. Engine compartment burn tests conducted under the GM/DoT project found occupant compartment penetration occurred in as little as 10 minutes in two different vehicles tested. Another vehicle resisted occupant compartment fire penetration for 23 5 minutes [FM 2005]. This difference illustrates that there are opportunities for delaying the progression of the fire.

4. Consider developing the basis for specifying fluid containment levels in the 301 tests based on fire propagation properties. Consider research to investigate hot surface ignition (HSI) of flammable under-hood fluids with mists, continuous flow, and mixtures of flammable fluids. Most research on HSI is currently done with single fluids and single drops (or small quantities) on a controlled hot surface in the laboratory.

5. Consider developing the basis for a standard test for under-hood fire suppression systems. Lack of a standard inhibits the development and application of promising systems. Several companies have developed under-hood fire suppression systems and Ford offers a tank fire suppression system on the police Crown Victoria. Non-crash fires may justify the cost and there may be additional benefits for crash fires.

6. Consider research to investigate ways of keeping flammable under-hood fluids from leaking and splashing onto hot engine compartment components after a crash. Develop specifications for improved protection of fluid lines and containers.

7. Consider research to develop non-flammable or less flammable under-hood fluids. (Order of priority: brake fluid, power steering fluid, engine oil, transmission fluid, engine coolant, windshield washer fluid). We suggest working with the auto industry and fluid suppliers – perhaps in conjunction with USCAR.

8. Consider research to periodically evaluate the safety of plastic tanks when exposed to pool fires and crash induced impacts. Limited tests by MVFRI indicated that all six of the plastic tanks tested appeared to be designed to pass the ECE R34 Standard for pool fire exposure. Three new tanks exposed to the impact test specified by Standard CFR 393.67 passed the test. However, two of three tanks taken from service failed the test. The results suggested that the tank seams of some plastic tanks may degrade with age [Digges 2003].

CONCLUSIONS

The charter of MVFRI was to focus on auto fires caused by crashes. We have built on the impressive body of work done by GM/NHTSA under the DOT settlement. Extensive work was done by the authors of this letter, various consultants, and by contracts with research organizations. We have developed extensive insight into fire safety issues and have presented many suggestions which can be used to advance the fire safety of current as well as future (hydrogen) vehicles. These suggestions have been described above and summarized in our numerous ESV papers.

We stand ready to brief NHTSA and discuss these items further.

Sincerely yours,

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Note: Additional information and reports on our work are available at: www.mvfri.org

APPENDICES

A. Door Opening Test Procedure

B. Compressed Gas Vehicle Burn Test

C. Bonfire Test Burst Time Margin

D. NCAP Test for Fire Safety

Appendix A

DOOR OPENING TEST PROCEDURE

Background:

FMVSS 301 currently does not require that the doors on a crashed vehicle be able to be opened. Such a requirement was considered by NHTSA during the last revision of FMVSS 301 but it was not included due to the lack of a door opening test procedure.

The first part of this paper is the proposed test procedure, and it is recommended that this be added to FMVSS 301. The second part of this paper describes a simple R & D project to determine a reasonable value for the maximum door opening force.

Proposed Door Opening Test Procedure for FMVSS 301:

1. The vehicle should be subjected to the three crash tests as specified in the upgraded FMVSS 301. A given car only needs to be crashed once.

2. At least one door per seating row which has a door must be able to be opened after the crash. This should apply to both hinge and sliding doors.

3. The door latch should be able to be unlatched with a force (or torque) no more than twice that which is needed for an un-crashed vehicle.

4. After the crash, the door should be able to be opened by applying a force of no more than X pounds. This force can be applied from either the inside or the outside of the door. For the inside, the force should be applied at the normal shoulder position with the seat far forward. For the outside pull, the force should be applied at the door handle.

R & D test to determine the maximum door opening force:

It is suggested that the maximum allowable door-opening force, X, be determined by doing a simple experiment on a few un-crashed cars.

The latch should be removed entirely. Then attach a load cell to the door. Have several volunteers push or pull on the door as hard as they can. The subjects should include an elderly woman, a 5% adult female, and a 50% male. They should both push from inside the car, and also try to open the door from the outside (as if they are trying to rescue someone). The load cell will hold the door in fixed position. The door does not need to actually open in this force test.

Once the data is in hand, NHTSA can set the force maximum by deciding what percentile of the population you want to protect. Maybe the 5% female will be enough and not design for the frail elderly. You might assume that the rescuer (from outside) will on average be stronger than the occupant inside.

