FIREWORTHINESS: A FINAL REPORT ON THE TECHNOLOGY BASE

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ABSTRACT

The findings provide a technology base for fireworthiness including the following: fire statistics on crash modes; the behavior of plastic gasoline tanks when subjected to fire and impact tests; finite element analysis of fuel tanks subjected to crash conditions; assessments of automotive fuel components that relate to fire safety; underhood temperatures under driving conditions; flammability of underhood liners; ignition and flammability properties of plastics and underhood fluids; an analysis and synthesis of 22 vehicle burns; fire suppression needs and a laboratory design and test; and examination of fire safety aspects of future vehicle technologies such as 42-volt electrical systems and hydrogen fueled vehicles.

These research results in conjunction with the GM/DoT Fire Research Project have been analyzed and recommendations for fire safety improvements have been proposed. The recommendations include vehicle level fire tests to increases survivability time for crashed vehicles subjected to exterior fires, particularly those that originate under the hood.

INTRODUCTION

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 [White, 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 will be completed in early 2009. The purpose of this paper is to document our major results and provide recommendations whereby the fire safety of motor vehicles 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 automobile fire safety.

Research projects that have been completed by MVFRI include the following:

1. A statistical analysis of field data to determine the frequency of fuel leaks and fires by model year and by other crash attributes (See Bahouth, 2006 and 2007, Digges, SAE 2005b, 2006 and 2007b, Fell, 2004 and 2007, Friedman, 2003 and 2005, and Kildare, 2006).
2. A case-by-case study of fuel leaks and fires in NHTSA's crashworthiness database (NASS/CDS) and an assessment of opportunities for reduction of vulnerability (See Bahouth, 2005, Digges, SAE 2007c; 2008 and 2009).
3. The assessment of the state-of-the-art technology to reduce the frequency of fires in motor vehicles and/or to delay the time for fires to propagate to the fuel or the interior of the occupant compartment (See Fournier, Dec 2004, April 2005). Additional work was done on leak prevention during rollover from severed lines connected to fuel tanks. (See Fournier, July 2004 and September, 2006)
4. The evaluation of gasoline fuel tanks of various shapes when subjected to fire and impact testing required by European (ECE) or other government standards (See J. Griffith, 2005).

5. The development of test procedures for the prevention of fires in vehicles equipped with 42-volt electrical systems; including high intensity arc testing, and carbon tracking properties of plastics (See Wagner 2003; Stimitz, 2004; Stephenson, 2005). Abuse tests were also conducted on 14 and 42 volt lead-acid batteries. (See Weyandt, May 2005)
6. The evaluation of the toxicity of the combustion products of motor vehicle components used in engine compartment and under-hood applications (See L. Griffith, 2005).
7. The evaluation of rescue times for first responders as it pertains to fire propagation into the passenger compartment (See Shields 2004, Digges, ESV 2005).
8. A comprehensive analysis of data from studies sponsored by GM, Motor Vehicle Fire Research Institute (MVFRI), and NHTSA (See Tewarson, April 2005; October 2005; 3 volumes and Digges et al, 2007d).
9. The development of an underhood foam fire suppression system (See Gunderson 2004, 2005).
10. The development of FEM models of fuel filled tanks subjected to crash forces (See Bedewi, 2004 and 2007).
11. Measurement of fire resistance of underhood insulation materials and of the electrical conductivity of underhood fluids. (See Fournier, Aug. 2005, Dey, 2004).
12. The measurement of underhood temperatures of four vehicles (See Fournier Sept. 2004 and Sept. 2006).
13. A bonfire test of an automotive type 4 compressed hydrogen fuel tank (See Zalosh, 2005 and Weyandt, 2005).
14. A full-scale SUV vehicle burn with a Type 3 compressed hydrogen tank. (See Weyandt, 2006).
15. Hydrogen and underhood leak experiments (See Weyandt, Dec. 2006).
16. A fatal compressed Natural Gas tank explosion was investigated for possible lessons learned to be applied to hydrogen tanks. (See Stephenson, 2008)
17. Research to support a special fire investigation methods appropriate for Hybrid and Hydrogen Vehicles for possible inclusion in NFPA 921. (See Stephenson, 2006)
18. A computer-based fire investigation training course was developed. (See Shields 0547, 2007 and Shields 0548, 2007)
19. The results of all the above research projects were summarized and placed on the MVFRI website. All final reports and summaries are located at mvfri.org.

