Post-crash Fuel Leakage and Fire Safety Experiments for Hydrogen Vehicles

Barbara Hennessey
U.S. National Highway Traffic Safety Administration (NHTSA)

James J Reuther, Jeffery S John, Paul E Shawcross, Gregory Kimmel
Battelle

Paper Number 11-0439

ABSTRACT

Federal Motor Vehicle Safety Standards (FMVSS) for fuel system integrity set limits for fuel spillage during and after crashes to reduce the occurrence of deaths and injuries from fire. FMVSS 301 and 303 respectively specify post-crash limits for liquid fuels and compressed natural gas (CNG) [1, 2]. These limits have been used as a benchmark for setting leakage limits for hydrogen, based on energy equivalence, in industry standards and proposed or enacted international regulations [3, 4]. However the properties of hydrogen with regard to leak behavior and combustion are very different from those of liquid fuels or CNG. Gasoline will pool and dissipate slowly. CNG and hydrogen will rise and dissipate more rapidly. Hydrogen has a much wider range of flammability in air than most fuels, including CNG: 4% to 75% for hydrogen versus 5% to 15% for CNG. Therefore, a research program was developed and executed to assess the safety of the proposed allowable leak rate for hydrogen, through leak and ignition experiments in and around vehicles and vehicle compartment simulators.

INTRODUCTION

NHTSA has been involved in alternative fuel vehicle safety research and regulation going as far back as 1978. At that time, pursuant to the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, NHTSA was charged with assisting the Department of Energy (DOE) in determining the applicability of the FMVSS's to electric and hybrid electric demonstration vehicles.

In the late 1980's and early 1990's additional legislation promoted the use of alternative fuels, including CNG. NHTSA responded to these initiatives by collecting information and conducting research which supported the promulgation of new standards setting crash integrity requirements for CNG vehicles, and life cycle strength, durability, and pressure relief requirements for high pressure natural gas storage cylinders (FMVSS 303, FMVSS 304).

The 2002 launch of the FreedomCAR and Hydrogen Fuel Initiative, a cooperative research partnership between government and industry to advance hydrogen fuel cell vehicle technology, led to initiation in 2006 of NHTSA's current, complementary effort to assess the safety of these unique fuel systems. Little real world data exists concerning the safety of hydrogen storage and high voltage fuel cell electrical systems. Therefore, NHTSA is conducting research to assess several aspects of hydrogen fuel system integrity and has initiated program tasks to develop data and test procedures in the following five areas:

- Safety of proposed fuel leakage limits for hydrogen fuel systems;
- Vulnerability of high-pressure hydrogen storage to impact loading;
- Cumulative expected/extended service life cycle testing of hydrogen storage cylinders;
- Electrical safety of high voltage fuel cell systems in crashes;
- Mitigation of explosion hazards posed by localized flame exposure on high-pressure composite storage cylinders.

This paper discusses the results of the first task listed above: The safety of the proposed allowable leak rate of hydrogen post-crash, which is based on energy equivalence to one ounce per minute of gasoline as specified in FMVSS 301, Fuel System Integrity or an equivalent amount of CNG as allowed in FMVSS 303, Fuel System Integrity of Natural Gas Vehicles.

This effort involved three series of experiments to assess the proposed allowable post-crash leak rate:

- Subtask A: Leak rate vs. concentration buildup in and around an intact automobile;
- Subtask B: Ignition and combustion tests in

an automobile compartment simulator (ACS) containing known concentrations of hydrogen;

- Subtask C: Full-scale leak, ignition and fire tests on intact and crashed automobiles

Because hydrogen fuel cell vehicles are currently in development, prohibitively expensive, and number only in the hundreds worldwide, none were available for the type of destructive testing required in this assessment. Therefore surrogates, in the form of an automobile compartment simulator, or late model conventional vehicles, were used to conduct the experiments.

A total of 88 tests were conducted in subtasks A, B, and C. Subtask A consisted of 15 tests: 14 were hydrogen accumulation tests in an intact vehicle and one was a sensor response test. Subtask B consisted of 19 tests in the ACS: 11 were accumulation tests and 8 were ignition tests. Subtask C consisted of 54 tests in intact, front, side and rear impacted vehicles that were obtained from other test programs: 39 of these tests were on accumulation, 8 were ignition tests, and 7 were sensor response time tests.

Battelle conducted this test program under contract DTNH22-08-D-00080.

DESCRIPTION OF EXPERIMENTS

Subtask A: Leak rate vs. concentration buildup in and around an intact automobile

A series of tests were conducted to simulate the effects of hydrogen leaks in and around a test vehicle in four locations: Under the vehicle, into the trunk, into the passenger compartment and under the hood. The reference leakage flow rate was 118 normal liters per minute (nlpm), which was derived from the energy equivalence of the allowable leakage rates in FMVSS 301 and 303. Subsequent tests utilized the traditional Bruceton "up-and-down method," at half and double the reference flow rate. The intent was to determine the role of flow rate in creating hazardous conditions. Hydrogen concentration data was recorded from initiation of the leak to either 60 minutes (per FMVSS 303) or until steady state concentration was achieved. Additionally in some tests the concentration decay time for the hydrogen remaining in the vehicle was also recorded. The decay time was a function of how rapidly hydrogen could escape through various routes in the vehicle compartment without an active or passive hydrogen venting system in place.

Test Facility, Instrumentation and Hardware

Tests were conducted at Battelle's High Energy Research Laboratory Area (HERLA) inside a 42-ft diameter blast containment chamber. The test vehicle was a 2008 Mitsubishi Lancer. Figure 1 shows the test vehicle in the blast chamber.

Figure 1. Mitsubishi Lancer in HERLA blast chamber for indoor testing of hydrogen leaks in and around a vehicle

The vehicle was equipped with an array of 12 hydrogen sensors positioned at specific locations as follows:

- 3 in the trunk compartment;
- 3 in the rear of the passenger compartment;
- 3 in the front of the passenger compartment;
- 3 in the engine compartment

The sensors were positioned at 10%, 50% and 90% of the vertical dimension of each compartment, along the vehicle center line, except in the case of the engine compartment, where a modified placement was necessary due to spatial constraints. Figures 2 and 3 show the positioning of the trunk and passenger front seat sensor suites.

Figure 2. Positioning of trunk sensors at 10%, 50%, and 90% heights

Figure 3. Positioning of front passenger compartment sensor suite at 10%, 50%, and 90% heights

Hydrogen leak locations The flow of hydrogen originated from specific locations into or underneath the vehicle as follows:

- 1 leak fed directly into the trunk
- 1 leak directly into the passenger compartment
- 1 leak straight up under the vehicle
- 1 leak straight down under the vehicle
- 1 leak at 45 degrees forward and down under the vehicle
- 1 leak at 45 degrees rearward and down under the vehicle
- 1 leak at 45 degrees forward and up toward the firewall

Figures 4, 5, and 6 photographically illustrate interior and exterior leak locations.