It should be possible for VRTC to do all the necessary tests in a week or so. The tests should be cheap because the vehicles will NOT be damaged. This does not require any crash tests.

It would also be a good idea to request a copy of the door opening test procedures that the OEMs use.

Appendix B

Compressed Gas Vehicle Burn Test

Scope: This is a proposed comprehensive vehicle-level test for compressed hydrogen or compressed natural gas vehicles. It can be used to replace or supplement the current fully-engulfed, bare-tank bonfire test (FMVSS 304 or a future hydrogen version of it).

Rationale: There are about 290,000 vehicle fires per year and about 520 fire fatalities per year [Ahrens, 2008]. Many of these fires are non-crash fires which initiate in the engine compartment but can spread to the passenger compartment. Over 2/3 of the crash fires start under the front hood (for conventionally fueled vehicles with IC engines) and more than half of the external fires also propagate into the passenger compartment [Digges 2005a]. These crash-induced fires are particularly harmful when the occupants are injured or entrapped. As vehicles become more energy efficient, increasing amounts of plastics and other flammable materials are being employed. Consequently, the amount of fuel available to feed an external fire is expected to increase. When fires spread to the occupant compartment, they could pose a threat to the compressed gas tank and its pressure relief device. In view of the large number of vehicle fires, occupant compartment fires could be expected to pose one of the greatest threats to the reliable function of the pressure relief device.

Many of the 290,000 vehicle fires are extinguished, but some will burn for a long time and can attack the compressed gas fuel storage tank(s). If a compressed gas tank explodes, there can be additional harm to emergency responders and by-standers, or to surrounding buildings.

Compressed gas tanks are protected from burst by one or more thermally-activated Pressure Relief Devices (PRDs). The PRD is sensitive to the increased temperature caused by a fire and is supposed to open and vent the contents of the tank(s) to the atmosphere before the tank wall structure becomes weakened and bursts.

Bursts of a high pressure tank are very damaging because of the large amount of mechanical potential energy stored in the tank – independent of the chemical energy contained in the fuel. Recent real world incidents and tests have shown the catastrophic results of high pressure tank bursts [Zalosh 2005, Weyandt 2007, Hansen 2007, Perrette 2007 and Stephenson 2008].

In an MVFRI research project [Zalosh 2005] a typical Type 4 composite 5000 psi compressed hydrogen tank was exposed to a bonfire to evaluate the consequence of fire induced tank rupture. The tank was tested without a PRD. The composite tank material supported combustion after about 45 seconds of exposure to the bonfire and ruptured after about 6.5 minutes. In this test, blast pressures of 6 psi were measured 21 ft away from the tank, and debris weighing 30 lbs. was propelled more than 250 ft. At the time of tank rupture, the pressure inside the 5,000 psig tank had only increased by 180 psi and the temperature at the cylinder ends had risen only to 103 ^{o}F.

In another MVFRI research project [Weyandt 2007], a typical Type 3 (aluminum liner) 5000 psi compressed hydrogen tank was mounted under an SUV and exposed to a bonfire test. The tank was tested without a PRD. Tank pieces and various vehicle components were ejected up to 300 feet from the vehicle. An exclusion zone if 150 feet was required to avoid overpressure greater than 0.3 psi (a lower limit to avoid ear drum damage to humans). However, higher overpressure could occur beyond the 150 feet radius if reflected waves from surrounding buildings came into play [Weyandt 2007].

In two recent incidents the fire started in the passenger compartment and attacked the tank(s) through holes in the back of the rear seats [Hansen 2007, NHTSA]. These two incidents occurred in vehicles made by OEM vehicle manufacturers – so these problems are not limited to aftermarket vehicle converters. The tank bursts are thought to have occurred because the fire attacked the tank away from the PRD and the PRD did not get hot enough to activate before the tank burst.

Every vehicle model design will have a unique tank(s) placement, vehicle geometry, and different pathways for the fire to approach the tank(s). Some will have physical (metal) or thermal barriers surrounding the tank compartment. The best way to demonstrate the correct operation of the PRD(s) is to conduct a real vehicle burn test.

Proposed Test Procedure: Four vehicles should be tested:

(1). An undamaged vehicle
(2). A vehicle after conducting the FMVSS 301 rear impact test*
(3) A vehicle after conducting the FMVSS 301 side impact test
(4) A vehicle after conducting the FMVSS 301/303 frontal impact test

The Following Procedures Apply to Tests of Vehicles 1 through 3:

The vehicles should be fully fueled and all the electrical systems charged and connected.