BACKGROUND

Automobiles fires are the single largest cause of death among all consumer goods sold in the United States [Ahrens, 2003 and 2005]. Of the nearly two million fires each year in the U.S., one out of five (300,000) are vehicle fires [USFA, 2002 and FEMA, 2003]. This is comparable to the number of fires in houses and apartments but vehicle fires claim more lives than either [Ahrens, 2005, USFA, 2002 and FEMA, 2003]. Three quarters of vehicle fires are caused by mechanical or electrical failures during normal operation, but these are not particularly deadly because the occupants are usually able to escape. Less than 10% of vehicle fires are caused by collisions but escape is more difficult in these situations, and collisions account for the overwhelming majority (60-75%) of vehicle fire fatalities [Bennett, 1990; USFA, 2002]. Vehicle fires cause some 3000 injuries and claim about 500 lives per year in the U.S., [Ahrens, 2005]. The rapid progression of fire and incapacitation of passengers were contributing factors in two thirds of vehicle fire deaths [USFA, 2002]. It has been suggested that the number of fatalities attributed to motor vehicle fires is an underestimate because of ambiguous reporting methods [Ahrens, 2005, Fell, 2004], but there is no doubt that motor vehicles are a major component of the national fire death problem.

The fire safety of motor vehicles is regulated by Federal Motor Vehicle Safety Standard (FMVSS) 301 for fuel system integrity, which was first issued by the NHTSA in 1967 and FMVSS 302 for flammability of interior materials in passenger cars, multipurpose passenger vehicles, trucks, and buses, which became effective on September 1, 1972. The requirements of FMVSS 301 are intended to strengthen and protect the vehicle's fuel system, so that in a crash event, the chances of fuel leakage, and consequently the chances of fire and occupant injury, will be reduced. For fatal crashes in which fire is coded as the most harmful event, over half are due to front impact. Rollovers account for about 25%, and the rest are about evenly divided between side and rear impacts [Digges, 2008]. Over the past decade, fires in frontal and rollovers crashes have increased in frequency. NASS data shows that for the major crash related fires that enter the occupant compartment over 60% originate underhood. For frontal crashes, 85% originate underhood. For rollovers, the underhood origin accounts for 50% [Digges, ESV 2007a]. These statistical studies show the need to focus fire safety improvements on underhood fires resulting from frontal crashes and rollovers

Since it went into effect, FMVSS 301 has reduced fires due to fuel tank rupture, but the number of fire deaths has remained relatively constant over the past few decades because of an increasing number of vehicle crashes and a ten fold increase in the amount of combustible materials used inside and outside the vehicle.

The intent of the FMVSS 302 standard for flammability of materials was to reduce deaths and injuries to motor vehicle occupants caused by vehicle fires, especially those originating in the interior of the vehicle from sources such as matches or cigarettes. At the time that FMVSS 302 was under development, a study estimated that 30% to 40% of vehicle fires originated in the interior (passenger compartment and trunk) [Goldsmith, 1969]. Over the past decade, less than 5% of the post-crash fires originate in the vehicle interior [Digges, 2007b]. As collisions have become more impact-survivable and fuel tanks better protected, the amount of combustible plastic has increased. In most of today's vehicles there is more combustible material outside the fuel tank than inside it [Digges, 2009].

RECENT RESULTS

The results from a series of vehicle burn tests conducted by General Motors were analyzed to determine the effect of vehicle construction materials on passenger survivability in a post-crash vehicle fire [Tewarson, 2005 Vol. 1-3]. The authors concluded that when the fire originates in the engine compartment, flames penetrate the vehicle interior within 10-20 minutes. Once flames penetrate the passenger compartment they spread several times faster than allowed by FMVSS 302 [Tewarson, 2005 Vol. 1], resulting in occupant death in 1 to3.5 minutes. For the rear end collisions characterized in the test program by a gasoline pool fire, flames penetrated the vehicle interior through body openings within 2 minutes, after which flame spread by interior materials was 10 times faster than allowed by FMVSS 302 [Tewarson, 2005 Vol. 1]. Consequently, once flames penetrate the passenger cabin from either the front or rear, death of all occupants will occur within about two minutes due to simultaneous effects of heat, burns, and toxic gases [Tewarson, 2005 SAE]. The rapid flame spread observed in vehicle fire tests is the dominant factor in fatal vehicle fires and the major cause of vehicle fire deaths [USFA, 2002]. Tewarson reported that the orientation of the combustible material, the radiant heating by the fire, and the burning of molten plastic that drips away from the fire, all induced more severe burn conditions than created in the FMVSS 302 regulatory test.

Southwest Research Institute summarized eleven series of automobile fire tests conducted in the United States, Europe and Japan [Janssens, 2008]. The data generally confirmed the high intensity of fires that burn the materials in the occupant compartment. Figures 1 and 2 show typical test results from a series of vehicle fire tests conducted in 2002 by the Building Research Institute (BRI) in Japan. Figure 1 shows the progression of an engine compartment fire 20 minutes after ignition. Figure 2 shows the same fire at 30 minutes when the occupant compartment is totally engulfed in flames.