Figure 4. Hydrogen leak originating in the trunk

Figure 5. Hydrogen leak originating in floor of passenger compartment

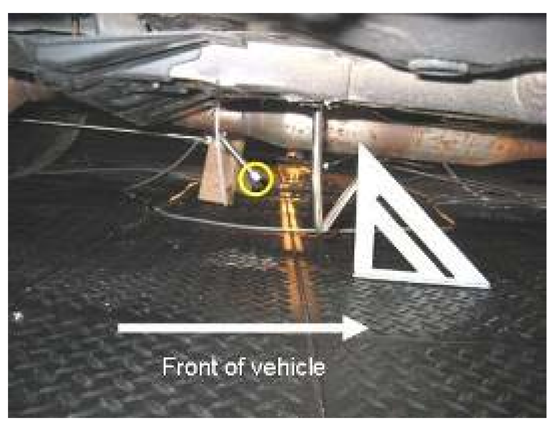

Figure 6. Hydrogen leak 45 degrees forward from the tank position underneath the vehicle

Test matrix The test matrix for the leak and accumulation tests is shown in Table1. Hydrogen concentration levels were monitored for 60 minutes or until steady-state was achieved. Tests 1 and 2 used a flow diffuser to provide less turbulence in the leak and limit mixing of the hydrogen with air. The remainder of the tests were conducted without the diffuser on the open end of the tubing, creating turbulence similar to a sheared fuel line.

Table 1
Test Matrix for Subtask A, Leak rate vs. concentration build-up in and around an intact vehicle

<table>
<tr><th colspan="2" rowspan="2">Leakage Location</th><th colspan="4">Flowrate of Hydrogen
(nlpm)</th><th rowspan="2">Duration
(min)</th></tr>
<tr><th>0</th><th>58</th><th>118</th><th>239</th></tr>
<tr><td colspan="2" rowspan="5">Trunk</td><td>--</td><td>--</td><td>Test 1*</td><td>--</td><td rowspan="9">60</td></tr>
<tr><td>Test 1 decay</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>--</td><td>--</td><td>Test 4</td><td>--</td></tr>
<tr><td>--</td><td>Test 11</td><td>--</td><td>--</td></tr>
<tr><td>--</td><td>--</td><td>--</td><td>Test 12</td></tr>
<tr><td colspan="2" rowspan="3">Passenger compartment</td><td>--</td><td>--</td><td>Test 5</td><td>--</td></tr>
<tr><td>Test 5 decay</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>--</td><td>--</td><td>Test 13</td><td>--</td></tr>
<tr><td rowspan="8">Under vehicle</td><td rowspan="4">Up</td><td>--</td><td>--</td><td>Test 2*</td><td>--</td></tr>
<tr><td>--</td><td>Test 8</td><td>--</td><td>--</td><td>30</td></tr>
<tr><td>--</td><td>--</td><td>Test 10</td><td>--</td><td rowspan="3">60</td></tr>
<tr><td>--</td><td>--</td><td>--</td><td>Test 9</td></tr>
<tr><td>down</td><td>--</td><td>--</td><td>Test 6</td><td>--</td></tr>
<tr><td>45° forward</td><td>--</td><td>--</td><td>Test 3</td><td>--</td><td rowspan="2">30</td></tr>
<tr><td>45° rearward</td><td>--</td><td>--</td><td>Test 7</td><td>--</td></tr>
<tr><td>engine</td><td>==</td><td>--</td><td>--</td><td>Test 14</td><td>60</td></tr>
</table>

*Test conducted with diffuser on end of tubing as opposed to tube being open-ended

Data recording and analysis As previously mentioned, hydrogen concentration data were recorded for three different leak rates at 12 positions in the Lancer. The purpose of the tests was to determine if, when, and how long the hydrogen concentration fell within the combustible regime of 4% to 75% hydrogen in air. The following graphs display spatial hydrogen concentration vs. time for representative tests. A yellow band highlights the flammability range of 4% to 75% hydrogen in air, and a darker yellow band denotes the stoichiometric concentration level of 28% to 32%. The data show that leak location dictated the extent to which hydrogen accumulated in the individual vehicle compartments. (Figures 7 and 8).

Leaks directly into the vehicle trunk or the passenger compartment resulted in combustible concentrations regardless of flowrate: 58, 118, or 239 nlpm. Figure 9 shows a comparison of the concentration levels attained in the trunk at various leak rates. The slowest leak rate of 58 nlpm resulted in a near-stoichiometric steady-state concentration in the top of the trunk, with the higher rate of 239 nlpm reaching the upper flammability limit throughout the trunk compartment.

The under-vehicle leaks did not result in any appreciable concentration levels inside the vehicle. The only under-vehicle leak to result in a combustible concentration was the one directed up toward the firewall at 239 nlpm. A peak concentration of under 10% hydrogen at the 10% sensor height location in the engine compartment occurred early in the test and over time fell below 4%.

