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HYDROGEN RELEASE AND COMBUSTION MEASUREMENTS IN A FULL SCALE GARAGE

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Prepared for
U.S. Department of Commerce
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8600

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<u>Notice</u>

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HYDROGEN RELEASE AND COMBUSTION MEASUREMENTS IN A FULL SCALE GARAGE

Final Test Report

Contract SB134109SE0612
SwRI® Project No. 01.15071

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January 22, 2010

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Consisting of 52 Pages

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1. EXECUTIVE SUMMARY

In compliance with the National Institute of Standards and Technology (NIST) requirements of RFP SB1341-09-RQ-0200, a reinforced concrete block garage system was constructed for the purpose of testing hydrogen dispersion in a garage configured with and without a vehicle. The inside dimensions of the garage were 6.1 m × 6.1 m × 3.05 m. The front wall and ceiling were stick built to relieve pressure strain and to determine the impact on wood frame construction. The garage was instrumented with hydrogen sensors arrayed on a vertical axis spaced every 0.38 m from the floor to the ceiling except for an additional sensor located at the ignition point 2.59 m above the floor. Thermocouples were arranged in both the vertical and horizontal direction (at the same height as the ignition point spaced every 60 cm) to measure the thermal distribution from each test. Additional instrumentation included two radiometers, two blast pressure probes, and six ion probes. The blast pressure probes and the ion probes were configured for high speed data collection at a scan rate of 10 μs for 60,000 total scans. A variety of video was collected for each test with high speed (1000 frames per second), infrared (IR), and high definition video (30 frames per second) cameras.

A series of 17 tests were performed without vehicles with hydrogen concentrations ranging from 8 % to 28.8 %. The damage generated from each test depended on the hydrogen concentration at the ignition point. All seven of the 8 % tests did not damage the garage structure and resulted in negligible pressure increases and minimal temperature rise. IR camera footage clearly shows deflagration burn speeds of less than 0.5 m/s and an upward-only burn profile that spreads across the ceiling. The six tests conducted at 12 % resulted in the detachment of the right side of the front wall with no loss of garage door function and a deflagration speed of approximately 1.6 m/s. The three tests conducted at 16 % resulted in complete removal of the front wall with minor damage to the roof and deflagration speeds of 7 m/s to 10 m/s. The test conducted at 28.8 % hydrogen without a vehicle resulted in complete destruction of the garage with complete removal of the front wall and roof, failure of the concrete walls, and a deflagration speed of 25 m/s. The debris field from the 28.8 % test extended 46 m to the front of the structure.

Additional tests were performed with a vehicle placed in the structure. The presence of the vehicle above the hydrogen introduction system at the floor resulted in complete disruption of the hydrogen concentration stratification as measured by the hydrogen sensors during the filling process. The 8 % test resulted in an anomalous burn as recorded by the IR camera. The flame front was measured and burned similarly to that seen without the vehicle, with the major difference being that the hydrogen continued to burn for several minutes in a torch like formation at approximately the 2.9 m height above the floor. This was attributed to the build-up of hydrogen in the engine compartment to relatively high concentrations (28 %) with subsequent slow release following ignition. Subsequent tests with a hydrogen sensor placed in the engine compartment confirmed this conclusion. Both of the 12 % tests conducted with a vehicle resulted in major damage to the garage structure. One of these tests cracked the reinforced concrete block walls at the corners. The burn process appeared to involve a deflagration to detonation transition (DDT) event as evidenced by the pressure probes and the high speed video, with 1.5 s elapsing between ignition of deflagration and the DDT. This is consistent with the flame front velocity noted previously and the expected time required to reach the bottom of the vehicle. Video footage for all of the 12 % and 16 % vehicle tests with vehicles included show a significant increase in velocity of the front wall movement following an intense flash inside the garage. Concentrations of hydrogen in the engine compartment were almost stoichiometric at 27 % to 28 %, and the concentrations in the garage were nearly uniform with no vertical stratification. The 16 % tests resulted in significant damage to the concrete structure and resulted in complete loss of the roof and front wall. The time delay of the transition for the 16 % test with vehicle was much shorter, 0.3 s, and is again consistent with flame front velocity. An attempted test with 28 % in the presence of a vehicle did not achieve the desired concentration, only reaching 17.7 % prior to ignition due to the loss of stratification and a somewhat higher leakage rate. The observed level of damage to the structure was similar to the test at 28 % without a vehicle.

The size of the vehicle appears to have a significant effect on the degree of damage. Larger engine compartments and other entrapping spaces resulted in increased damage. Because the vehicle was replaced for each test due to the damage sustained and different types of vehicles were used, it is difficult to quantify this effect. The internal configuration of the engine compartment and passenger compartment varied greatly, and the configurations of entrapping spaces were also highly variable. No measurements were made of the volume under the hood in the engine compartment or in the passenger compartment. Additional testing with either identical vehicles or a mock-up that controls these three parameters would be required to accurately characterize the role of vehicle configuration.

2. INTRODUCTION

Under the auspices of contract SB134109SE0612, The NIST contracted with Southwest Research Institute (SwRI) to perform a testing program designed to support NIST efforts on characterizing the behavior of hydrogen when released into enclosed spaces (e.g. leakage of hydrogen from a fuel-cell powered automobile parked inside a residential garage). The experiments were designed to characterize both the dispersion of hydrogen and combustion behavior of any flammable mixtures that were formed. The combustion behavior was characterized by visual observation, temperature, flame ion front speed measurements, radiative energy measurements, and the overpressures generated within the enclosure.

A test facility simulating a residential garage was constructed and instrumented to measure the combustion temperatures, pressures, and flame velocities of hydrogen for four concentrations at the ignition point. The inner dimensions of the garage were 6.1 m × 6.1 m × 3.05 m. Multiple iterations for each concentration were performed in order to characterize the variability of the results and uncertainties of the measurements. An additional six tests were conducted at four hydrogen concentrations with the addition of a vehicle in the garage. Ignition of each test event was originally planned to simulate the actuation of a garage door opener. A 0.1 J electric spark proved inadequate to ignite both 4 % and 8 % concentrations of hydrogen. The ignition system was converted to an 80-J electric match system. The garage design simulated the environment expected in an average garage with an unmixed atmosphere that had an air inward leakage rate between 3 and 10 enclosure volumes per hour at 4 Pa. The inward leakage rate was measured prior to the initiation of each test. Weather conditions were also recorded for each test.

3. OBJECTIVE

3.1 Goals

In a simulated garage, the effect of hydrogen combustion at four concentration gradients was measured with ignition at a height of 2.59 m above the floor. Measured parameters were overpressure, hydrogen concentration and stratification, fill rate, inward leakage of the structure, impulse pressure, peak temperature, and flame propagation speed.

3.2 Deliverables

The deliverables for this effort include:

- Risk Assessment – included as Appendix A,
- Test Data – provided digitally on a DVD, and
- Final Test Report.

4. MATERIALS

4.1 Instrumentation/Sensors

4.1.1 Pressure Transducers

Fast response pressure transducers (PTs) were used to measure transient pressures generated by the combustion as well as the total overpressure for the event. Two PCB Piezotronic 137A21 sensors were located at heights of 2.59 m above the floor at the center of the right concrete side wall (looking from the front of the garage) and 0.3 m in front of the garage door along the garage centerline. The PTs had been recently calibrated to ensure that accurate readings were measured. Initially, the measurement range of the detectors was 6.9 kPa – 6.9 MPa (1 psig to 1000 psig) with a maximum pressure of 17.3 MPa (2500 psi), incident rise times were ≤ 4 ms, and the resonant frequency was ≥ 500 kHz. The pressure sensors were changed to 137A23 after the first series of tests to more sensitive probes having similar performance with ranges of 6.9 kPa – 345 kPa (1 psig to 50 psig).

4.1.2 Thermocouples

The temperature distribution of the system was monitored using 0.16-cm diameter (1/16th in.) thermocouples (Omega K type thermocouples were used, catalog number TJFT72-K-SS-116G-6-SMPW-M, 304 Stainless steel sheath, grounded with fine tip). A total of eight sensors were arrayed on the vertical axis of the test structure along a line located 30.5 cm from the center of the back wall. An additional seven sensors were arrayed along a horizontal line at a height of 2.59 m from the floor and spaced evenly every 60 cm from 0.3 m to 3.05 m from the point of ignition. The horizontal thermocouples were added with the intent of determining flame front speeds, but the data acquisition system could not be operated faster than 1 Hz without making the hydrogen sensors signals very noisy.

4.1.3 Ionization Probes

A Dynasin Ionization probe system was used to measure flame propagation rates. When the flame front reached a ionization probe, a voltage signal was generated and recorded by a data acquisition system that recorded the time to within 0.01 ms. The flame propagation velocity was measured with six probes located at 0.3 m intervals along the back to front axis of the garage at the same height as the flame ignition point, i.e., 2.59 m above the floor. For many of the tests, the performance of the ion probes was unreliable, however, for some tests the data were usable and were confirmed by IR camera results. The erratic results indicate that either the system should be redesigned or a different sensor system should be used for flame speed measurements.

4.1.4 Video Cameras

Two high definition video cameras were positioned to capture the combustion behavior on the inside of the garage. One was positioned outside of the structure focusing on the area where the electronic match was located. This camera was protected by a polymethyl methacrylate window in the wall. A second camera was positioned inside the structure within a protective box and was focused on the front wall or the vehicle depending on the type of test being conducted. High speed video was captured for most runs with a camera positioned approximately 25 m at a 30° angle from the front of the test facility at a position outside of the expected debris zone for the front wall. An IR camera was used for many of the runs, positioned to observe the ignition point and an approximate distance of 3.05 m from the ignition point. The IR camera proved useful in calculating flame velocities in the 8 %, 12 %, and 16 % tests.

4.1.5 Radiometers

A narrow focus (30° or 0.52 rad) radiometer was positioned 3.3 m from the ignition point at the same height and mounted near the right wall to measure radiant heat flux. A second wide angle (180° or 3.14 rad) radiometer was mounted at the floor level in the center of the structure to measure radiant heat flux. The floor mounted radiometer was removed for the vehicle tests.

4.1.6 Inward Leakage Tester

A model E-3 Blower Door test system manufactured by INFILTEC was used to measure the inward leakage of the structure prior to initiating testing each day. Working in negative pressure mode the pressure was measured in pascals (Pa) and flow in m^3 per hour. Pressure and flow were measured at several fan settings and plotted to create a best fit plot fitting the exponential formula $q = Cp^n$ where q is the flow rate, C is the flow coefficient, p = pressure in Pa, and n = flow exponent for the building. The result was used to calculate the inward leakage rate at 4 Pa. The target inward leakage rate was 3 to 10 air changes per hour $(ACH)_4$ for the internal volume of 113 m^3 for the garage. All of the inward leakage data is present in the electronic data in a single spreadsheet organized by date of testing. In Figure 1, a total of eight data points were collected and the best exponential fit was calculated using Excel™. In this case the result was C = 111 and n = 0.755, giving an inward leakage rate of 2.8 $(ACH)_4$.

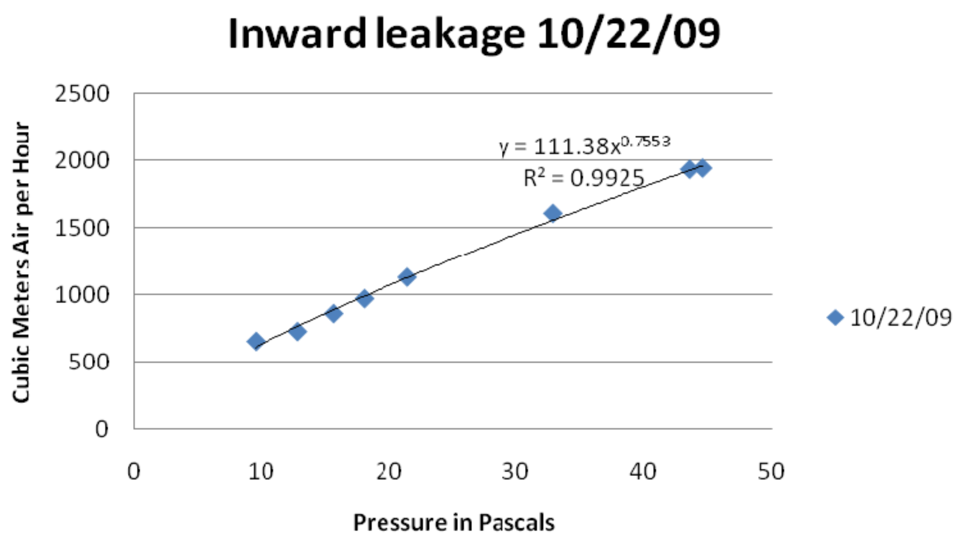

Figure 1. Inward Leakage Calculation for Test Conducted on 10/22/09.