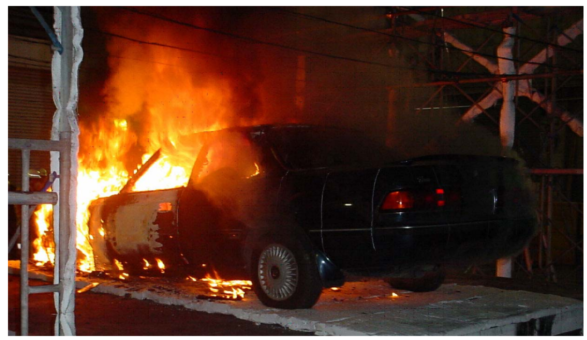

Figure 1. Tests by BRI of engine compartment fire -20 minutes after fire initiation.

Figure 2. Tests by BRI of engine compartment fire -30 minutes after fire initiation.

Rescue data from FARS showed that in rural crashes, the 75 percentile rescue time was 24 minutes [Digges, 2005 ESV]. For urban crashes the equivalent time was 12 minutes. The survivability time measured in the GM vehicle burn tests was often less that that needed for first responders to reach a typical rural accident scene and begin rescue operations for trapped or incapacitated passengers.

DISCUSSION

The changing design of motor vehicles is such that collisions are more impact-survivable, most fuel tanks are better protected in rear collisions and plastics have surpassed gasoline as the main fire load. These changing conditions present new safety challenges and opportunities. The following observations were based on recent test data or observed changes in the vehicle fleet:

1. Automobile fires account for 95% of motor vehicle fires and 92% of vehicle fire fatalities. The vast majority of fatal automobile fires result from sources outside the passenger compartment rather than from ignition of interior materials by a cigarette or small flame as envisioned when FMVSS 302 was issued.

2. Plastics that are exterior to the passenger cabin (i.e., in the engine compartment and body panels) represent a comparable fire load and fire hazard to the interior materials but are not required to pass FMVSS 302 or any other fire safety standard.

3. The flame spread rate of combustible materials inside the occupant compartment increases significantly when in proximity to a vehicle fire, but this factor was neglected in the FMVSS 302 test. Fire tests of vehicles indicate a tenability time of less than four minutes once an external fire penetrates the occupant compartment [Tewearson, 2005].

4. Tests of aircraft materials fireworthiness indicate that it is not possible to use a material-level flame test, e.g., FMVSS 302, to predict the fire behavior of a vehicle without validating the material-level performance at full-scale [Hill, 1979, 1985].

5. Tests of fire safety features in current vehicles indicate that many vehicles incorporate features to improve fire safety, but the features are not uniformly applied [Digges, 2009; ESV 2007a]. There was no relationship between the cost of the vehicle and the presence or absence of some of the fire safety features.

In view of the increased frequency of crash induced fires in frontal crashes and rollovers, regulations that would encourage technology to delay the penetration of fire into the highly flammable occupant compartment appear to be warranted.

For hydrogen fueled vehicles, an occupant compartment fire poses a threat to the high pressure hydrogen tank(s). Safety standards need to insure that the safety systems will protect people and structures in the vicinity of a vehicle fire from the explosive pressures that would occur in the event of a hydrogen fuel tank rupture. The safety standards should include fire tests of vehicles that have been exposed to representative crash scenarios.

RECOMMENDED RULEMAKING CHANGES

1. FMVSS 301 – Fuel System Integrity

a. Add a door opening requirement to the FMVSS 301 crash tests. 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. A recommended procedure is contained in Appendix A.

b. Consider a lower fluid leakage limit for 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 the present leak rate was not based on fire science considering the probability of ignition or flame propagation to other parts of the vehicle. It was chosen as the smallest amount that could be conveniently measured in a cup to collect any leaks. It was also similar to the volume of a carburetor float chamber (carburetors are rarely used anymore since fuel injection has become nearly universal). One could consider a lower leak limit based on real ignition and fire propagation tests.

c. Consider conducting all crash tests (including NCAP) with all electrical systems charged and connected, with all underhood fluids present, and with the engine running and hot. If a post-crash fire breaks out, the vehicle would have failed the test. (See Digges, ESV 2009, Santrock, 2007)

2.FMVSS 302 - Flammability of Materials

a. 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 underhood fire, the tenability time of materials that comply with 302 is less than 5 minutes [Digges ESV, 2005a]. Extensive research on alternative test methods has been conducted under NHTSA, GM/DoT, and the MVFRI projects. A better test method is required with more stringent acceptance criteria that will result in less flammable interior materials. See [Digges et al, 2007d] and [SwRI, 2003] for more discussion.

b. Regulate the flammability of underhood solid materials. .Most auto fires start in the engine compartment. There are many solid materials under the hood that are flammable and can spread the fire into the passenger compartment. In fact in modern cars, plastic materials have surpassed motor fuel as the main underhood fire load. This regulation on underhood materials could either be an extension of FMVSS 302 or a new fire safety standard. See [SwRI, 2003]. Special attention should be paid to underhood liners. Measurements show that the heat release rate of underhood liners varies by a factor of 100 between different vehicles [Fournier, Aug 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. As a minimum, the underhood liner should not add fuel to the engine compartment fire.