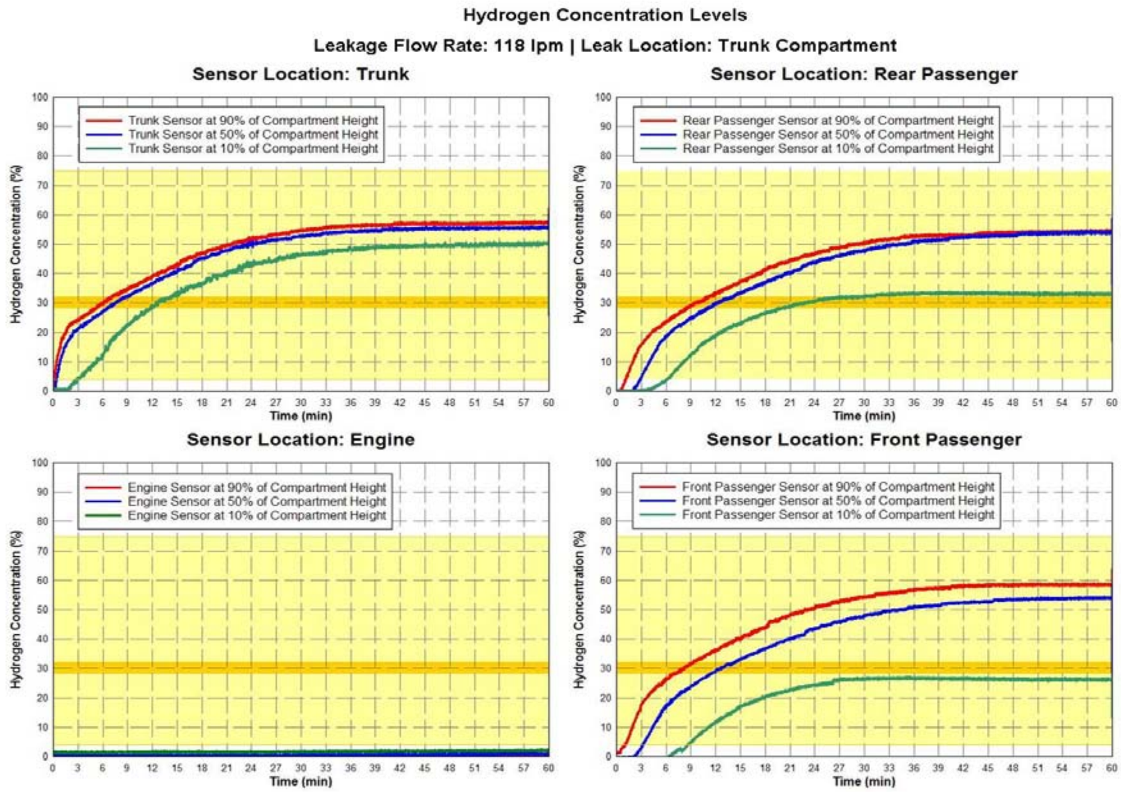

Figure 7. Test Number 4 - 118 nlpm into Lancer trunk compartment

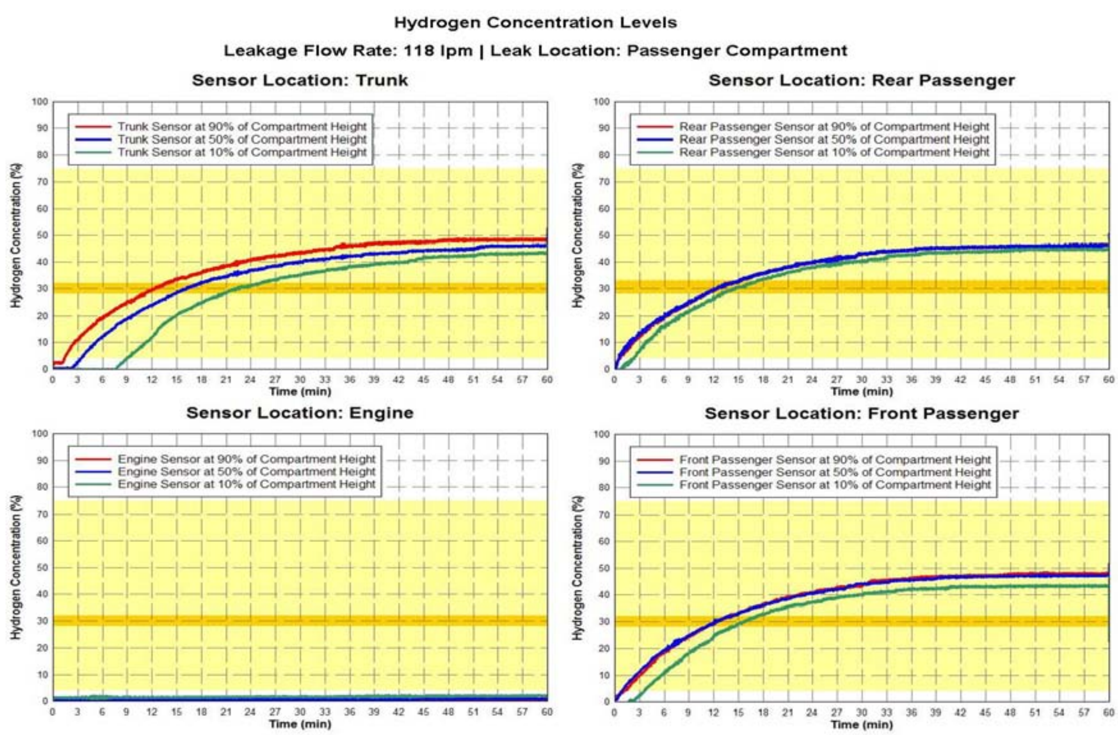

Figure 8. 118 Test Number 5 – 118 nlpm into Lancer passenger compartment

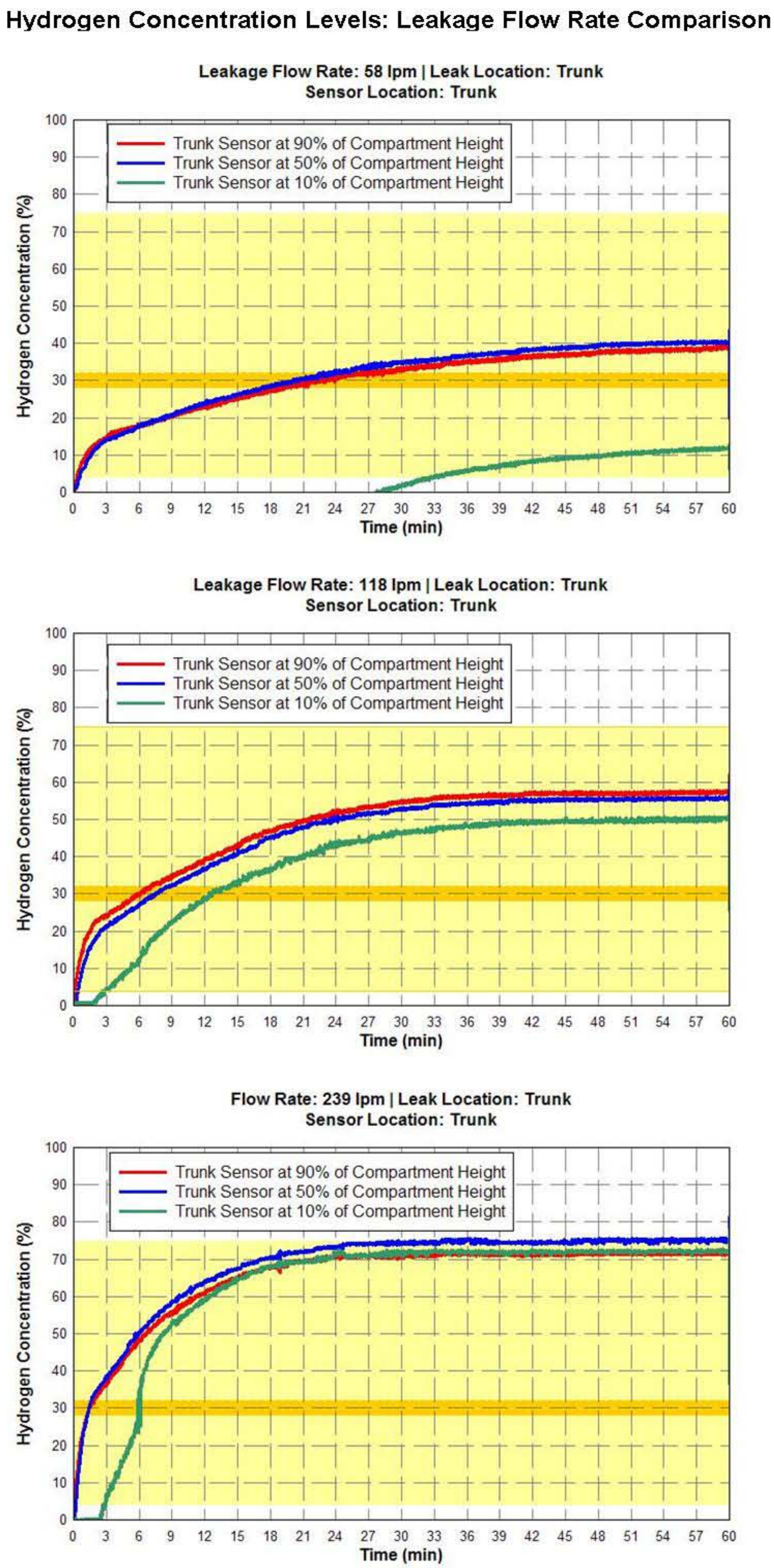

Figure 9. Hydrogen concentration levels: flow rate comparison

Post-leak decay The decay rate of hydrogen concentration following cessation of hydrogen flow was recorded for several tests. These data were used to assess how long a combustible mixture remained in the vehicle after the source leak was removed. Figure 10 shows the decay rate of hydrogen by compartment and stratification layer for an additional 60 minutes after the hydrogen injection test was complete. The data show that hydrogen is depleted from the lower regions first, most likely as a function of hydrogen moving up or out through various pathways as it is replaced by heavier air molecules. From the data presented, without ventilation the hydrogen concentration remains within the flammability range for the hour after the source of the leak was removed.