4.1.7 Hydrogen Introduction System

The hydrogen introduction system used in these experiments was specifically fabricated to provide a maximum flow of 5 kg/hr from a location at the center of the garage floor with a linear velocity of less than 30 m/s. To this end, a 12 pack, cascade hydrogen cylinders system containing 6.8 kg of hydrogen was equipped with a high flow pressure regulator. A 1000 SLPM (standard L/min) mass flow controller was installed that required 0.52 Pa (75 psi) back pressure to operate within calibration. A ball valve was installed downstream of the flow controller. This was attached to a 3.8-cm (1.5–in.) flexible high pressure fuel line rated for hydrogen. The flexible line was connected to a solenoid-actuated ball valve at the site of the garage test simulator. A final manual ball valve was installed downstream of the solenoid-actuated valve for safety. This line was then attached to the 3.8-cm (1.5–in.) diameter fuel pipe that passed through the side wall of the garage and under the floor to a point where it terminated in the side of a burner box having dimensions of 0.30 m × 0.30 m × 0.15 m with its top placed flush with the dirt floor. The box was equipped with a support screen (diffuser) on which a 0.10-m layer of 12-mm crushed stone was held in place by a second wire mesh screen. At a flow rate of 990 SLPM, the average linear velocity of the hydrogen into the structure was reduced to 11 m/s. All of the reported data had flow rates between 982 SLPM and 990 SLPM, yielding linear velocities between 10.9 m/s and 11.0 m/s. Flow velocities are estimated based on the volume flow rate and the open area of the burner box.

4.1.8 Ignition Systems

The initial ignition system was a custom built spark system using a discharge capacitor and adjustable gap spark plug equipped with a trigger switch. A 3-kV power supply was able to deliver multiple sparks per second at 100 mJ. The gap was adjusted and capacitor changed to achieve both 1-J and 10-J sparks. None of these proved successful in igniting an 8 % hydrogen mixture at a height of 2.59 m. The system was replaced with an 80-J electric match powered by a 12-V DC battery and triggered with a 5-position firing switch. A total of three matches were included for each test at 8 % hydrogen. The electric matches were triggered one at a time to provide redundancy in case of malfunction or if the target concentration failed to ignite. These were reduced to two for subsequent higher concentration runs.

4.1.9 Hydrogen Sensors

Thermal conductivity sensors were used to measure real-time hydrogen concentrations along a vertical line for locations above the floor separated by 0.38-m intervals. Model TCG-3880 sensors manufactured by Xensor Integration were installed and calibrated before each test. A calibration method developed by Dr. William Pitts at NIST, based on measured thermal conductivities for hydrogen/nitrogen mixtures, was used to create individual calibration curves for each sensor using measured sensor response to 0 % and 100 % hydrogen. The approach was validated by demonstrating that it correctly predicted sensor response to a 4.0 % calibration gas standard. The sample calibration shown in Figure 2 includes the third order polynomial best fit line for the hydrogen sensor. The constants shown vary from sensor to sensor. Plots of hydrogen concentration were prepared by converting the mV signals from the thermal conductivity detectors to percentage concentration of hydrogen using the formula shown in Figure 2. The conversion of the data resulted in average biases of -0.9 % at zero concentration. The cause of the negative biases is still being investigated.

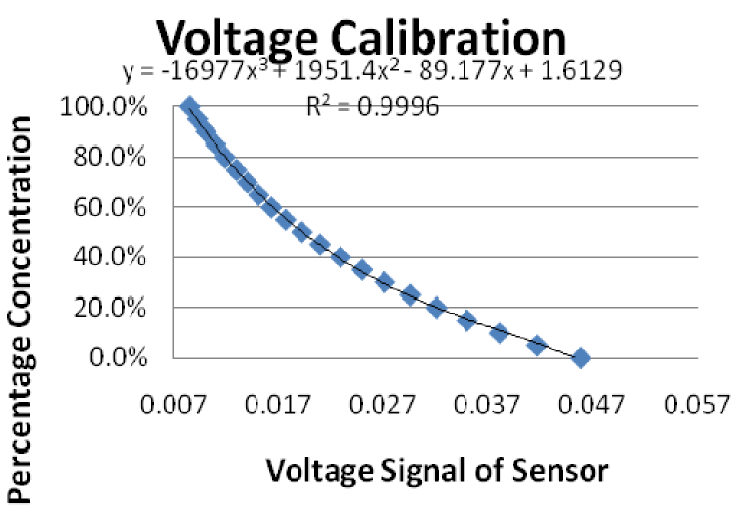

Figure 2. Hydrogen Sensor Calibration Curve with Best Fit Line Formula.

4.1.10 Data Acquisition System

The data acquisition system was configured with both high speed (100 kHz) and low-speed data collection boards. The low-speed system was used to collect data at a single real-time rate of 1 Hz for all of the weather, hydrogen concentration, radiometer, and thermocouple channels. The high speed (HS) acquisition board was run in trigger mode where data is saved in a buffer format that was only saved when triggered by either a 1 volt change in one of the ion probe sensors or a 3.4 kPa change in the pressure. The voltages for the HS data are found in two formats due to a change-out of the DAC computer after its failure due to a slightly different version of the software. Data is collected for 50 ms before the triggering event and for 550 ms after the triggering event at 10-μs intervals. A total of 60,000 data points are collected for each sensor and triggering event. In this format, the timeline shows both positive and negative times. In the second format, all time data is positive and is collected from time zero of the triggering event. Unfortunately, the HS timeline is not directly time correlated to the real-time data timeline.

4.1.11 Automobiles Used in Testing

A total of five non-functioning automobiles were purchased for this testing. All vehicles had intact body panels and windows. The degree to which the passenger compartment was sealed varied from one vehicle to the next. All vehicles were prepared by removing the gas tanks, draining the fuel lines, and draining the air conditioning system. Each car was equipped with a hydrogen sensor attached to the rear view mirror in the passenger compartment. This was added as a safety measure to prevent personnel exposure to potentially hazardous conditions. For the last four tests a second hydrogen sensor was added to the engine compartment just above the manifold to determine the concentration of entrapped hydrogen. The make, model, and year of each car can be found in the test matrix included in Table 1.

4.2 Chemicals - Hydrogen

Compressed hydrogen was used as the source for all of the experiments. A combination of 6 and 12 pack 0.0.028-m^3 (K type) compressed gas cylinders, obtained from Matheson Tri Gas, were used to provide a continuous flow of 982 SLPM of hydrogen at a purity of 99 % or better.

5. EXPERIMENTAL

5.1 Technical Approach

5.1.1 Experimental Concept

The purpose of this test series was to simulate the consequences of a hydrogen leak from a fuel cell powered vehicle in a normal garage initiated by an electrical spark as a result of actuating a garage door opener. Parameters measured or controlled in this series of tests include hydrogen percent concentration, inward leakage of outside air, flow rate for hydrogen addition, temperature of room, peak temperatures, flame propagation speed, peak pressure, and overpressure. The data obtained will improve the understanding of the impacts of an unintended release of hydrogen in an enclosed space and serve as the basis for developing and validating models used to predict hazards associated with hydrogen fuels. The hydrogen combustion behaviors were measured at various concentration levels chosen to cover the flammable concentration range from the lean limit up to concentrations expected to generate the maximum flame temperatures, propagation rates, and overpressure.

5.2 Risk Assessment

5.2.1 Risk Assessment Methodology

A risk assessment was performed based on the testing scenario that identified potential hazards, assessed the hazards based on the matrix shown in Figure 3, and proposed mitigation methods for each identified hazard with a risk number greater than six. All risks were mitigated to the point that their final evaluated risk number was less than seven. Risk numbers were calculated by taking the probability number for the likelihood of occurrence and multiplying it by the consequence number to obtain the matrix value. This was most easily done by using the intersecting block for consequence and probability in the matrix shown in Figure 3.

No risks were identified that could not be mitigated with engineering controls. The completed risk analysis was submitted to the COTR at NIST for review and approval prior to initiation of the test program. The final analysis is found in Appendix A.

5.2.2 Garage Construction

A simulated garage structure was constructed on the Ballistics Range at SwRI in San Antonio, TX, to determine the effects of a hydrogen deflagration scenario. The garage was fabricated with inner dimensions of 6.1 m × 6.1 m × 3.05 m. Three of the walls (rear and two sides) were constructed of stacked, interlaced mortar-filled concrete block. Rebar reinforcing, 19 mm, was welded to the I-beam foundation frame every 0.81 m and passed upward through the blocks to the top of the wall. The original structure had I-beam buttress supports located in the middle of each wall for additional strength as well as wing walls on the front of the structure. Subsequent to the 28.8 % test, I-beam supports were added to the corners for additional strength. The front wall was constructed from 3.7 m long pine 2 × 4 framing beams at 0.60-m intervals with 1.3-cm (½-in.) thick gypsum board inner surfaces. The bottom of the front wall was constructed of two pieces of 1.8-m long pine 2 × 4 framing that rested on but were not attached to the I-beam foundation. The front wall was attached to the 2 × 6 cap beams of the side walls at one point on both sidewalls using 3 in wood screws. An un-insulated metal panel 2.1-m × 2.4-m garage door was installed in the center of the front wall. The roof of the structure was constructed with 30.5-cm (12-in.) high engineered wooden I-beams constructed of oriented strand board (OSB) and 2.5-cm plywood spaced every 0.46 m covered with 1.6-cm (⅝-in.) thick plywood. The roof was attached to the block construction by 25 mm all thread rods with 0.45 m lengths exposed above the roof decking. Each of the all thread rods was capped with a nut and washer. The all thread allowed for some pressure release by allowing the ceiling to travel straight upward in a controlled manner, thus creating an opening between the rear and side walls and the roof. Once the pressure was released, the roof would settle back down on the walls. The inside of the ceiling was lined with 1.3-cm (½-in.) gypsum board and all seams were sealed with latex caulking and/or duct tape. Figures 4A–D show inside and outside views of the test garage. Two 0.2-m × 0.2-m square windows at a height above the floor of 2.59 m were installed in the right side wall to facilitate the videography of testing, as shown in Figure 4C. A (0.3-m × 0.3-m) square window was also installed in the ceiling above the sensor array and ignition point to allow for light to increase visibility as shown in Figure 4B.

RISK MATRIX						
POTENTIAL CONSEQUENCES		PROBABILITY				
		VERY UNLIKELY	UNLIKELY	MAY HAPPEN	LIKELY	CERTAIN OR IMMINENT
		1	2	3	4	5
No Hazard of injury	1	1	2	3	4	5
Minor Injury	2	2	4	6	8	10
Major Injury	3	3	6	9	12	15
Single Fatality	4	4	8	12	16	20
Multiple Fatality	5	5	10	15	20	25

LOOK UP TABLE	
Low	1 to 6
Moderate	7 to 10
High	11 to 16
Very High	17 to 25

Figure 3. Risk Matrix.

Figure 4A–D. Inside and Outside Views of Test Garage.

Figure 4B shows a portion of the vertical and horizontal sensor arrays and the ignition point. This photo shows the spark ignition system prior to its replacement with electronic matches. The vertical sensor array is mounted on a 0.25-m diameter pipe attached to a flat metal plate acting as a stand. The horizontal sensor array is mounted on a hallow steel (2 × 4) construction stud that was 5.5 m long. The stud passed through an opening in the rear concrete wall and was suspended from the ceiling at the front with a piece of all thread that penetrated the roof. The horizontal sensor array was along a nearly constant height of 2.59 m above the floor and extended from near the back wall to just short of the garage door, bisecting the garage.

Figure 5 shows the positioning of critical sensors in a cut-away schematic side view of the garage. This figure represents the as-built garage which was modified to have thermocouples on the horizontal axis.