The ignition source for the fire should be a rag soaked in alcohol. It should be large enough to ensure ignition of the passenger compartment materials. It should be placed under the dashboard or on the floor under the dashboard. Two windows should be partially opened to provide adequate ventilation for the fire to spread.

It is suggested that the fire be started in the front passenger compartment because:

(1) There may be many fewer under-hood fires in H2/fuel cell vehicles.

(2) Even if the fire starts under the front hood, the fire doesn't become dangerous until it spreads into the passenger compartment.

(3) In many H2 vehicle configurations the H2 tanks are toward the rear of the vehicle

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* FMVSS 301 is specified for the rear impact since it has a higher rear impact speed (80 km/h) than FMVSS 303 and uses the deformable barrier.

The Following Procedures Apply to Test of Vehicle 4:

After being subjected to the FMVSS 301 frontal crash, the vehicle would be tested for fire safety in the event of a major under-hood fire. The test vehicle should be fully fueled and all the electrical systems charged and connected. The ignition source should be located near the front of the engine compartment The fire test procedure should be similar to that recommended by Hamins and incorporated in a research projected funded by MVFRI [Gunderson 2004]. This test procedure involved initiating a fire of a sufficient intensity to ignite conventional engine compartment solid materials and fluids. Two passenger compartment windows should be open as in the tests of vehicles 1 thru 3.

It is proposed that the fire be started in the engine compartment because:

(1) Most fires in frontal crashes originate there [Digges 2005a]

(2) About 2/3 of the crash fires with fatalities originate there [Digges 2005b]

(3) Most under-hood fires are fueled primarily by under-hood fluids and solid materials other than the motor fuel [Digges 2008].

Instrumentation: The pressure in each compressed gas tank shall be measured in a way which will survive the fire. A recommended way is to run high-pressure tubing from the tank(s) to several feet from the vehicle and attach the pressure transducers to the end of the tube(s) away from the fire. The pressure instrumentation will confirm that the tanks have vented down to at most 20 bar without burst.

Test Criteria: A successful test is one in which the compressed gas tanks vent to less than 20 bar (ca 300 psi) before any of the tanks burst.

If the fire goes out, or does not spread in the direction of the tank(s), the test should be repeated with a larger ignition source fire. It is necessary to provide adequate ventilation to ensure that the fire spreads and grows.

Safety Caution: If a tank has been exposed to fire and is still pressurized, it can still burst – even after some delay. Personnel should stay safely away from the vehicle until the tank is de-pressurized. This can be accomplished by a remotely activated valve (not in the fire zone) or by puncturing the wall of the tank with a rifle bullet.

Discussion: A full-scale vehicle burn test was conducted by SwRI [Weyandt 2007]. In this case the ignition source was a propane burner under the vehicle simulating a pool fire.

GM conducted a large series of well-instrumented vehicle burn tests under its agreement with DOT [Project 3.B]. These were for conventionally-fueled vehicles.

It is believed that several OEMs have performed vehicle burn tests for CNG vehicles – in some cases to validate the fix for the tank bursts [Hansen 2007, NHTSA]

Another report containing over 20 vehicle burn tests with heat release rate versus time curves is available [Janssens 2008].

So clearly performing such vehicle burn tests is feasible.

It should also be noted that the government and industry have been conducting full scale crash tests for occupant crash protection for many decades. It is obvious that testing a complete vehicle is preferable to testing the various components that are involved in a vehicle crash. A similar rationale shows that a complete vehicle burn is the best way to demonstrate vehicle fire safety. The best way to test a complex system is to test it as a complete vehicle system.

Advantages of performing this vehicle burn test include:

1. The combustible materials are those of the real vehicle.

2. The flame spread paths are the same as for the actual vehicle. Thus the direction that the fire attacks the tank(s) is representative of the real world

3. The tank(s) and PRD(s) are in the intended positions relative to other parts of the vehicle.

4. All physical and thermal barriers are in place as designed.

5. The PRD(s) will then experience real temperatures which should demonstrate that it can protect the tank(s). Demonstrating this during the design qualification phase will prevent accidents and possible recalls after the vehicles are on the road.

6. Test vehicles 2, 3 and 4 would have real world crash deformations and are performed in standardized tests used by the government and industry for many years.

Disadvantages of performing these tests:

1. There are personnel safety issues that must be carefully considered (there are similar issues with the current bonfire test.)