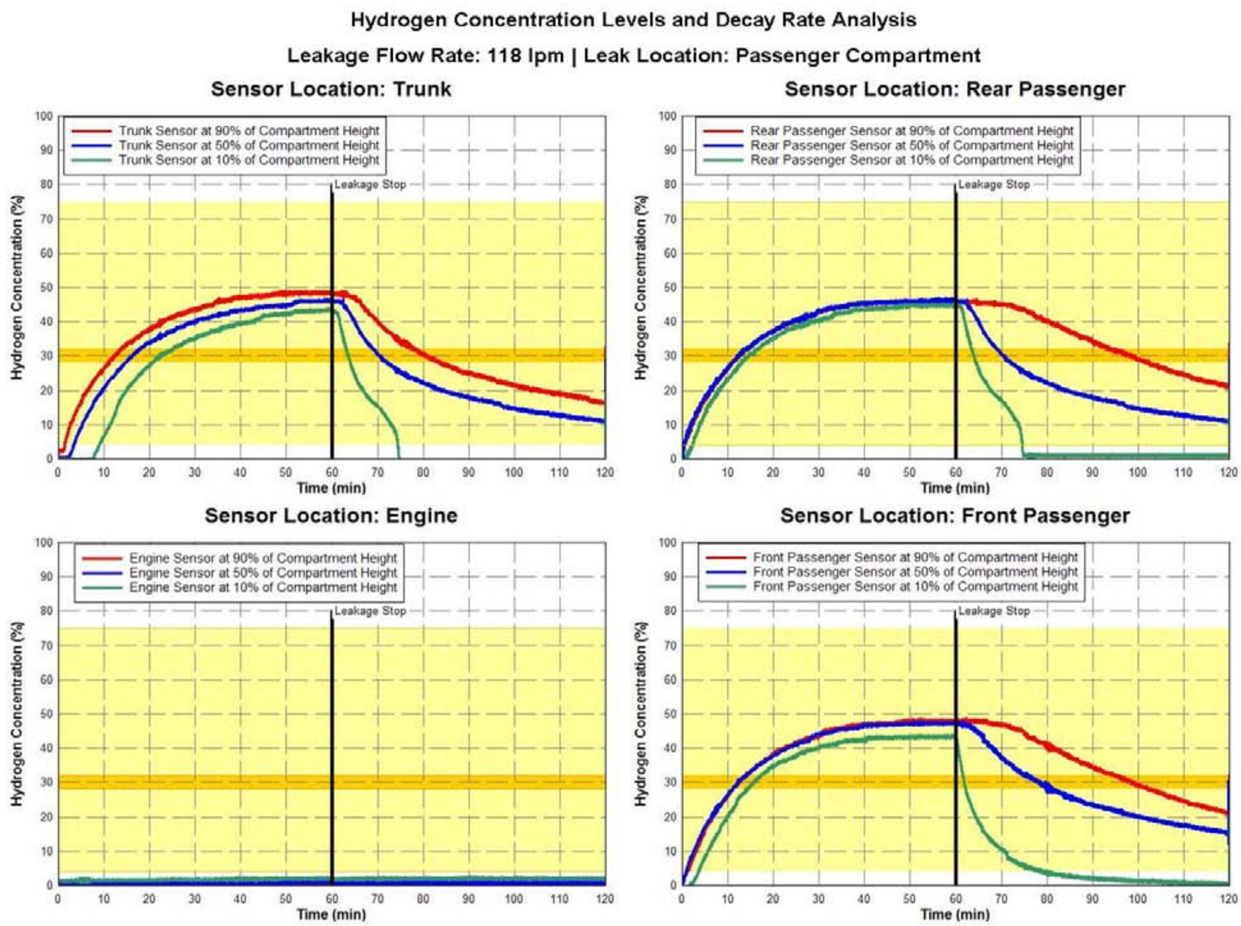

Figure 10. Hydrogen concentration rise and decay times

Subtask B: Ignition and combustion tests in an automobile compartment simulator (ACS) containing known concentrations of hydrogen

The scope of this task was to measure the heat flux and overpressure created subsequent to ignition, if combustible levels of hydrogen were to accumulate in the trunk or passenger compartment from a post-crash fuel system leak. These tests were conducted in an ACS that approximately reconstructed the geometry and volumes of the trunk and passenger compartment of the 2008 Mitsubishi Lancer test vehicle used in Subtask A. The purpose of the ACS was to allow multiple ignition tests that would not be possible in an automobile due to the resultant damage. The ACS was constructed with breakaway steel and Lexan panels that could be easily replaced to allow multiple ignition tests in a short period of time and using minimal resources. During the ignition tests, an instrumented manikin (Denton Hybrid III) was utilized to measure relevant burn (heat flux) and overpressure injury characteristics from the combustion of hydrogen mixtures.

Specific accumulation levels were selected for the ignition experiments representing just over the minimum flammability limit (5%), fuel-lean (15%), stoichiometric (30%), and fuel rich (60%) levels of hydrogen in air.

Test matrix Two types of tests were conducted in Subtask B. Accumulation calibration tests, and ignition tests. The accumulation tests focused on obtaining a representative leakage rate between the trunk and passenger compartment of the ACS that approximated the flow characteristics of the leak tests in the Mitsubishi Lancer in Subtask A. For the purposes of this paper, only the ignition tests will be discussed. Table 2 shows the test matrix for the Subtask B ignition tests.

Table 2
ACS Ignition Tests

Ignition Tests			
Leakage Location	**Test #**	**Hydrogen Concentration (%)**	**Leak Duration (min:sec)**
Trunk	32	5	1:30
	33	15	4:30
	34	60	24:30
Passenger compartment	24	15	5:00
	25	15	4:30
	26	30	20:00
	28	60	24:30
	29	5	1:30

Data recording and analysis For the hydrogen accumulation calibration tests, a suite of sensors, similar to those used in the Mitsubishi Lancer in Subtask A, were installed at the 10%, 50% and 90% height locations of the trunk and passenger compartment. A series of calibration tests were conducted to determine the time at which the target concentrations of hydrogen were achieved. For the ignition tests, only the 50% sensors were left in place to avoid damaging the entire arrays.

Overpressure transducers were mounted on a test stand outside the ACS and on the manikin at the right ear, mouth, and left chest. Heat flux sensors were mounted at several discrete positions on the manikin as shown in Table 3 and Figure 11.