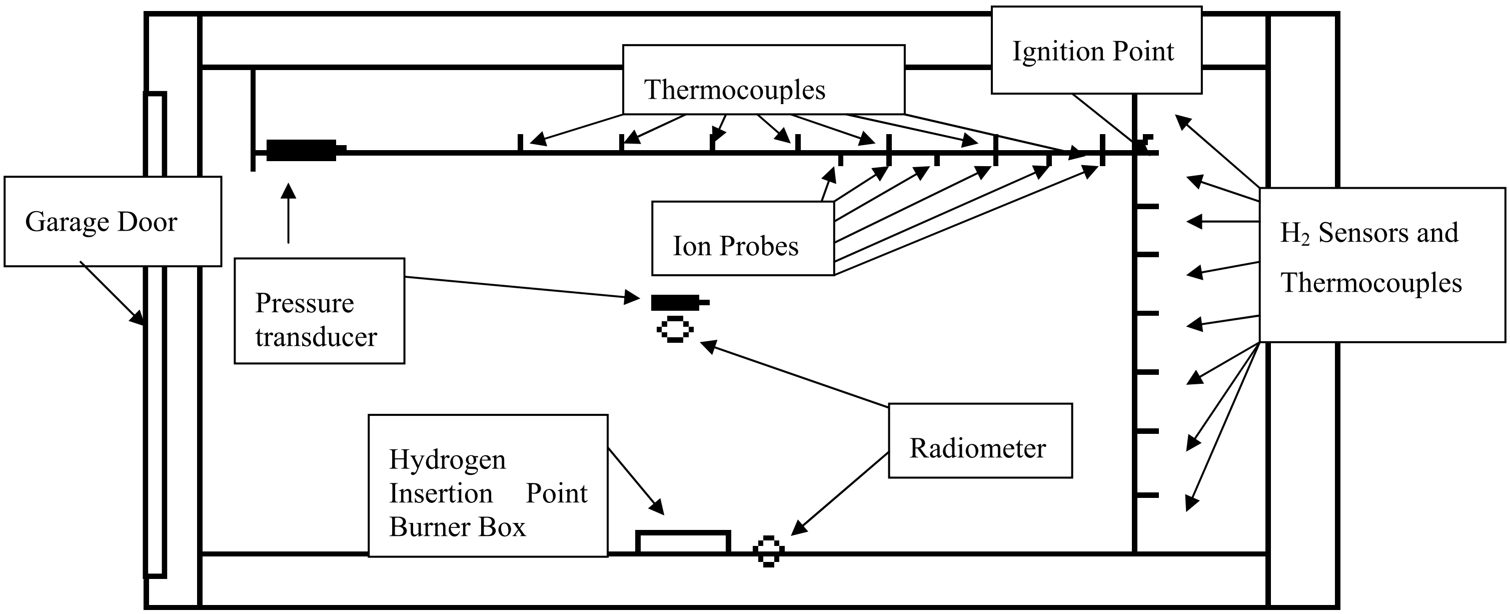

Figure 5. Side View Cutaway of Garage Simulator.

Ion probes were located at 30-cm intervals from the ignition point along the horizontal axis to the front of the garage. A total of six ion probes were installed to measure flame propagation velocity. An additional seven thermocouples were added after the initial 8 % and 16 % tests along this axis located at 30 cm, 90 cm, 150 cm, 210 cm, 270 cm, 330 cm, and 390 cm from the ignition point.

Hydrogen concentration sensors and standard thermocouples were attached to a metal frame in a vertical column 2 ft from the back wall and in the center of structure. The sensor pairs were located at a spacing of 0.38 m, starting at 0.38 m from the floor and continuing to 2.3 m. Two additional sensor pairs were located at 2.59 m (8.5 ft, ignition point) and 3.05 m (10 ft), at ceiling height).

A total of two high speed pressure transducers were positioned in the garage to measure both impulses and overpressures. One sensor was located at the middle of one wall at a height of 2.59 m and the other was located on the sensor rail just in front of the garage door.

5.2.3 Garage Pre-Test Preparation

A functional check was performed on all sensors prior to initiation of the test. The data logging system was validated to ensure that data was being recorded at the correct rate, 100 kHz for the ion probes and pressure transducers. A sampling rate of 1 Hz was used for the hydrogen sensors, thermocouples, and radiometers. Attempts to collect data at higher frequency for the hydrogen sensors resulted in very noisy signals.

Prior to each days testing, the inward leakage rate of the garage structure was measured using the blower door method. The inward leakage rate was kept between 3 $(ACH)_4$ and 10 $(ACH)_4$ for the garage structure. The height of the opening between the floor and the base of the garage door was adjusted using spacers to control the inward leakage rate to the desired value. During early testing, the walls contained numerous narrow slits between concrete blocks and the wood joints. Leakage rates during these tests were near the upper end of the desired range, and, as a result, longer times were required to reach a desired hydrogen concentration. Sealing the walls and joints with caulking lowered the inward leakage rate to below 3 $(ACH)_{4,}$ requiring that the garage door be raised between 1.9 and 2.5 cm in order to increase $(ACH)_4$ into the specified range . The inward leakage rates were recorded for each day of testing or when a change occurred in the garage configuration during a day of multiple tests. Results are summarized in the results section and actual data and calculations are provided with the project data DVD. Appendix B has a listing of the file names and corresponding test for all data, video, and photos collected during this testing program.

5.2.4 Testing

Prior to initiating every test, the safety precautions of the test range and SOP 15071.01.003 were reviewed and the range safety ensured.

The notification checklist was executed informing that an extended test was being conducted at the test site and for all unauthorized personnel to stay clear.

All sensors were verified to be reporting normally. In some cases the ion probes errantly triggered the high-speed data collection system. This caused the system to overload during two of the tests. Replicate tests were conducted to collect the necessary data, and the results were almost identical to the ones with successful data collection.

Hydrogen flow into the system was initiated by the following steps. First, the manual valve closest to the garage and past the air-actuated solenoid valve was opened. Next, the tank and ball valves on the low pressure side of the regulator were opened. The last ball valve on the downstream side of mass flow controller (MFC) was opened next. Flow was initiated when the air-actuated solenoid valve was opened remotely. Pressure on the low pressure side of the regulator was verified to be 517 kPa (75 psi), and the MFC was set to just under 1000 SLPM (average of 982 SLPM). It was discovered that setting the MFC to 1000 SLPM resulted in a wide open and uncontrolled hydrogen release rate, so a lower setting was used to ensure actual control of the filling rate. Based on the daily calibration, the expected mV reading for the hydrogen sensor at 2.59 m was calculated for the target concentration. When this sensor reached this voltage, the solenoid valve was actuated stopping hydrogen flow into the garage. A second ball valve near the MFC was closed and the firing switch was closed. The high speed video switch was activated as soon as the firing switch was closed, capturing the 3 s before and 5 s after the firing.

After each test the data recording system was checked to ensure that the firing event had been captured. The high speed system was not triggered by any of the 8 % tests. In one of the 12 % tests and one of the 16 % tests the concentration/temperature/radiometer data was lost due to data overload from the high speed system shorting repeatedly. This data was also abruptly loss after ignition for the 28.8 % test when the power of the event cut off all of the cables. The high speed data was collected for this test and shows a very fast and sharp pressure rise.

After the ignition of each test, the test manager confirmed that the hydrogen supply was turned off at all valves. The site was examined for thermal hazards or other safety issues. If the area was free of hazards, the test team captured photographic data, examined the garage test facility for damage, processed the video signals, and initiated clean-up operations in preparation for the next test.

All electronic data was immediately copied for back-up to ensure that no measurements were lost. The test matrix shown in Table 1 was executed in compliance with the contract and in coordination with the NIST COTR.

Table 1. Test Matrix.

Hydrogen Concentration	Number of Replicate Tests	Ignition source	Car in Garage
4 % - 8 %	1	100 mJ Spark	No
4 % - 8 %	1	1 J Spark	No
4 % - 8 %	1	10 J Spark	No
8 %	7	80 J Squib	No
12 %	5	80 J Squib	No
16 %	3	80 J Squib	No
28.8 %	1	80 J Squib	No
8 %	1	80 J Squib	Chevy Cavalier, 2001
12 %	2	80 J Squib	Chevy Cavalier, 2001 Ford Aspire, 1996
16 %	2	80 J Squib	Buick Century Limited, 1996 BMW 325i 1995
17.7 %	1	80 J Squib	Ford Explorer, 1995
Total	25 tests		5 cars destroyed

The garage simulator was examined after each test to determine structural integrity. If necessary, repairs were executed to restore the simulator to operational condition. Ceiling, front wall, and garage door were replaced as necessary. All sensors were inspected and tested to ensure function and replaced if necessary. The hydrogen sensors proved to be remarkably resistant to damage and survived many of the tests. Some failed after impact or due to melted wires. All failed in the 28.8 % test. Hydrogen sensors remained active during all repair operations and portable flammable gas meters were available when test sensors were not operational.

Test range operation termination was instituted at the successful completion of all of the matrix tests. Range clean-up was performed to the standards of the SwRI Division 18 range supervisor.

6. RESULTS AND DISCUSSION

6.1 Summary of Data Collected Per Test

Table 2 contains a listing of all of the data collected for each test. The hypothesis that the 8 % and 12 % tests were not energetic enough to trigger the high speed system was verified by the IR cameras. Failures to trigger were also caused by shorts in wiring not detected before the tests. Additional problems were also encountered with the data acquisition system due to ion probe repeated triggering in wet conditions resulting in data overload and freezing of the data acquisition system.

Table 2. Summary of Data Collected for Each Test.

Date and Test #	High Speed Data collected, 100 kHz sampling rate	Low speed data collected, 1 Hz sampling rate	Types of Video Collected	Comments
9/11/09, 8 %-1	None	Hydrogen Conc. Radiometer, Thermocouple, Weather	None	Not energetic enough to trigger High Speed Data collection
9/11/09, 8 %-2	None	Hydrogen Conc. Radiometer, Thermocouple, Weather	None	Not energetic enough to trigger High Speed Data collection
9/11/09, 8 %-3	None	Hydrogen Conc. Radiometer, Thermocouple, Weather	None	Not energetic enough to trigger High Speed Data collection
9/14/09, 16 %-1	Pressure data	Hydrogen Conc. Radiometer, Thermocouple, Weather	High Speed Video, 3 HD views	Ion probes did not trigger, malfunction
9/18/09, 16 %-2	Pressure and ion probe data	Hydrogen Conc. Radiometer, Thermocouple, Plus 4 thermocouple on horizontal Weather	High Speed Video, 3 HD views	
9/21/09, 16 %-3	Pressure and Ion probe data	Hydrogen Conc. Radiometer, Thermocouple, Plus 4 thermocouple on horizontal Weather	High Speed Video, 3 HD views plus still frame of video	

Table 2. Summary of Data Collected for Each Test (Continued).

Date and Test #	High Speed Data collected, 100 kHz sampling rate	Normal data collected, 1 Hz sampling rate	Types of Video Collected	Comments
9/23/09, 12 %-1	Pressure and Ion probe data	Hydrogen Conc. Radiometer, Thermocouple, Plus 4 thermocouple on horizontal Weather	High Speed Video, 2 HD views plus still frame of video	
9/24/09, 12 %-2	None	Hydrogen Conc. Radiometer, Thermocouple, Plus 4 thermocouples on horizontal Weather	High Speed Video, 2 HD views plus still frame of video (pictures)	High speed data collection did not trigger
9/28/09, 8 %-4	None	Hydrogen Conc. Radiometer Thermocouple Plus 4 thermocouples on horizontal Weather	High Speed Video, 3 HD views	Not energetic enough to trigger High Speed Data collection
9/28/09, 12 %-3	None	Hydrogen Conc. Radiometer Thermocouple Plus 4 thermocouples on horizontal Weather	High Speed Video, 3 HD views	High speed data collection did not trigger
10/1/09, 28.8 %-1	Ion probe and pressure data	Hydrogen Conc. Weather	High Speed Video	Rea-ltime temperature, radiometer, and HD video lost due to extreme shock
10/16/09, 8 %-5	None	Hydrogen Conc. Radiometer Thermocouple Plus 7 thermocouples on horizontal Weather	1 HD view 1 IR view	High speed data collection did not trigger

Table 2. Summary of Data Collected for Each Test (Continued).

Date and Test #	High Speed Data collected, 100 kHz sampling rate	Low Speed Data collected, 1 Hz sampling rate	Types of Video Collected	Comments
10/16/09, 8 %-6	None	Hydrogen Conc. Radiometer Thermocouple Plus 7 thermocouples on horizontal Weather	1 HD view 1 IR view	High speed data collection did not trigger
10/16/09, 8 %-7	None	Hydrogen Conc. Radiometer Thermocouple Plus 7 thermocouples on horizontal axis Weather	1 IR view	High speed data collection did not trigger
10/16/09, 12 %-4	Ion Probe and pressure data	Hydrogen Conc. Radiometer Thermocouple, Plus 7 thermocouples on horizontal axis Weather	1 HD view 1 IR view	Rail Pressure probe wire shorted, data lost
10/19/09, 12 %-5	Ion Probe and pressure data	Hydrogen Conc. Radiometer Thermocouple, Plus 7 thermocouples on horizontal axis Weather	1 HD view 1 IR view	Rail Pressure probe wire shorted, data lost
10/22/09, 8 %-1V	None	Hydrogen Conc. Radiometer, Thermocouple, Plus 7 thermocouples on horizontal axis Weather	1 IR view	High speed data collection did not trigger
10/22/09, 12 %-1V	None	None	1 IR view	DAC system overloaded – damp conditions caused random firing of the ion probes
10/30/09, 12 %-2V	Ion Probe and Pressure Data	Hydrogen Conc., 3.05 m sensor dropped, vehicle compartment added. Radiometer Thermocouple, Plus 7 thermocouples on horizontal axis Weather	High Speed Video, 3 HD views, 1 IR view	

Table 2. Summary of Data Collected for Each Test (Continued).