2. One additional vehicle (the undamaged one) will need to be tested. (Note: the front, rear, and side impact vehicles already need to be crashed for FMVSS 301/303).

3. Cost of performing the four tests.

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Appendix C

Bonfire Test Burst Time Margin

Scope: This test procedure applies to any high-pressure Compressed Hydrogen or Compressed Natural Gas vehicular storage tanks.

Rationale:

A vehicle-level burn test (See Appendix B) is preferable to a bare-tank bonfire test. But if it is decided to keep the tank-level (or high pressure containment system) bonfire test, then it should be improved to provide a burst time margin.

The current fire exposure test (bonfire test) for compressed gas storage tanks and their protective thermally-activated Pressure Relief Devices is a pass/fail test on a single tank. There is no information on whether the tank "passes" (fails to burst) by 5 seconds or 5 minutes.

Tank burst is a very violent event [Hansen, 2007; Perrette, 2007; Weyandt, 2007; and Zalosh, 2005]. These referenced tests and real-world tank explosions caused by fire show that sizable tank and/or vehicle fragments can be thrown up to 350 feet. These fragments can do damage to people or property and thus the probability of occurrence of a tank burst must be kept very low.

Other common tank-level tests which are designed to avoid burst have explicitly known margins.

-Tank burst – >1.8 times nominal working pressure
    -Sample size in design qualification = 3 (SAE J2579 Section 5.2.2.3.3)

-Fatigue life – 3 times expected number of cycles.
    -Sample size in design qualification = "at least one" (SAE J2579)

Proposed Test Procedure:

The bonfire should be set up as specified in FMVSS 304 (CNG) or SAE J2579 (H2).

One tank should be bonfire tested without a PRD to establish a baseline tank burst time.

A second tank with the PRD and other specified hardware in the high pressure containment system should be tested as specified in FMVSS 304 or SAE J2579. Subsequent to the bonfire test, the tank should be pressurized until burst (without the PRD) to determine its strength margin.

Instrumentation: The pressure in the compressed gas tank should be measured in a way which will survive the fire. A recommended way is to run high-pressure tubing several feet from the tank and attach the pressure transducer to the end of the tube away from the bonfire.

This pressure measurement will document the PRD activation time and the tank vent-down, and confirm that the tank does not burst until it reaches 20 bar (ca 300 psig) or below. The 20 bar vent-down pressure is thought to be low enough that even if the tank would burst, that the damage would be minimal. Also, in most systems, the venting will occur more rapidly than the tank wall will weaken – so once the PRD starts venting it is unlikely that the tank will subsequently burst.

Test Criteria: A successful test is one in which the second compressed gas tank vents to less than 20 bar (ca 300 psi) at 60% or less of the baseline tank burst time. The resulting 40% time margin should be adequate to cover tank-to-tank and test-to-test variations.

It is suggested that the post-test burst pressure be greater than 1.5 times the nominal working pressure.

Safety Caution: If a tank has been exposed to fire and is still pressurized, it can still burst – even after some delay. Personnel should stay safely away from the tank until the tank is de-pressurized. This can be accomplished by a remotely activated valve (not in the fire zone) or by puncturing the wall of the tank with a rifle bullet.

Discussion:

The purpose of this burst time margin test is to demonstrate a fire exposure time margin and a burst strength margin for the surviving tank of test two.

Advantages of performing this extra bonfire test include:

1. It will establish a known time margin between the exposure to fire and the tank burst.

2. We will know the residual strength of the tank after successful venting of its contents.

3. It is consistent with the demand and capability probability distribution (SAE J2579, Figure B1) below.

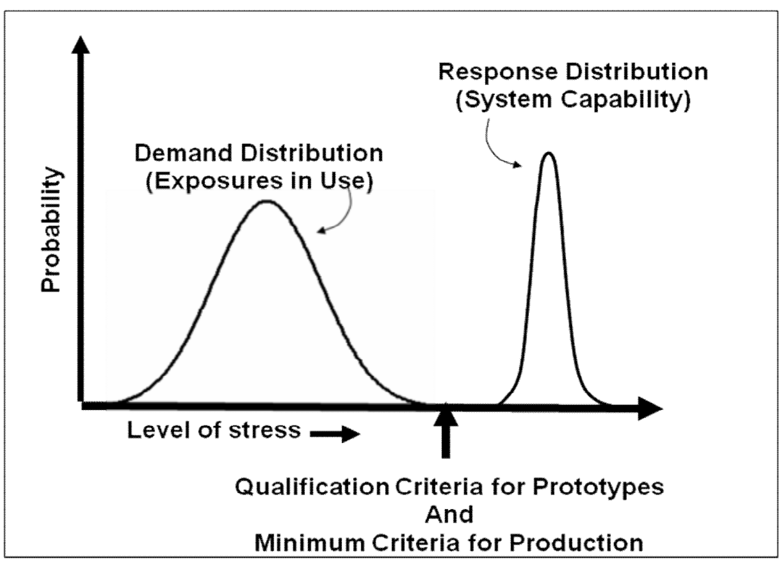

Figure B1. Demand and Capability Probability Distributions

For the bonfire test the level of stress represents time. The "demand distribution" is the severity of the fire exposure (either in the bonfire test itself or in real world vehicle fires). The "response distribution" represents the probability of a tank burst if the PRD does not successfully open and vent the tank. The time margin (shown by the vertical arrow) provides a separation of these two distributions.

Disadvantages of performing this extra test:

1. Requires one extra tank and tank test.

2. The extra cost to perform the first test.

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Appendix D

NCAP Test for Fire Safety

Scope: This is a proposed comprehensive vehicle-level test for conventional vehicles containing an internal combustion engine and burning liquid fuels (gasoline, diesel, and liquid bio-fuels). It would also apply to hybrids or plug-in hybrids as long as they have an ICE and liquid fuel on board.

Rationale: There are about 290,000 vehicle fires per year [Ahrens 2008]. Many of these fires are non-crash fires which initiate in the engine compartment and can spread to the passenger compartment – but are rarely fatal. According to FARS data, there are about 400 fatalities per year in motor vehicle crashes with fire as the most harmful event [Digges 2005]. Over 2/3 of the crash fires, including the fatal fires, occur in crashes with the principal damage to the vehicle front. Rollover crashes are second to frontal crashes in the frequency of fires [Digges 2007d; 2009].

Most of the frontal and rollover fires start under the front hood and can propagate into the passenger compartment [Digges 2007a; 2008]. It is probable that under-hood spilled fluids other than gasoline are the principal source of the engine compartment fires [Digges 2007b; 2009, and Fournier 2004]. Tests of several vehicles under operational conditions indicated that the surface temperature of the exhaust manifold and catalytic converter can exceed the ignition temperature of many under-hood fluids [Fournier 2004].

These crash fires are particularly hazardous because the occupants may be injured or entrapped.

Many car fires are extinguished, but some will spread and enter the passenger compartment. Tenability (the ability to survive inside the passenger compartment) can be assessed by measuring temperature and toxic gas (CO, and consideration should also be given to HCN, HCL, and HBr) levels.

It is proposed that NCAP be expanded to encourage countermeasures to reduce crash induced fires. Three added tests are recommended. These tests would accomplish the following:

1. Provide incentive to improve egress from the crashed vehicle
2. Provide incentive to prevent leakage of all flammable fluids after a crash
3. Provide incentive to delay the time at which the occupant compartment becomes untenable.

Note that tests 1 and 2 require only minor modifications to the present test protocols and would add negligible costs. They could be incorporated immediately. Test 3 would be more expensive and may require some development of the test protocol. However, Test 3 may be possible in the near term.

Proposed Test Procedures:

Test vehicles for all the following tests:

> Three vehicles that have been subjected to all three FMVSS 301 crash tests (frontal, side, and rear – one for each vehicle).

Test 1 - Vehicle Egress Test

1. At least one door per seating row which has a door must be able to be opened after the crash and the seatback deformation should not impede egress. These requirements should apply to both hinge and sliding doors.

2. The door latch should be able to be unlatched with a force (or torque) no more than twice that which is needed for an un-crashed vehicle.

3. After the crash, the door should be able to be opened by applying a force of no more than 65 pounds. This force can be applied from either the inside or the outside. For the inside, the force should be applied at the normal shoulder position with the seat far forward. For the outside pull, the force should be applied at the door handle.

4. The Star Rating will be awarded in inverse proportion to the force required to open the doors. Five stars will be awarded for doors opening within 15% of the force required for an uncrashed vehicle. One star would be assigned if the door opening force is 65 pounds or greater. The extent of seatback deformation will also be considered in the star rating.

Test 2 - Test for Leakage of all Flammable Fluids

FMVSS Standard 301, "Fuel System Integrity" prescribes impact tests that include frontal, side, and rear impacts to the vehicle. Subsequent to each of these crash tests, the crashed vehicle is subjected to a static rollover. FMVSS 301 permits a maximum acceptable fuel leakage rate of 28 grams per minute in the upright orientation and in successive 90^{O} rollover increments. There is no requirement for measuring the leakage of other flammable fluids. For this NCAP Fire Safety test we propose performing the rollover (spit) test in 45 degree increments.