Table 3
Manikin Heat Flux Sensors

Right eye (A)	Left outer wrist (I)
Right cheek (B)	Right palm (J)
Left cheek (C)	Left backside hand (K)
Right shoulder (D)	Right hand between fingers (L)
Right underarm (E)	Left hand between fingers (M)
Left underarm (F)	Groin (N)
Right inner elbow (G)	Right back knee (O)
Right inner wrist (H)	

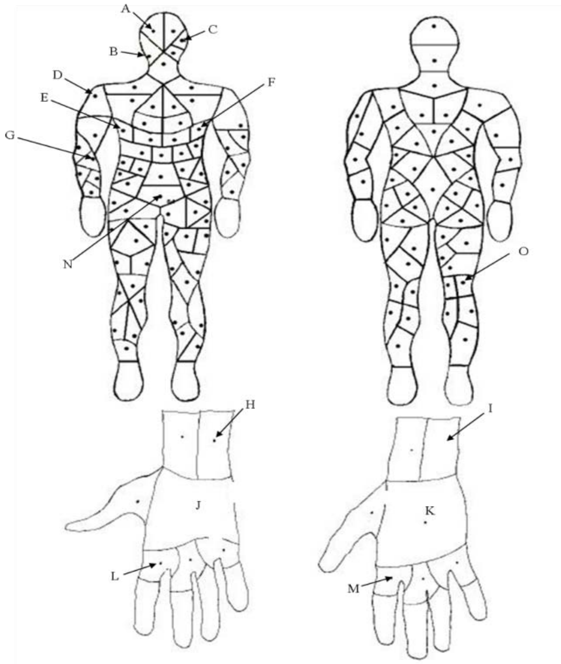

Figure 11. Heat flux sensor locations on manikin

A heat flux sensor was also mounted on the test stand outside the vehicle, just forward of the B-pillar, to measure thermal exposure experienced by anyone, such as first responders, approaching the outside of the vehicle.

The heat flux measurements were processed using the BURNSIM computer model to predict potential burn injury [5]. BURNSIM uses heat flux data to compute the tissue temperature as a function of exposure time and depth. The model determines the burn depth, and by extension, the degree of injury.

Hydrogen ignition tests Calibration tests in the Lancer and in the ACS showed stratification, inversion, and a lack of uniform mixing of hydrogen. Ignition time was selected based on calibration curves when the sensor at the 50% height reached the target concentration level. Results from representative tests are discussed below.

Test 29: 5% ignition, passenger compartment Leak The ASC panels were held in place with magnets. All exterior panel seams were taped with duct tape, and hydrogen sensors were positioned at the 50% trunk and front seat passenger compartment levels. The ignition source was located on the dashboard. The right underarm, back knee, left outer wrist, and left cheek heat flux sensors were not used in this test. The setup for test 29 is shown in Figure 12.

Figure 12. Test 29 ACS setup

Heat flux sensors in the right eye, right check, right shoulder, right inner elbow, left underarm, right inner wrist, right hand between fingers, left hand between fingers, and left hand backside positions registered thermal levels that could result in first- or second-degree burns. The heat flux sensor on the test stand outside the ACS did not detect any significant radiant energy. No detectable overpressure was observed. No luminous combustion was observed using high-speed imagery. The panels remained attached to the ACS, but displayed slight bulging.

Test 33: 15% ignition, trunk leak In this test heat flux sensors located in the right back knee, right underarm, left cheek, right inner wrist, and left outer wrist were not used. Figure 13 shows the concentrations recorded in the Lancer and ACS calibration tests, and in the ignition test.

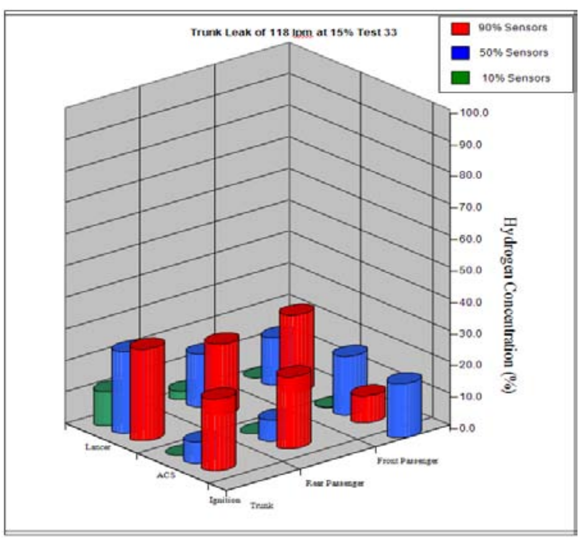

Figure 13. Calibration and ignition at 15% hydrogen in air

Sensors in the right eye, right cheek, right shoulder, right inner elbow, groin, left underarm, right hand palm, right hand between fingers, and left hand between fingers, detected heat fluxes that could cause second-degree burns. No overpressure was measured by the pressure transducers. High speed stills in Figure 14 show some luminosity during combustion. The slight overpressure from combustion caused panels to separate from the ACS framework.

Figure 14. High speed stills showing combustion in Test 33.

Test 26: 30% ignition, passenger compartment leak This test was expected to be the worst case, as the ignition target was the stoichiometric concentration of hydrogen in air. The BURNSIM injury predictions are provide in Table 4. The highest temperature occurred at the left outer wrist, with the most severe depth occurring at the right palm. The heat flux recorded at the test stand also could pose serious burn injury potential to other persons at this location.

Table 4
BURNSIM data for Test 26 (30% hydrogen)

Sensor Location	Degree of Burn	Maximum Temperature (°C)	Burn Threshold Depth (μm)
Right Eye	1st	146	111
Left Cheek	1st	100	35
Right Cheek	2nd	113	364
Right Shoulder	1st	76	113
Right Inner Elbow	2nd	215	1240
Right Underarm	2nd	180	431
Right Back Knee	2nd	122	195
Right Inner Wrist	2nd	251	857
Right Hand Palm	2nd	187	1317
Right Hand between Fingers	2nd	238	252
Left Outer Wrist	2nd	267	696
Left Hand Backside	2nd	174	1281
Left Hand between Fingers	2nd	187	132
Test Stand	1st	133	175

Significant overpressure was generated inside the passenger compartment during combustion, apparently a transition from deflagration to detonation. Low pressures are evident at about 15 msec and rapidly transition to about 80 psi at about 22 msec. Assuming that time zero is defined as the time at which the spark is applied (zero induction time) and that the shock front was measured at the window (37 in. away on the test stand), the approximate velocity of the combustion is ≈ 2400 ft/sec, about twice (Mach 2) the speed of sound. The three separate shocks observed at the test stand location can be rapid, separate detonations of the front, rear, and then trunk compartment volumes. Figure 15 is an overpressure composite. The consequence of this overpressure exposure is probably lethal to passengers [6].

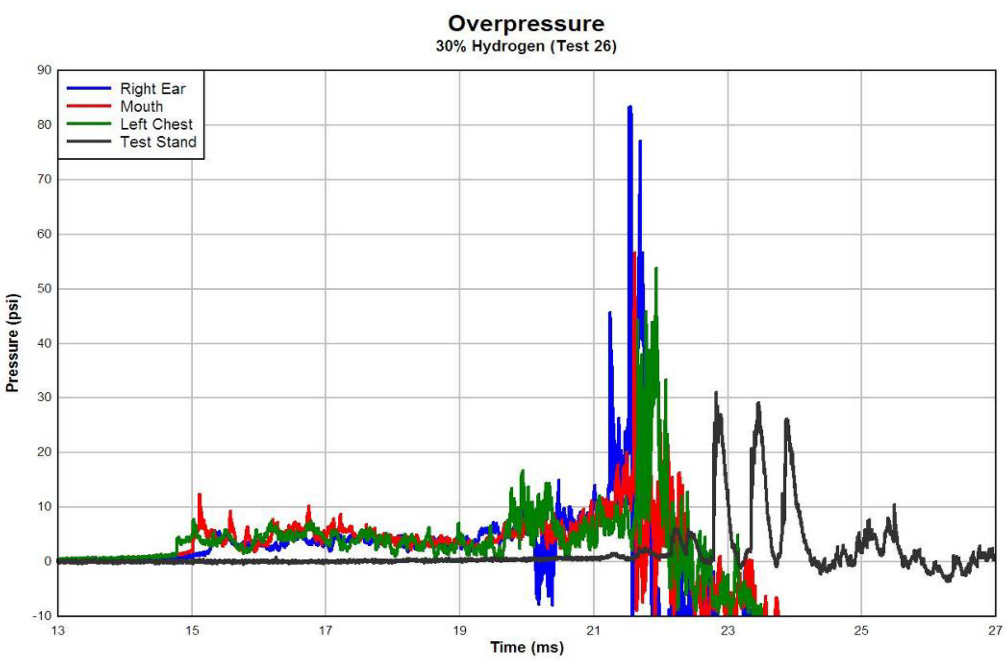

Figure 15. Test 26: pressure vs. time, 30% hydrogen in ACS

Figure 16 shows the ignition event in Test 26.