Date and Test #	High Speed Data collected, 100 kHz sampling rate	Normal data collected, 1 Hz sampling rate	Types of Video Collected	Comments
11/4/09, 16 %-1V	Ion Probe and Pressure Data	Partial - 3.05 m sensor dropped, vehicle and engine compartment sensors added	High Speed Video, 2 HD views, 1 IR view, plus still frames	DAC froze for low speed data IR camera severely damaged
11/12/09, 16 %-2V	None	Hydrogen Conc. 3.05 m sensor dropped, vehicle and engine compartment sensors added Radiometer, Thermocouple, Plus 7 thermocouples on horizontal axis Weather	High Speed Video, 2 HD views	Wet conditions caused ion probes to fire, system disabled
11/23/09, 17.7 %V	Ion Probe and Pressure Data	Hydrogen Conc. - 3.05 m sensor dropped, vehicle and engine compartment sensor added, Radiometer, Thermocouple, Plus 7 thermocouples on horizontal axis Weather	3 HD views, plus still frames	

6.2 8% Tests

6.2.1 Tests without Vehicle

The 8 % runs were all very consistent with no damage to the garage and flame front velocities measured at between 0.34 m/s and 0.74 m/s. These runs were not energetic enough to engage the high speed sensors for either the ion or pressure probes. This was difficult to explain until review of the IR camera data showed that the flame propagates up to the roof, travels along the roof in slow waves, repeatedly traveling back and forth from back to front. The burn did not extend down to the sensor level at the 2.59 m height above the floor. The hydrogen concentrations for the 8 % runs were highly stratified with 2.59-m to 1.52-m sensors reading approximately 8.5 % to 9 %, the 1.14-m sensor at 7 %, the 0.76-m sensor at 6 % and the 0.38-m sensor at 2 %. Only the 3.05-m sensor indicated an actual burn event with a rapid drop in concentration. A sample concentration profile for the 8 % tests is shown in Figure 6. There is a clear stratification of the hydrogen concentration. The point of ignition is shown at 535 s into the test with only the 3.05-m sensor showing a significant drop in hydrogen concentration, which quickly recovers. The big drop is likely due to the thermal pulse at this sensor. The thermocouple profile shows the corresponding temperature spike for the thermocouple at

3.05 m, as seen in Figure 7. The IR video of the 8 % tests adds to the evidence that this type burn propagates from the 2.59-m ignition point upward to the ceiling and spreads laterally along the ceiling much like what is seen in a flashover event. The IR camera video revealed some interesting longer term processes that continued for several seconds, rolling waves of hydrogen flame appeared to traverse the ceiling along different axes. It is instructive to watch the entire sequence for each event. The energy of the event is not very exciting and is barely noticed in the visible spectrum as seen on the other video cameras. The radiometers had negligible responses to these events.

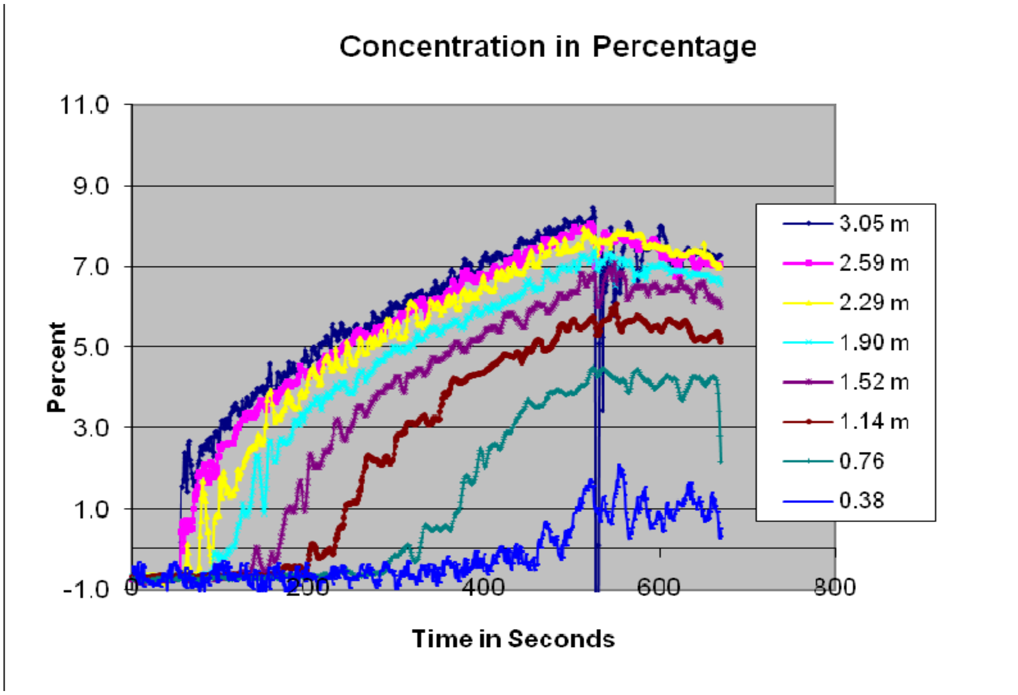

Figure 6. Hydrogen Concentration Profiles for Test 10/16/09, 8 %-6.

6.2.2 Tests with Vehicle

The addition of a vehicle to the garage radically upset the stratification. All sensors recorded roughly the same concentration as can be seen in Figure 8. In addition, the presence of the vehicle induced a major change in the burn behavior. A similar flame to the cases without vehicle was seen spreading along the roof, but the flame did not extinguish in the same manner. It continued to burn at a location above the engine compartment of the vehicle between the 2.59-m and 3.05-m heights. This torch-like flame burned for several minutes and was clearly visible in the IR video. Comparison of the concentration profile in Figure 8 to the temperature profile in Figure 9 shows an interesting correlation between the flame continuing to burn and heating of the sensor at the 3.05-m height. Comparing these results to the IR video explains this phenomenon with the observation of the torch-like burn. The hydrogen trapped in the engine compartment appears to have been released slowly enough to maintain the combustion for an extended period. The hydrogen concentrations in the passenger compartment indicate that it was fairly well sealed before the test and that hydrogen did not build up to a dangerous level.

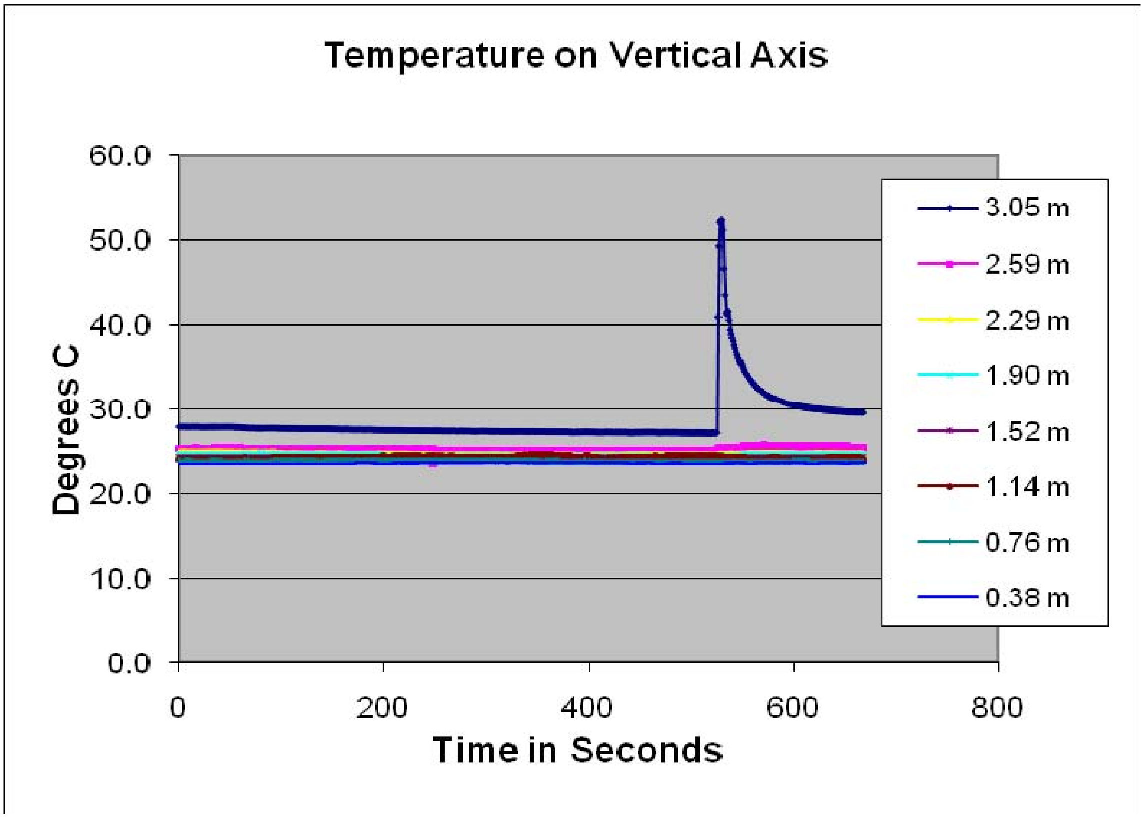

Figure 7. Temperature Profile for 10/16/09, 2-8 %-6 Test.

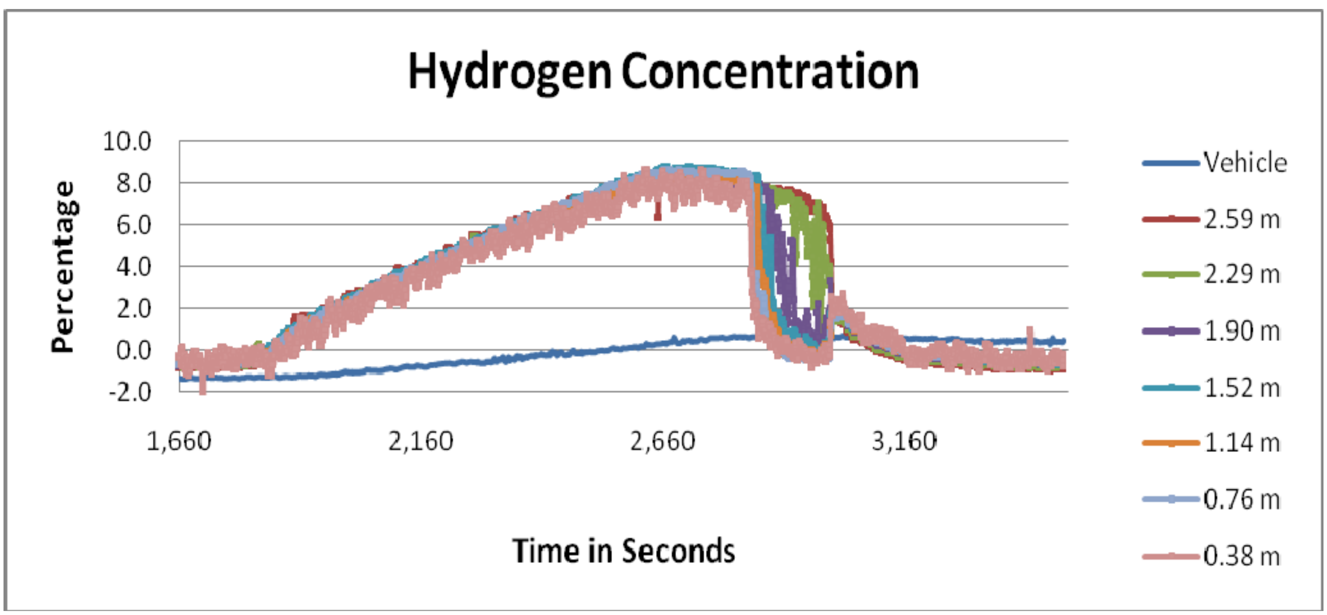

Figure 8. Hydrogen Concentration Profile of the 8 %-1V Test .