It is proposed that future NCAP tests include leakage measurements of all fluids and of safety features to prevent electrical faults. These evaluations should be conducted initially before the crash test, by subjecting the vehicle to the static rollover test proscribed in FMVSS 301. Star ratings should be awarded for safety features that effectively disconnect power from the fuel pump and from the unfused battery-to-starter and battery-to-distribution box connections. In addition, no fluid leakage should occur during the rollover of the undamaged vehicle. The fluid leakage and electrical safety should also be evaluated after the crash tests and during the subsequent static rollover tests. If fluid leakage is observed, ratings would be assigned based on the amount of the flammable fluid leakage and its Hot Surface Ignition (HSI) temperature.

Fluid containment and electrical safety should be included as an element in the star rating for fire safety. Five stars would be awarded if there is battery and fuel pump disconnect for all test conditions and there is no flammable fluid leakage other than radiator coolant. Lesser star ratings would be assigned if there are flammable fluids leaked (fuel, brake fluid, power steering fluid, engine oil, transmission oil, clutch fluid, windshield washer fluid).

Test 3 - Vehicle Burn Test

After being subjected to the FMVSS 301 frontal crash, the vehicle would be tested to determine the survival time for occupants in the event of a major under-hood fire. The vehicles should be fully fueled and all the electrical systems charged and connected. The engine manifold and catalytic converter should be heated to operating temperature. The ignition source liquid fuel should be contained in a metal pan of the size specified in [Gunderson 2004] and located just behind the front radiator. The ignition procedure should be similar to that used in [Gunderson 2004]. Two windows in the passenger compartment should be open to provide ventilation for the fire to spread.

It is proposed that the fire be started in the engine compartment because:

(1) Most non-crash fires originate there

(2) About 2/3 of the crash fires with fatalities originate there.

Instrumentation: Temperature and CO should be measured at the location of the driver's head. Consideration should be given to also measuring NHC, HCl, and HBr.

Test Criteria: Time to untenability is defined as the time after ignition at which the CO level reaches 1 % or the temperature at the driver's head location reaches 200 C [Tewarson 2005, Digges 2007, and GM].

Star Rating for Test 3: Five stars will be assigned if the passenger compartment remains tenable for 30 minutes or longer. One star would be assigned if tenability is 5 minutes or less.

Discussion of the three tests:

GM conducted a series of 11 well-instrumented vehicle burn tests under its agreement with DOT [GM]. These were for conventionally fueled vehicles.

Another report containing over 20 vehicle burn tests with heat release rate versus time curves is available in [Janssens 2008].

Clearly performing such vehicle burn tests is feasible.

It should also be noted that the government and industry have been conducting full scale crash tests for occupant crash protection for many decades. It is obvious that testing a complete vehicle is preferable to testing the various components that are involved in a vehicle crash. A similar rationale shows that a complete vehicle burn is the best way to demonstrate vehicle fire safety.

Advantages of performing this vehicle burn test include:

1. It better simulates real world under-hood fires.

2. It is a vehicle system-level test – not a material or component test.

3. The flame spread paths are the same as in a real vehicle. Thus the penetration of fire into the passenger compartment is more representative of the real world.

4. This test will encourage design improvements such as:

   -Less flammable under-hood liners [Fournier, 2005].

   -Less flammable under-hood solid materials and fluids. (Note FMVSS 302 only applies to passenger compartment materials and not to those under the hood).

   -Less leakage of under-hood flammable fluids.

   -Fire stopping the bulkhead. Some bulkheads contain very large holes which allow the fire to spread into the passenger compartment. Others have many fewer and smaller openings (see Digges 2007c). The cable and other penetrations can be fire-stopped with expansive materials and other techniques as used in modern buildings.

   -Under-hood fire suppression systems (See [Gunderson 2004] for one example).

Disadvantages of performing these tests:

1. Added cost

2. Special fire safe facilities may be required for Test 3. (Note: this test could be performed outdoors).

3. There may be concerns about repeatability. A test program can demonstrate the degree of repeatability.

Overall NCAP Vehicle Fire Safety Rating: The ability for egress easily through the doors (test 1), the flammable fluid leakage (test 2), and the time for tenability (test 3) should be combined to determine the overall fire safety rating.

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