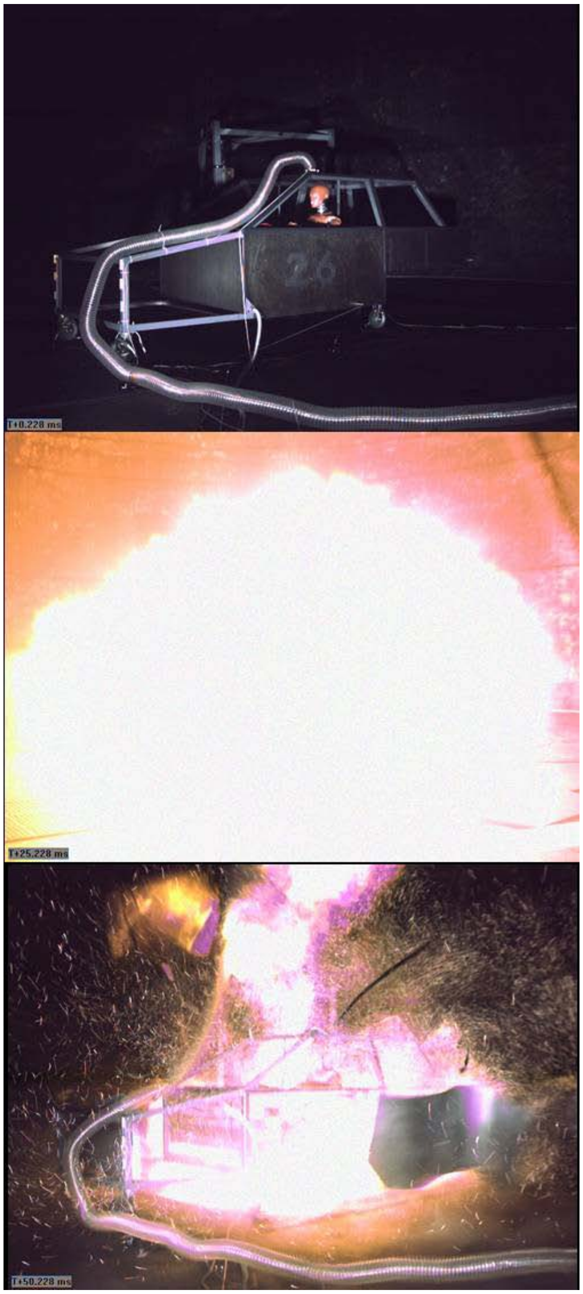

Figure 16. High-speed stills showing detonation and separation of ACS panels in Test 26

<u>Test 34 : 60% ignition, trunk leak</u> This test represented a fuel rich environment closer to the upper flammability limit of 75% hydrogen in air. BURNSIM data predicted second degree burns on the manikin and at the test stand outside the ACS. A small overpressure resulted from combustion of this test of just over 1 psi, the physiological consequence of which is 20% probability of eardrum rupture [7]. Figure 17 shows stills from the comparatively long duration fireball and separation of the panels from the ACS in this test.

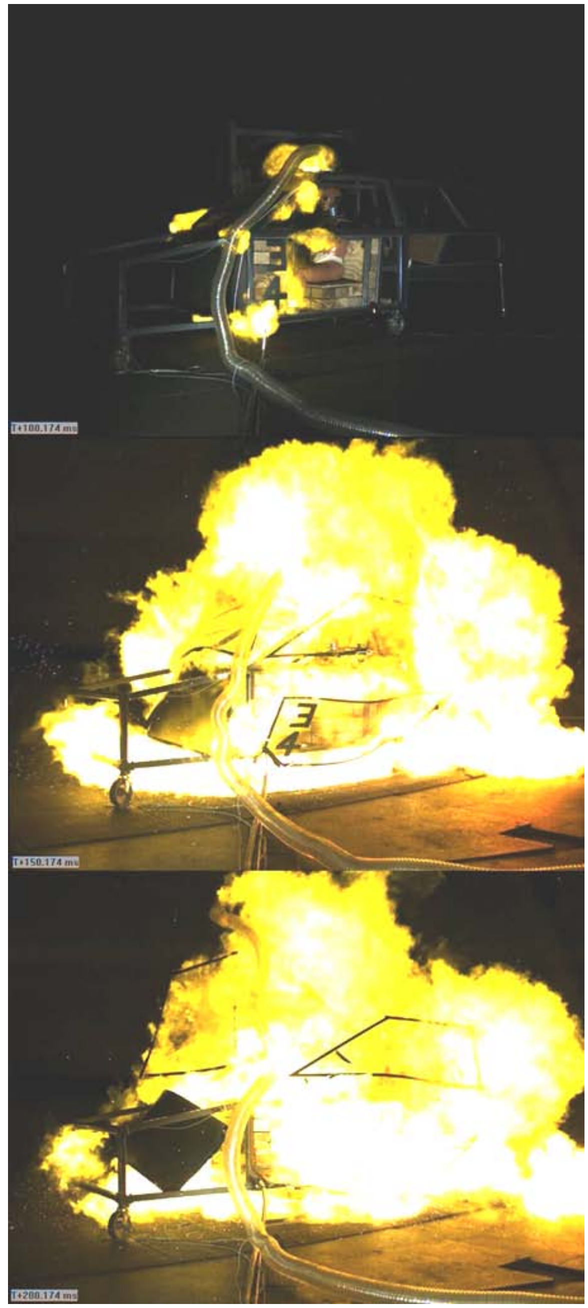

Figure 17. High speed stills showing combustion and panel separation in Test 34

Subtask C: Full-scale leak, ignition and fire tests on intact and crashed automobiles

The objective of this task was to quantify the effects of crash damage on hydrogen accumulation and combustion characteristics for three leak parameters—location, rate, and duration. These tests were conducted on four vehicles: intact and front-impacted 2008 Mitsubishi Lancers; side-impacted 2009 Mazda6 Sedan; and rear-impacted 2008 Ford Taurus. These test vehicles were transferred from NHTSA's Compliance and New Car Assessment crash test programs. The test vehicles are shown in Figure 18.

Figure 18. Test vehicles for accumulation and ignition experiments

Test matrix Thirty-nine leak-accumulation tests were conducted at seven leak rates ranging from 3 to 236 nlpm over 60 minutes, and originating from the trunk, rear-passenger compartment, or under the vehicle, as in Subtask A. Vehicles were equipped with the same array of 12 hydrogen sensors as in Subtask A. In some of the tests employing a lower leak rate (<59 nlpm) additional sensors were added at the top (100%) vertical height of the trunk and passenger compartments.