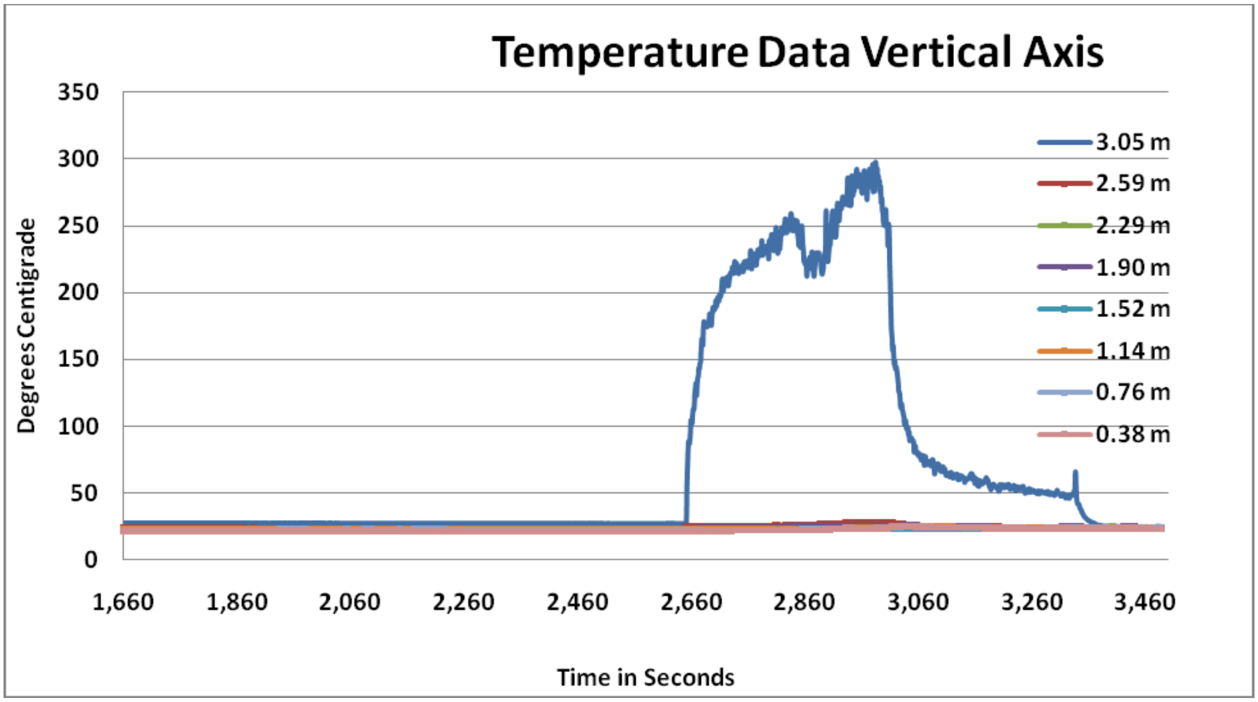

Figure 9. Temperature Profile for 10/22/09, 8 %-1V Test.

Table 3 summarizes the data for the 8 % tests. The pressure transducers and ion probes did not give signals for the 8 % tests, and most of the hydrogen remains unburned. Flame speeds were estimated based on video evidence, either with the HD cameras or the IR cameras.

Table 3. Summary of 8 % Test Data.

Date / test	Measured Inward Leakage $(ACH)_4$ (time to fill)	Actual H_2 Conc. At Trigger	Radiometer Readings	Flame Speed	Peak Temp.	Notes
9-11 8 %-1	7.8 $(ACH)_4$ (724 s)	8.6 %	1.5 mW/m^2 – wall 0.5 mW/m^2 floor	-	180 °C	Temp rise down to 2.29 m height 160°C
9-11 8 %-2	7.8 $(ACH)_4$ (883 s)	8.8 %	1.0 mW/ m^2 – wall 0.1 mW / m^2 floor	-	184 °C	Only got thermal response at 3.05 and 2.59 m height sensors
9-11 8 %-3	7.8 $(ACH)_4$ (765 s)	8.6 %	Wall – malf. 0.1 mW/ m^2 – floor	-	151 °C	Temp rise down to 2.29 m height 82°C
9-28 8 %-4	6.2 $(ACH)_4$ (508 s)	10.3 %	1.0 mW/ m^2 – wall 0.1 mW/ m^2 - floor	3 m/s estimated from video	300 °C	Temp rise down to 2.29 m height at 160°C
10-16 8 %-5	3.8 $(ACH)_4$ (378 s)	7.6 %	-	0.62 m/s from IR camera	60 °C	3.05 m height only response

Table 3. Summary of 8 % Test Data (Continued).

Date / test	Measured Inward Leakage Air Exch./hr	Actual H_2 Conc. At Trigger	Radiometer Readings	Flame Speed	Peak Temp.	Notes
10-16 8 %-6	3.8 $(ACH)_4$ (455 s)	8.1 %	-	0.82 m/s from IR camera	52 °C	3.05 m height only response
10-16 8 %-7	3.8 $(ACH)_4$ (545 s)	8.1 %	-	0.76 m/s from IR camera	54°C	3.05 m height only response
10-22 8 %-1V	2.8 $(ACH)_4$ (1006 s)	8.3 % garage 1.9 % pass. comp.	-	0.91 m/s from IR camera	300°C*	*Continuous torch like burn for 400 s at 3.05 m height

6.3 12 % Tests

6.3.1 Tests without Vehicle

The 12 % runs were all very consistent with minimal damage resulting to the front wall of the garage and the flame front velocity measured at between 1.3 m/s and 2 m/s. A total of five 12 % runs without a vehicle were conducted. The last two runs had an IR camera installed to complement the results from the ion probes. The flame front appeared to accelerate and then decelerate. Some of these runs did trigger the data acquisition system for the pressure sensors and ion probes. The hydrogen concentrations for the 12 % tests were highly stratified, but the degree of stratification seemed to be dependent on the weather conditions and inward leakage rate. The damage to the structure for the non-vehicle runs was primarily detachment of the front wall at the upper left corner. The effect of the deflagration was a slow pressure increase that was non-shattering. The wall was easily repaired and resealed. Figure 10 shows an example to illustrate the degree of hydrogen concentration stratification. Figures 11 and 12 show representative vertical and horizontal temperature profiles from the 12 % tests. It is important to note that the 12 % runs resulted in burning down to the 0.38-m level as indicated by both the temperature and the hydrogen concentration measurements.

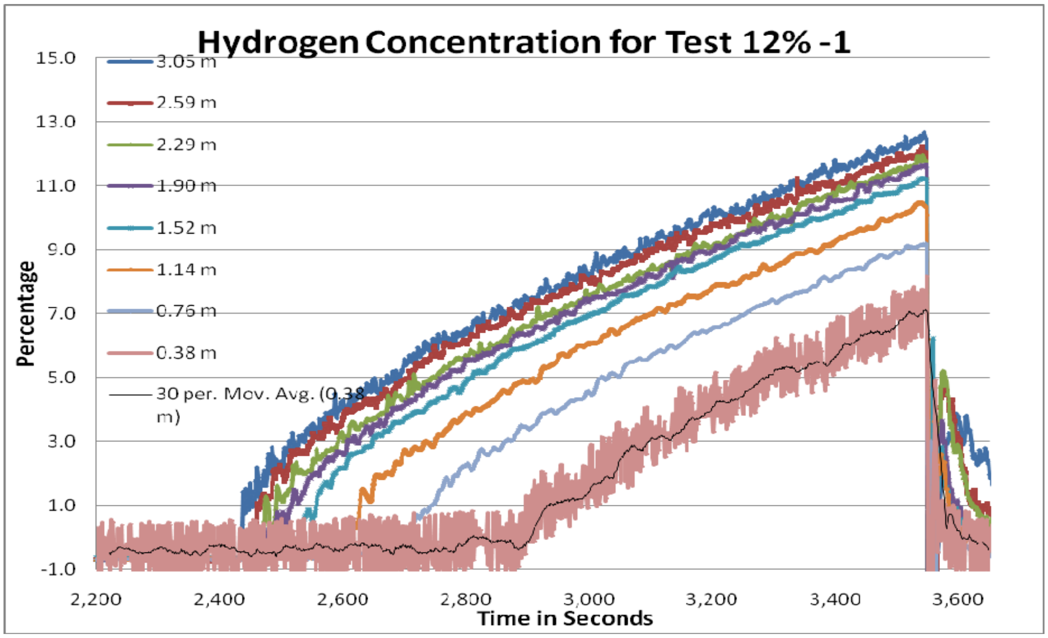

Figure 10. Hydrogen Concentration Profile from Test # 09/23/09, 12 %-1.

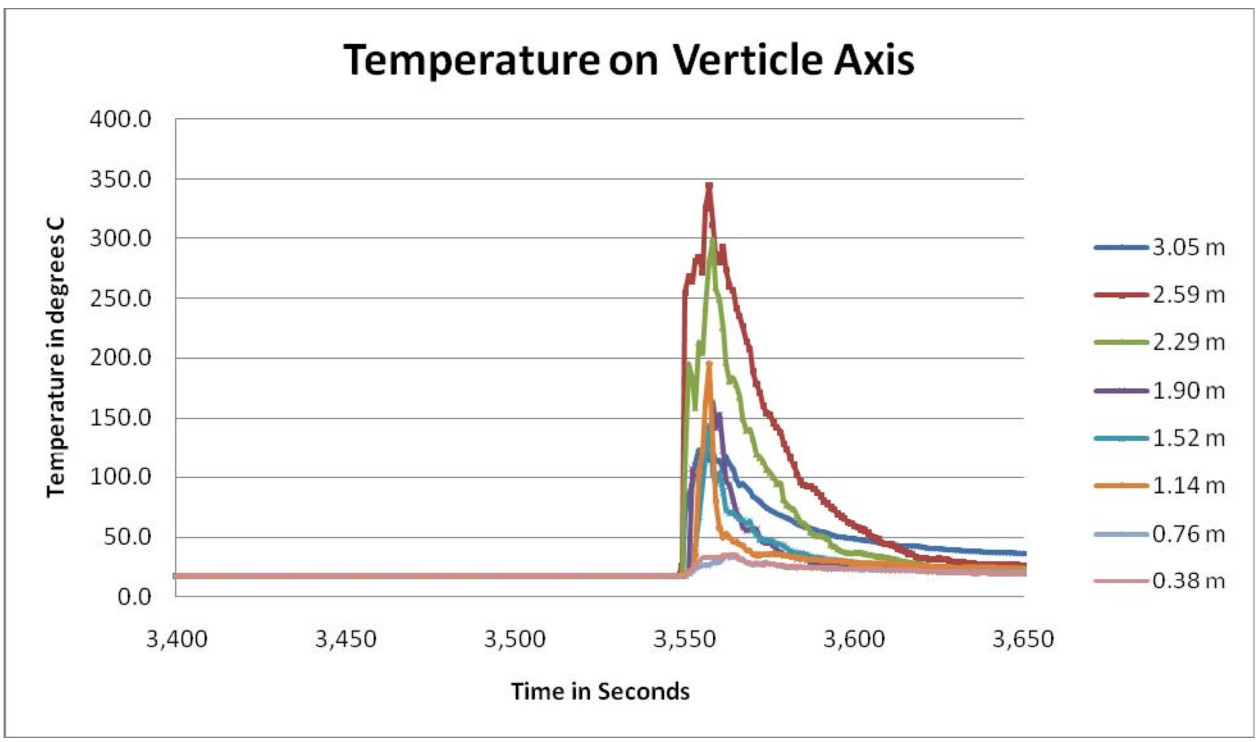

Figure 11. Temperature Profile at Different Heights from Test # 09/23/09, 12 %-1.

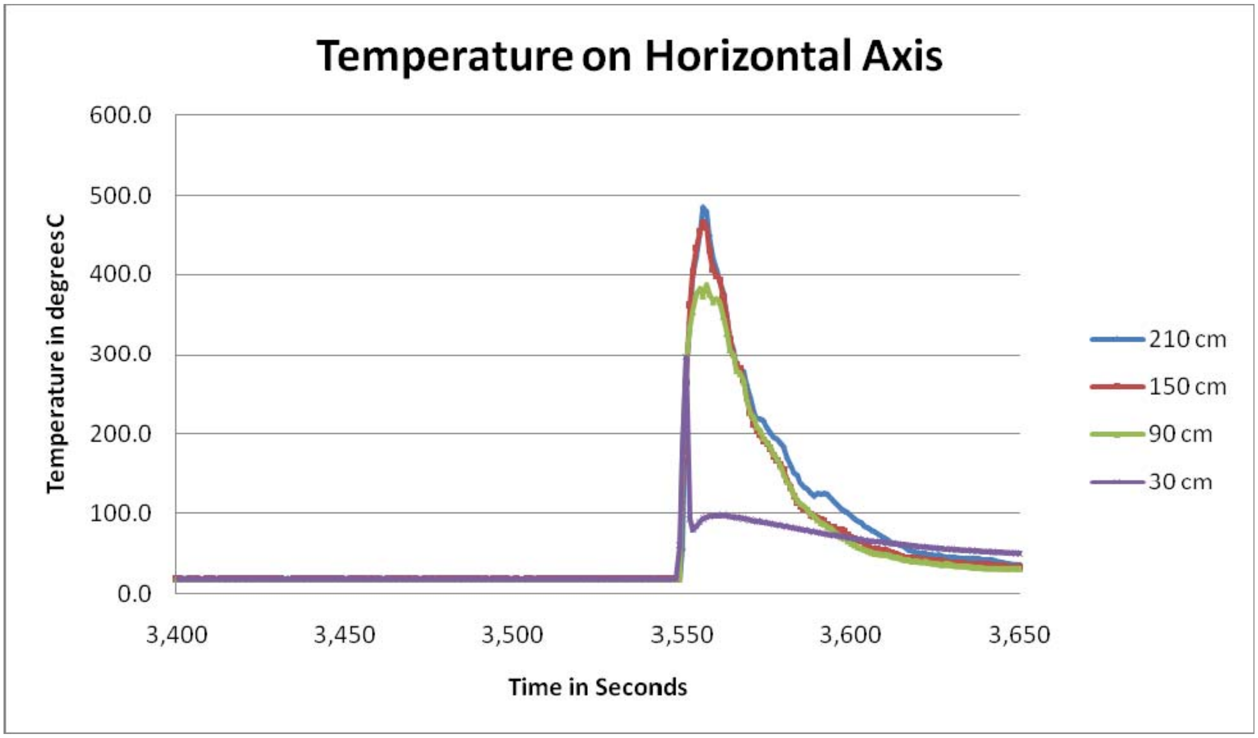

Figure 12. Temperature Profile at Different Distances from the Initiation Point for Test # 09/23/09, 12 %-1.