3.FMVSS 303 – Natural Gas Fuel System Integrity

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

4. FMVSS 304 – Natural Gas Tanks

a. Replace 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 NHTSA decides to keep a bare tank bonfire test similar to FMVSS 304 (for Natural Gas and/or Hydrogen), then perform 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 NHTSA to establish a time margin between the beginning of fire exposure and the time of tank burst. (See Appendix C for more details)

c. If NHTSA doesn't do the vehicle-level burn test, consider adding a localized fire tank test which will simulate a tank exposed to a localized fire away from the location of the pressure relief device (PRD).

d. Require a thermal shield between the passenger compartment and the tank(s).

e. Prohibit "vent boxes" which shield the PRD from hot gases or flames (vent boxes are designed to collect and vent small CNG leaks).

f. The bonfire test fire should be standardized. We should agree on the fuel (propane or natural gas) and the heat release rate (We suggest using a flow rate that will provide 200 to 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.

5. FMVSS 305 – Battery Safety

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 NHTSA consider a full vehicle burn test for compressed gas vehicles. See Appendix B.

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

7. A New Fireworthiness Standard

NHTSA should adopt a strategy for improving vehicle fire safety that is consistent with its philosophy of using system (vehicle) level tests to develop minimum performance requirements based on objective measures of human tolerance. In particular, NHTSA should address the magnitude and changing character of the motor vehicle fire problem by developing fire performance (fireworthiness) requirements for motor vehicles that will guarantee sufficient time for escape or rescue from a post-crash fire. Supporting standards should be developed based on human tolerance to the effects of fire and toxic gases (especially carbon monoxide), which are well defined [Tewarson, 2005 Vol. 1] and easily measured [Tewarson, 2005 Vol. 1; Hill, 1979 and 1985]. To have a meaningful effect on post crash survivability, fireworthiness standards will guarantee passengers survivable conditions until rescue crews can arrive in the event of restricted egress or incapacitation. Based on the analysis of emergency rescue operations 10-24 minutes are needed for emergency personnel to arrive at the scene after an incident occurs [Digges, ESV 2005a]. An additional 5-10 minutes are probably required to perform the rescue operations (e.g., jaws of life), so that a realistic survival time is of the order of 15-30 minutes after impact. Based on the analysis of full-scale vehicle fire test data [Tewarson ,2005 Vol. 1; Hill, 1979 and 1985], there are a variety of technologies for improving fireworthiness.

There are a number of technologies that will act to delay the fire penetration from the engine compartment to the passenger compartment [Digges, ESV 2007a]. These include: preventing the leakage of all flammable fluids, reducing the flammability of plastics used under the hood, fire-hardening bulkheads, openings, and conduits between the engine and passenger compartments, using fire resistant materials or intumescent seals around penetrations, and using less-flammable underhood liners, or other active or passive fire suppression systems.

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APPENDICES

APPENDIX A: DOOR OPENING TEST PROCEDURE

BACKGROUND:

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 that 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.

The tests should be cheap because the vehicles will NOT be damaged. This does not require any crash tests.

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 60% of the crash fires start under the front hood (for conventionally fueled vehicles with IC engines) and can also propagate into the passenger compartment [Digges 2005a, 2005b and 2007a]. 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 underhood fire is expected to increase.

Many of the 290,000 vehicle fires do not spread. About half of the crash induced fires spread to the occupant compartment. Some fires, especially those that engulf the occupant compartment will burn at high intensity 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 (PRD). 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 [Weyand, 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, ODI]. 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 underhood 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

* 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 underhood 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 2005]. 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 underhood fires are fueled primarily by underhood 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 B.3]. 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 D) 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 the pressure burst 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 C1).

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.

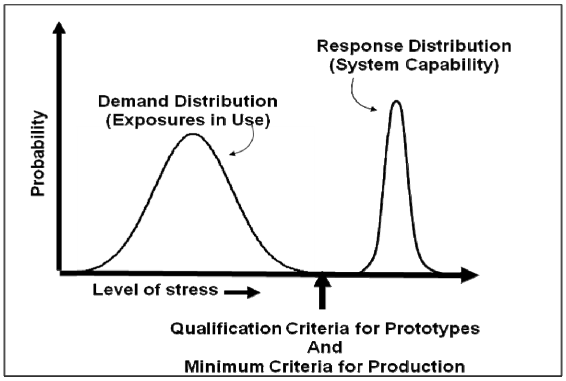

Figure C1. Basis of Criteria for Bonfire Test

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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