Altogether, eight ignition tests were conducted on the intact, front, rear and side-impacted vehicles. Vehicles were equipped with the same sensors including the instrumented manikin and exterior test fixture measuring heat flux and overpressure, as the ACS test article in Subtask B.

Observations from accumulation tests Front-crashed vehicle: (1) leaks as low as 30 nlpm in the trunk or passenger compartment resulted in detectable flammable levels in the other compartment; (2) leaks as high as 236 nlpm underneath the vehicle did not result in detectable accumulation inside the vehicle; and (3) low leak rates resulted in random (inversions; pockets), but sometimes detectably flammable, levels of hydrogen.

Figure 19 shows an example of these characteristics of a slow leak rate.

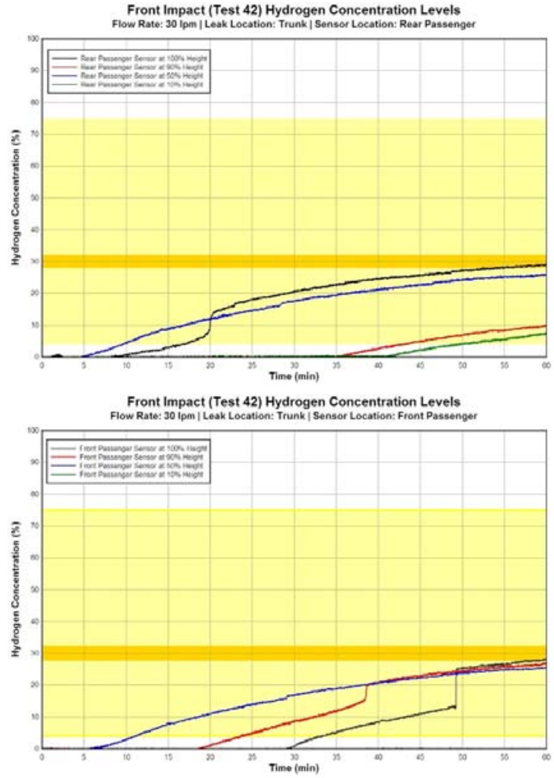

Figure 19. Inversions of slow leak (30 nlpm)

Side-crashed vehicle: (1) leaks ≥59 nlpm in the passenger compartment resulted in detectable flammable levels, but leaks as high as 236 nlpm in the trunk did not result in detectable flammable atmospheres in the passenger compartment; (2) leaks underneath the vehicle as high as 236 nlpm did not result in detectable accumulation inside the vehicle; and (3) even with high leak rates, accumulations sometimes appeared random and elusive with respect to migrating to the highest locations.

Rear-crashed vehicle: (1) leaks as low as 30 nlpm in the rear-passenger compartment resulted in low but detectable flammable levels; (2) leaks as high as 236 nlpm underneath the vehicle did not result in detectable accumulation inside; and (3) leaks originating in passenger and trunk compartments resulted in random accumulations, all of which were flammable.

Overall observations from Subtask C hydrogen accumulation tests were: (1) at low leak rates (≤60 nlpm), hydrogen did not mix well in air, resulting in its concentrations being random, exhibiting characteristics similar to a lava lamp in which slow motion causes media of different densities to remain unmixed, pocketing locally, varying and moving in random fashion, and inverting where higher-sensor locations register lower concentrations than do lower-sensors locations, or being absent at highest locations; (2) at high leak rates (≥118 nlpm), hydrogen mixes more homogenously, resulting in more stratified levels, increasing more uniformly throughout the vehicle, being detectable nearest the leak source first, generally seeking higher elevations, and reaching more uniform and steady-state concentrations with time; and (3) door, window, and frame seals in front or rear-impacted vehicles were not compromised to the extent of allowing hydrogen from leaks underneath to accumulate inside the vehicle. Such flow, mixing, and stratification behavior has been predicted by computational fluid dynamic modeling by Breitung [8].

Observations for ignition tests Two types of ignition tests were conducted: (1) at the in-going potential standard leak rate of 118 nlpm for a duration of 1.5 min, which introduced a just-flammable ~5% hydrogen inside the car if distributed evenly; and (2) at the lowest leak rate experimentally possible (3 nlpm) over 60 min, which could result in accumulated hydrogen (~5%) that might be ignited by sparking at the top of the passenger compartment (leaking 3 nlpm for 60 min was near-equivalent to the volume of hydrogen leaking at 118 nlpm for 1.5 min).

Fire effects varied in terms of peak thermal flux, overpressure, and internal vehicular damage. Aftereffects ranged from window fogging (condensation from hydrogen combustion) to structural damage (deformed doors, broken windows) to second-degree burns and eardrum rupture [9].

One additional significant finding was a propensity for secondary fire after sparking and hydrogen ignition, which was replicated. These secondary fires, that consumed flammable material inside the vehicles, occurred in the intact and front and side-impacted cars. The origin of these secondary fires, that erupted within minutes after initial sparking and severely damaged the vehicles, appeared to be flammable material inside the trunk (spare tire) or cabin (headliner).

Representative test results for ignition tests Table 5 shows the results for the eight ignition tests that were conducted on the intact and crashed vehicles.

Table 5
Matrix and critical data from Task C ignition tests

Task 2c Vehicle Ignition Tests					
Vehicle	**Leak Rate (nlpm)**	**Leak Duration (min)**	**Test #**	**Ignition?**	**Secondary Fire?**
Front Impact	**118**	**1.5**	**68**	**Yes**	***Yes***
Intact	3	60	82	No	No
	6	**60**	**83**	**Yes**	***Yes***
Rear Impact	6	60	84	No	No
	12	60	85	No	No
	24	**60**	**86**	**Yes**	**No**
	48	60	87	Yes	No
Side Impact	**60**	**60**	**88**	**Yes**	***Yes***

Test 68 was the first test in the series. The leak was located in the trunk and flowed at a rate of 118 nlpm for 90 sec. The total hydrogen volume delivered was 177 liters into 3,012 liters, or ≈ 5% of the trunk and passenger compartment volumes. A hydrogen sensor was located at 50% height in both the front-passenger and trunk compartments. The ignition source was a spark plug (100 J), located a few inches between the leak in the trunk and the 50% sensor location.

Although neither hydrogen sensor detected a flammable hydrogen concentration, sparking resulted in a combustion event more damaging than expected based on Subtask B testing.

The graph of the concentration vs. time history from the hydrogen accumulation test 34 at 118 nlpm (Figure 20 below) may provide some insight into why the sensors did not detect hydrogen in the ignition test.

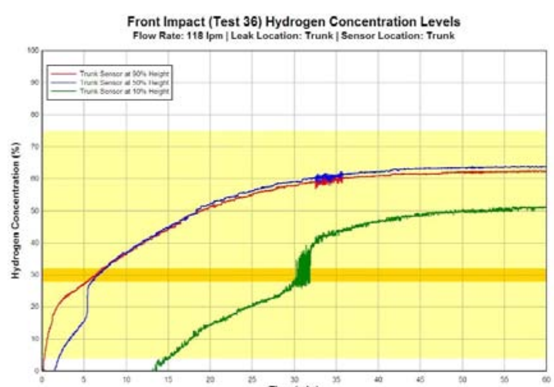

Figure 20. Test 34: 118 nlpm trunk leak (Subtask A)

Note that at 90 seconds, the trunk sensors detect 0 to 20% hydrogen depending on whether the sensor is at the 10%, 50%, or 90% compartment height location. Therefore, though this leak rate provided 5% by volume, the concentrations were highly variable at the time of ignition, and locally probably closer to 20%.