6.3.2 Tests with Vehicle

The addition of a vehicle to the garage radically upset the hydrogen concentration stratification. The concentrations at different heights were within the range of 11 % to 13 % hydrogen as illustrated in Figure 13. An additional sensor was placed inside the engine compartment of the vehicle to determine the cause for the secondary combustion event seen in earlier vehicle runs. The concentration in the engine compartment rose to 19.5 % immediately and then climbed to 27 % at the time of ignition. The flame speed and a secondary combustion event are clearly visible in the IR video. The timing and sequence clearly indicate that combustion initiated at the ceiling took approximately 1.5 s to 2 s to reach the bottom of the vehicle where it then ignited hydrogen built up in the engine compartment with shattering effect. Both 12 %-with-vehicle tests behaved the same, with major damage to the vehicle and structure. The size and configuration of the engine compartment appears to be a major factor in the amount of damage observed.

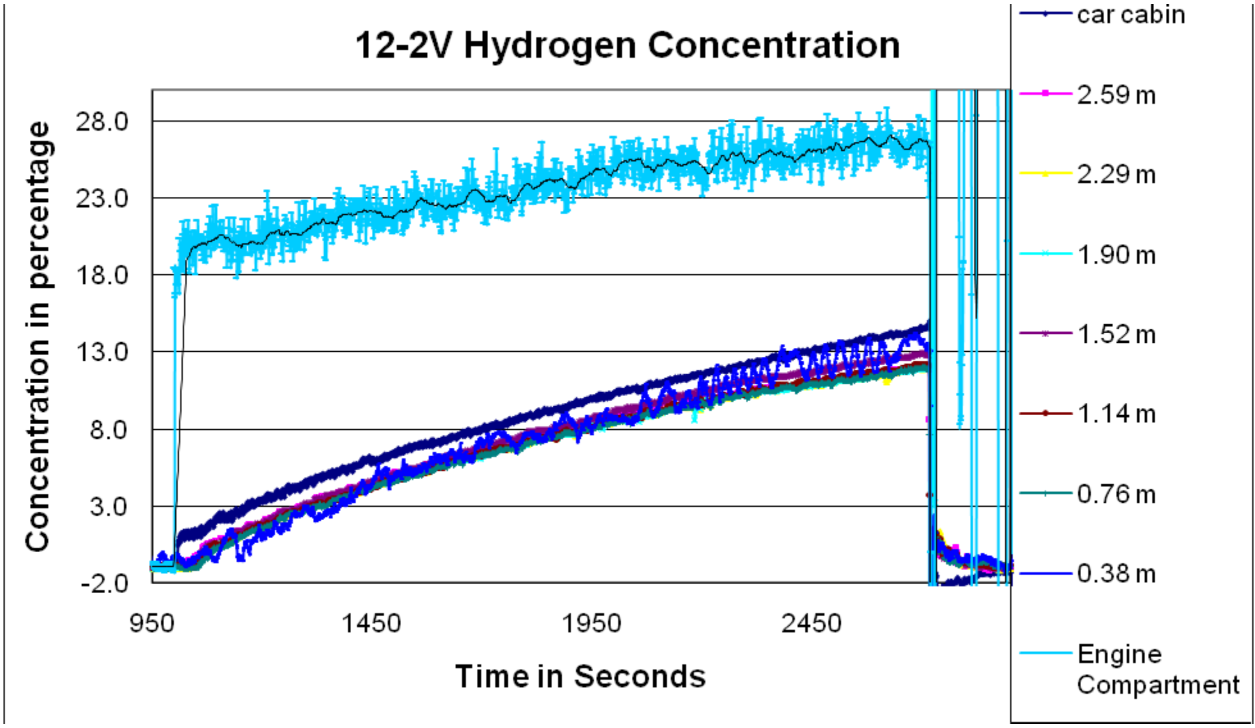

Figure 13. Hydrogen Concentration for Test # 10/30/09, 12 %V2.

The first vehicle was a Chevy Cavalier and the second was a Ford Aspire. The presence of the Cavalier caused significantly more damage to the structure, resulting in loss of the roof beams. This vehicle did not have much damage to windows or door, which is attributed to the low hydrogen concentration measured inside of the vehicle passenger compartment. The sheet metal of the engine compartment hood was blown off, acting as a projectile that destroyed the sensor rail above the vehicle. The back bumper blew off. The Ford Aspire was leakier in the passenger compartment and built up to 14.6 % hydrogen prior to ignition. The sheet metal of the engine compartment hood again was blown off, destroying the sensor rail above the vehicle. The glass windows in the driver door fragmented into small shards. The underside of the vehicle also ignited in this test. Much less damage was done to the garage from this test than for the Cavalier test. Figures 14A–D show both vehicles and the damage to the garage (A and B are of the Cavalier and C and D are the Aspire).

Figure 14. 12 % with Vehicle Damage Photos (A and B-Cavalier, C and D-Aspire).

Table 4 give a summary of the data obtained for the 12 % tests. Additional temperature and hydrogen sensors were used for several of the runs. The concentration at the time of trigger impacts the temperatures achieved, the speed of the flame front, and the height down to which the burn extends. In the final test, 12 %-2V, there was a significant impulse pressure of very short duration. The expanded time scale pressure measurements on the wall pressure sensor are shown in Figure 15. The pressure impulse is approximately 31.7 kPa (4.6 psi) and has an impulse time span of about 5 milliseconds

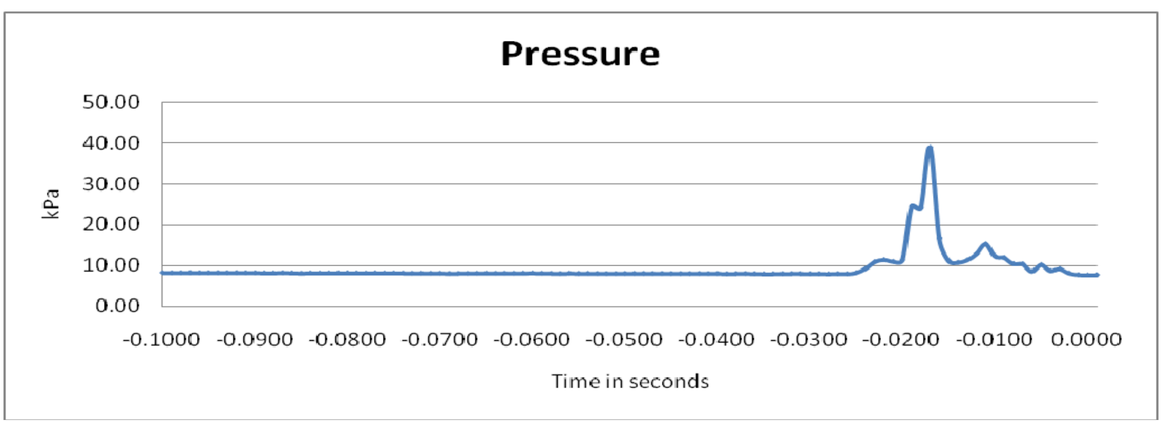

Figure 15. Sample Pressure Impulse from Test # 10/30/09, 12 %-2V.

Table 4. Summary of 12 % Test Data.

Date / test	Measured Inward Leakage Air Exch./ hr. (Time to fill)	Actual H_2 Conc. at trigger	Radiometer Readings	Flame Speed	Peak Temp.	Notes
9-23 / 12 %-1	1.0 $(ACH)_4$ (1111 s)	12.1 %	16 mW/ m^2 – wall 0.77 mW/ m^2 floor	1.6 m/s to 6.4 m/s avg 3.4 m/s	345 °C-2.59 m Height 485 °C-120cm Horizontal array	Burn down to 1.14 m at 195 °C
9-24 / 12 %-2	2.3 $(ACH)_4$ (935 s)	12.9 %	33.8 mW/ m^2 – wall 1.3 mW/ m^2 floor	-	312°C-2.59 m Height 492 °C-210cm Horizontal array	Burn down to 0.38 m at 88 °C
9-27 / 12 %-3	3.0 $(ACH)_4$ (992 s)	13.7 %	49.9mW/ m^2 - wall 1.7 mW/ m^2 – floor	-	376 °C-2.59 m Height 476 °C-150cm Horizontal array	Burn down to 0.38 m at 150 °C
10-16 / 12 %-4	3.8 $(ACH)_4$ (1077 s)	11.0 %	16.2 mW/ m^2 – wall 1.7 mW/ m^2 - floor	1.4 to 6.9 m/s avg is 4.1 m/s	366 °C-2.59 m Height 409 °C-120cm Horizontal array	Burn down to 1.14 m at 97 °C
10-19 / 12 %-5	3.9 $(ACH)_4$ (1985 s)	12.7 %	38.3 mW/ m^2 – wall 1.2 mW/ m^2 - floor	1.6 m/s by IR camera	398 °C-2.59 m Height 492 °C-210cm Horizontal array	Burn down to 0.38 m at 165 °C
10-22 / 12 %-1V	2.8 (ACH)	12.0 % Garage Passenger Compartment ≈4 %	-	1.6 m/s by IR camera		Data lost due to DAC failure
10-30 / 12 %-2V	4.4 $(ACH)_4$ (1717 s)	12.1 % Garage 14.6 % pass. 26.6 % engine	45.8 mW/ m^2 – wall	1.6 m/s by IR camera	467 °C-1.90 m Height 473 °C-330cm Horizontal array	Burn down to 0.38 m at 368 °C

6.4 16 % Tests

6.4.1 Tests without Vehicle

A total of five 16 % runs were conducted, three without vehicle and two with vehicle. All of the 16 % tests without vehicle did damage to the structure, completely blowing out the front wall with debris traveling up to 9 m. These tests generally raised the roof a few inches to a foot before it returned to its original position as designed. There was some loss of gypsum board from the ceiling. All of the thermocouples and hydrogen sensors survived the test unless directly struck by falling gypsum board. Figure 16 shows the hydrogen concentration stratification for a 16 % test. Significant amounts of hydrogen built up even down to the 0.38 m height above the floor. Consumption of the fuel following ignition around 5000 s is more complete than seen in the 12 % runs. The temperature data shows significant temperature rises down to the 0.38 m height and along the horizontal axis in Figures 17 and 18.

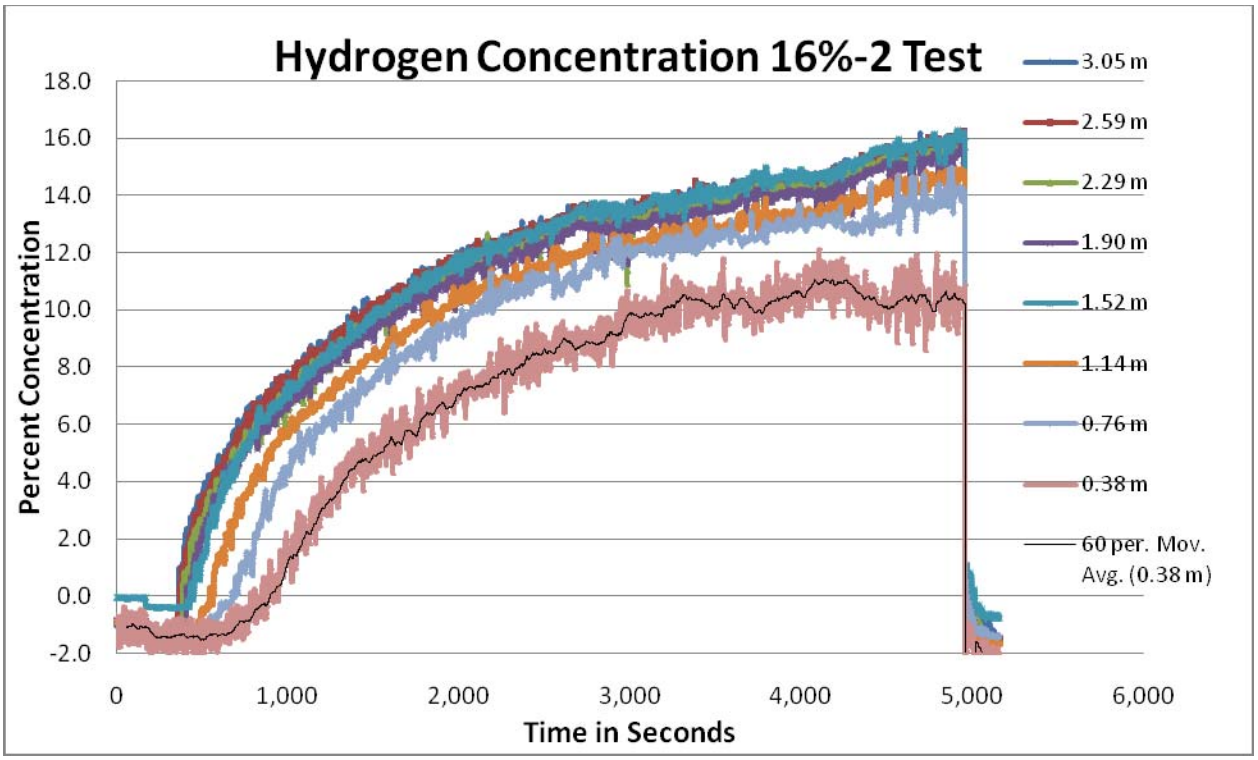

Figure 16. Hydrogen Concentration Profile Test # 09/18/09, 16 %-2.