The increased confinement of the vehicle, albeit after impacted (front), when compared to that of the ACS that was sealed with magnets and tape, appears to have held pressure generated longer after ignition and allowed it to build to significantly higher levels. The resulting overpressure inside the vehicle peaked at approximately 9 psi, significantly higher than that generated in the ACS ignition test under the same flow conditions. In contrast, the heat flux was similar for tests in both subtasks.

The hydrogen accumulation tests showed that a leak rate of 118 nlpm into the trunk and passenger compartments of intact and crashed vehicles over the course of an hour can result in the presence of flammable concentrations inside the vehicle in as little at 90 seconds. Therefore, the remainder of the vehicle ignition tests in Subtask C sought to determine the minimum leak rate that could result in a flammable concentration over the course of an hour.

Table 5 shows that test number 82, with a leak rate of 3 nlpm for 60 minutes did not result in ignition, but test 83, with a leak rate of 6 nlpm did. Moreover, in three of the vehicle ignition tests, secondary fires broke out due to ignition of interior components. Figures 21, 22, and 23, show the time line of the secondary fires that broke out in tests 68, 83 and 88. These fires originated in the spare tire compartment (86 and 88), and the headliner (test 83).

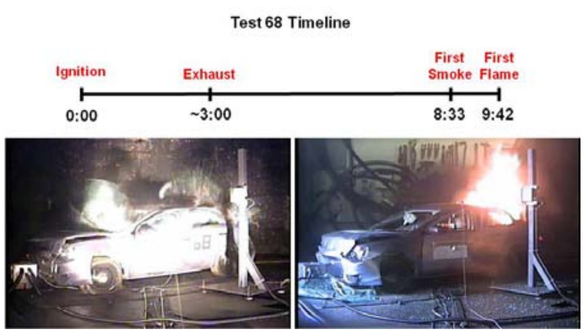

Figure 21. Test 68: Secondary fire observed at ≈ 10 minutes

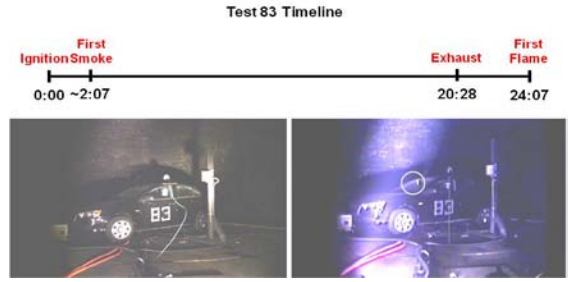

Figure 22. Test 83: Secondary fire observed at ≈ 24 minutes

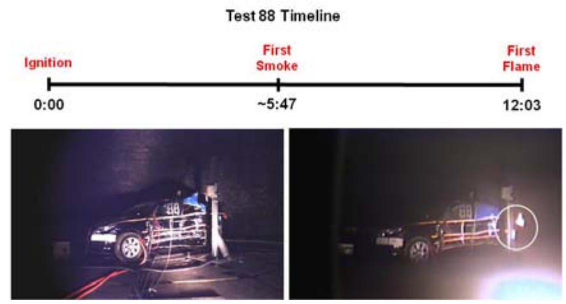

Figure 23. Test 88: Secondary fire observed at≈ 12 minutes

CONCLUSIONS

The tests conducted in this program were simulations utilizing conventional vehicles and vehicle compartment simulators, into which the proposed allowable energy equivalent of hydrogen was purposefully introduced, into or around the vehicle. The hydrogen was purposely ignited to determine whether the outcome presented a hazardous condition. The study is not indicative of how a hydrogen fuel system would perform in a crash. However it does show what consequences could be expected, should various volumes or concentrations of hydrogen accumulate within a vehicle in the presence of an ignition source.

With regard to the objective of determining the safety of the proposed minimum allowable post-crash leak rate, data indicate that leak rate is not the most important metric, but instead the volume of hydrogen leaked into the automobile compartments to accumulate locally to 5%, or to a level exceeding the lower flammability limit of 4%. It appears to be unimportant if this lower flammability limit is reached via a low leak after long duration (up to 60 minutes) or a higher leak rate over a very short duration.

Fire effects varied in terms of peak thermal flux, overpressure, and vehicle damage. Subtask A revealed that hydrogen can remain in an enclosed compartment for a significant amount of time even after cessation of a leak. Higher leak rates can reach steady state concentrations at or above the upper flammability limit where, in the absence of ignition, asphyxiation could also become a concern. Lower leak rates can reach steady state near the stoichiometric level where detonation can occur.

Subtask B provided data on the combustion effects of lean, stoichiometric, and fuel rich concentrations of hydrogen. However, the magnetic and taped seals on the ACS allowed the panels to bulge and break away, which likely mitigated the overpressure effects seen in the actual vehicle tests in Subtask C, which all utilized only 5% by total volume of hydrogen. Also, the ACS did not contain any combustible materials like the real vehicles.

There was a propensity in the Subtask C tests for secondary fire after the initial hydrogen ignition. These secondary fires consumed flammable material inside the vehicles and occurred in both the intact, front-impacted, and side-impacted automobiles.

The research shows that based on these test results:

- All accumulation of hydrogen within passenger compartments should be avoided.
- More than one sensor in vehicle compartments may be required for alarm purposes.
- Vehicle devices that vent passenger compartments upon impact are warranted.
- Flammability tests on fabrics exposed to hydrogen or hydrogen flames may have merit.

REFERENCES

[1] CFR 49, Transportation, Chapter V – National Highway Traffic Safety Administration, Part 571 – Federal Motor Vehicle Safety Standards, §571.301

[2] CFR 49, Transportation, Chapter V – National Highway Traffic Safety Administration, Part 571 – Federal Motor Vehicle Safety Standards, §571.303

[3] SAE 2578: Recommended Practice for General Fuel Cell Vehicle Safety. 1/12/2009

[4] Draft Global Technical Regulation for Hydrogen Vehicles, http://www.unece.org/trans/doc/2011/wp29grsp/SGS-11-02e.pdf

[5] Knox, T., S. Mosher, M. McFall., BURNSIM Version 3.0.2 USER Guide, Document Number WPAFB88ABW-2009-0309. August 1, 2008.

[6] Test Methodology for Protection of Vehicle Occupants against Anti-Vehicular Landmine Effects, Annex H – Supplemental Information on Overpressure Injury Assessment, NATO 2007, http://ftp.rta.nato.int/public//PubFullText/RTO/TR/RTO-TR-HFM-090///TR-HFM-090-ANN-H.pdf

[7] Altman, J., 2001, Acoustic Weapons-A Prospective Assessment. Science and Global Security. Volume 9, pp. 165-234.

[8] Breitung W., et al, 2000. Numerical Simulation and Safety Evaluation of Tunnel Accidents with a Hydrogen Powered Vehicle, 13th World Hydrogen Energy Conference, Beijing, China

[9] Battelle Memorial Institute. Post-crash Hydrogen Leakage Limits and Fire Safety Research. Test Report Task Order 3 for National Highway Traffic Safety Administration. May 2010.