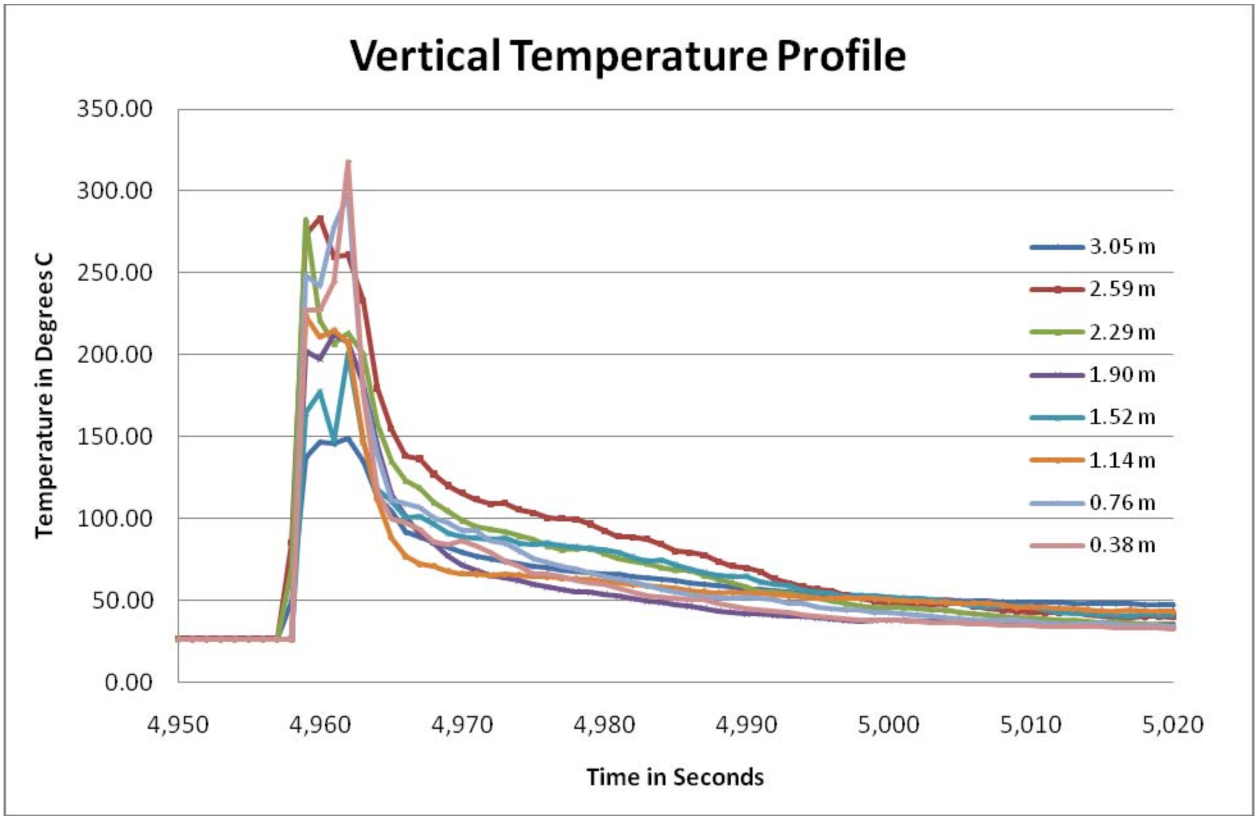

Figure 17. Vertical Temperature Profile for Test # 09/18/09, 16 %-2.

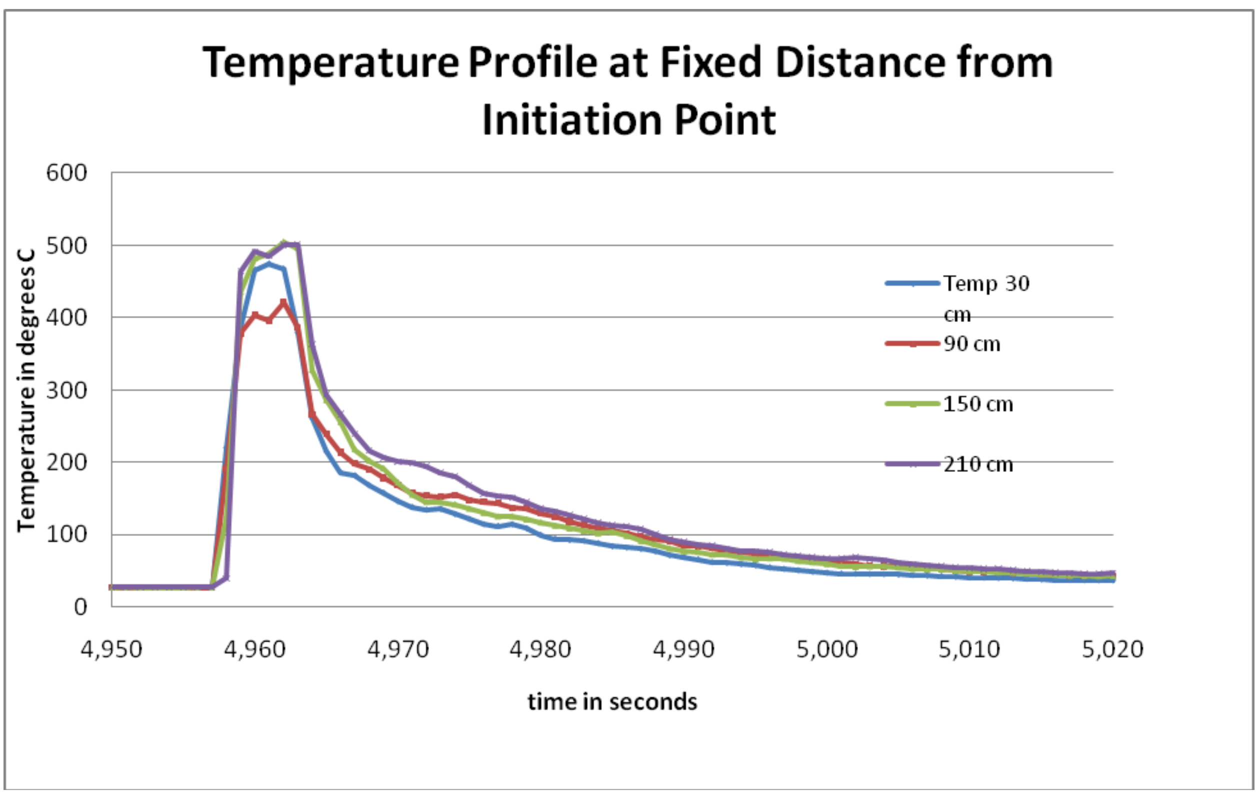

Figure 18. Horizontal Temperature Profile for Test # 09/18/09, 16 %-2.

The 16 % tests were very consistent in the damage done to the structure. The pictures shown in Figures 19A and 19B exhibit common results observed for the tests with this concentration. Debris was launched 9 m at the furthest point from the structure, and the high speed video clearly shows the event to be a relatively low speed push of the front wall until it detaches with the roof moving upwards about 0.3 m before again settling down onto the intact block walls.

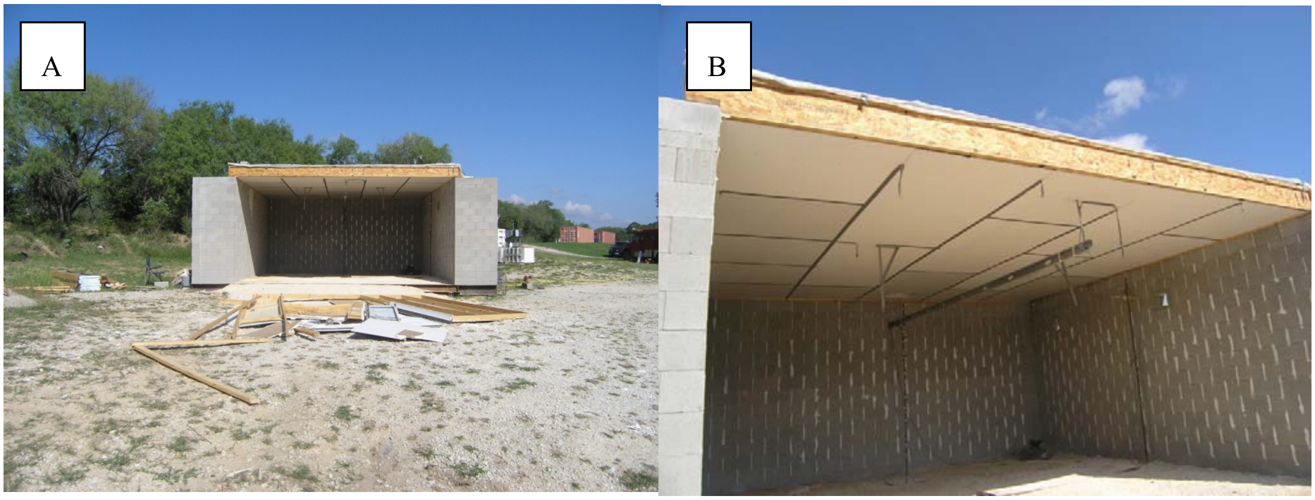

Figure 19. Destruction caused by 16 % Tests without Vehicle.

6.4.2 Tests with Vehicle

Inclusion of a vehicle in the garage radically changes the degree of damage caused by the 16 % hydrogen concentration. A two-stage event was seen that was similar to those observed during the vehicle tests for the 12 % runs. The data acquisition system overloaded from the high speed data and the hydrogen concentration data was lost shortly after ignition for Test 16 %-1V, but at the time of the ignition the concentration inside the engine compartment was approximately 28 %, the concentration inside the vehicle was greater than 16 % and the concentration inside of the garage was right at 16 %. The garage required 58 min or 3480 s to fill. Excellent high speed data was obtained from the pressure sensors and the ion probes. The high speed video captured the two stage event very clearly with a slow deflagration pushing out the wall, a flash occurring at 0.05 s into the event and a subsequent dramatic increase in the rate of the breakup of the front wall and ceiling of the building. Debris was spread to a distance of greater than 30.5 m, with much smaller pieces being generated. Pictures of the debris field are included in Figure 20 for comparison to the non vehicle case. The vehicle used in the test was a Buick Century Limited. This is an indication that vehicle size was especially important, due to the larger amounts of hydrogen that can be trapped in the engine compartment, passenger compartment and, in this case, the trunk. Most of the vehicle glass was blown out, the rear bumper was blown off, traveling 24.4 m, but remaining as a single piece, and a small fire was started in the trunk space of the car. In the second vehicle test at 16 % hydrogen, a BMW 325i was used. This vehicle has smaller interior volumes than the Buick Century and much less damage was caused by the fire, with the roof of the structure surviving the event and debris projected out to 24.4 m.

Figure 20. Damage caused by Test # 11/4/09, 16 %-1V.

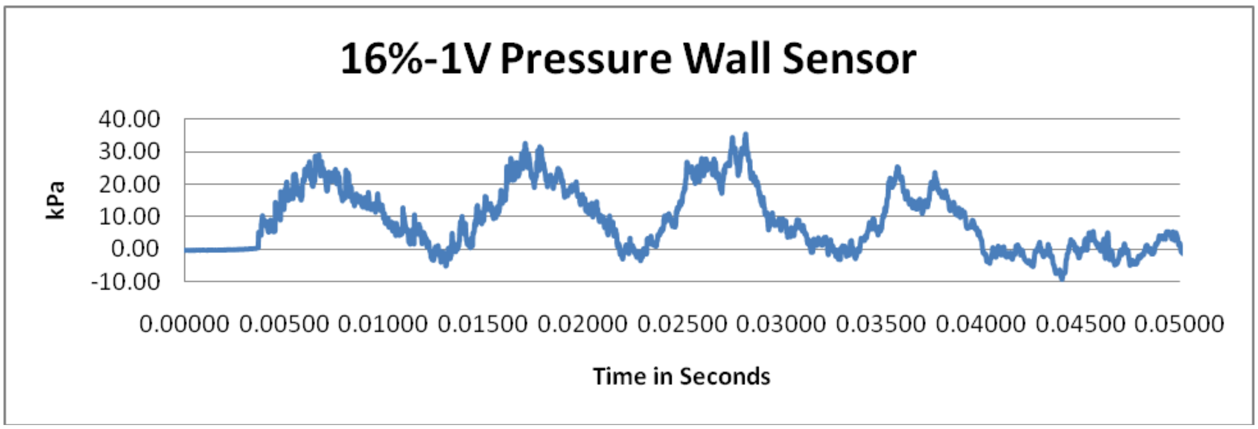

Figure 21. Pressure measured at the wall for Test # 11/4/09, 16 %-1V.

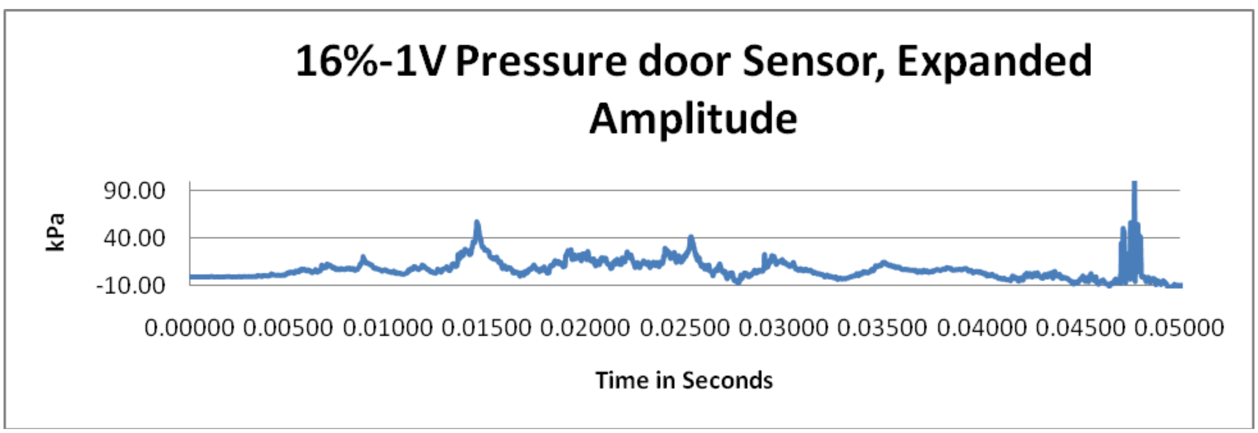

Figure 22. Garage Door Pressure Sensor for Test # 11/4/09, 16 %-1V.

Impulse pressures from Test 16 %-1V are shown in Figures 21–23. A rolling pressure wave with a magnitude of 27.5 kPa (4 psi) was measured at the wall as shown in Figure 21. The rolling wave is also seen in the pressure plot for the sensor near the door with a peak magnitude of 57.9 kPa (8.4 psi) followed by a second, much narrower impulse of 55.2 kPa (8 psi), and a single data point reading 406 kPa (59 psi) as shown in Figure 22. This one data point is likely aberrant. Figure 23 shows the expanded region for the impulse. All of the peaks in this region have definite structure (a multiple point rise and fall of intensity, not random noise) except the single intense peak. The intense peak may be due to an impact on the sensor of a hard object or an electrical spike in the sensor caused by the disassembly of the building.

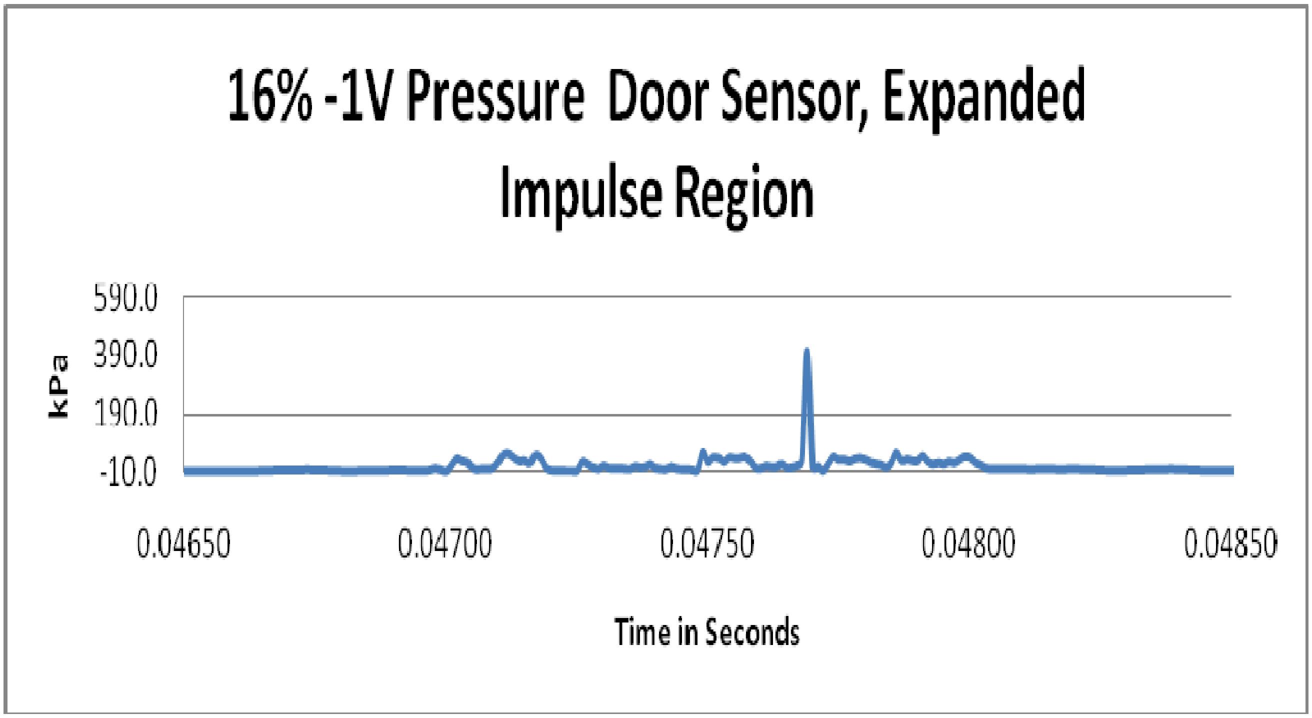

Figure 23. Expanded Garage Door Pressure Sensor for Test # 11/4/09, 16 %-1V.

The low speed DAC system functioned during the entire test for Test 16 %-2V. The concentration data clearly shows the disruption of the hydrogen stratification in the garage. The engine compartment trapped significant hydrogen concentrations, but the concentration dropped significantly due to leakage from the compartment between the times of hydrogen flow cut-off and burn ignition. The subsequent damage to the structure was less than for Test 16 %-1V, but still significant. High speed data did not record for the trigger event but was recorded due to erroneous multiple triggers prior to the event. High speed camera video shows clearly the same sequence of events as observed for earlier tests with vehicles. A two stage event with a relatively slow burn occurred followed by acceleration and rapid destruction of the garage front wall. Figure 24 shows the hydrogen concentration profiles for this event. The radiometer reading for this test was interesting, giving the highest values observed at 13 W/m^2 as seen in Figure 25. Peak temperature measurements were consistent with those seen in tests without a vehicle.

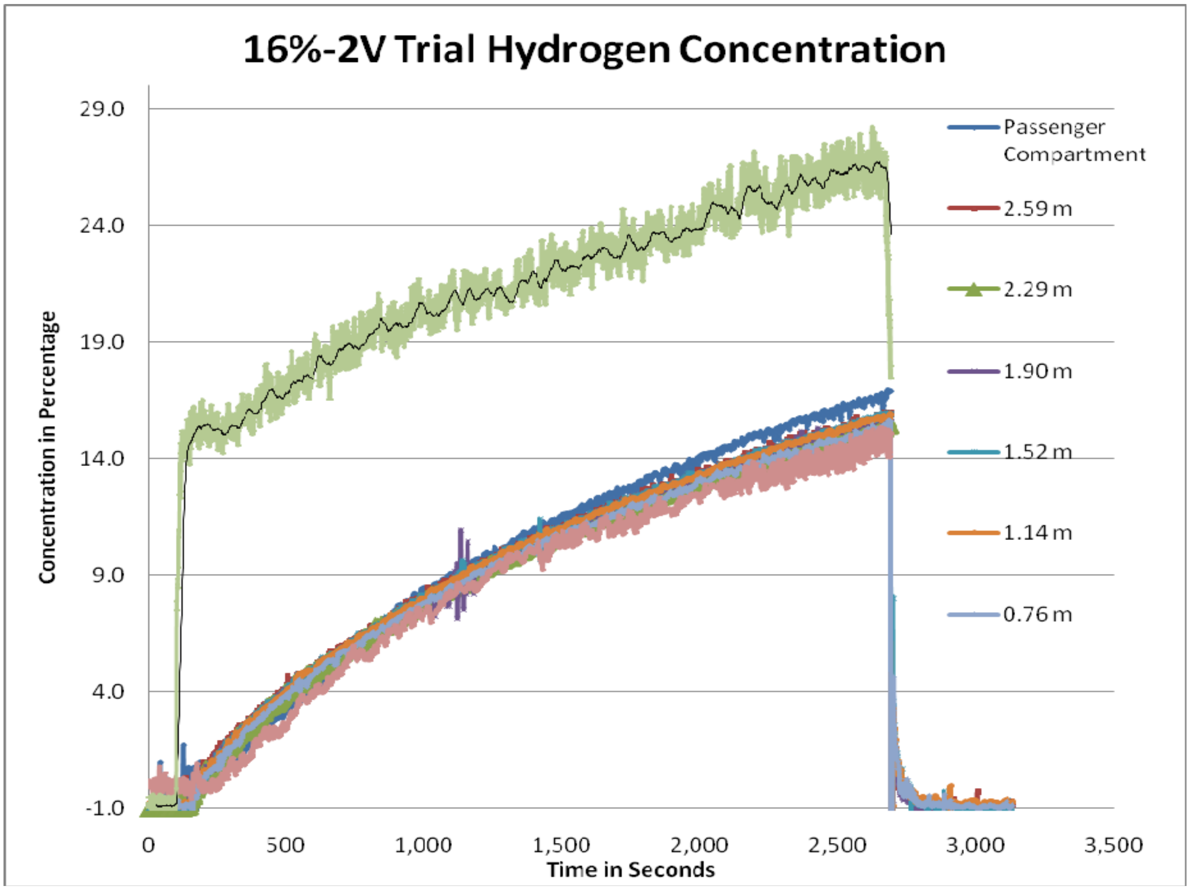

Figure 24. Hydrogen Concentration Profile for Test # 11/12/09, 16 %-2V.

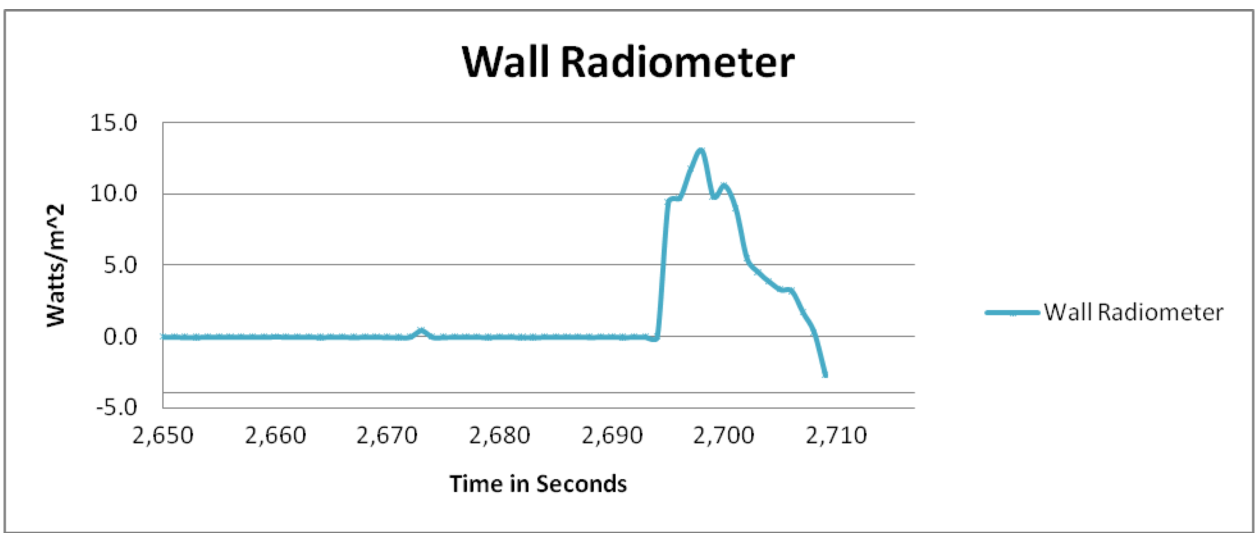

Figure 25. Radiometer Readings for Test # 11/12/09, 16 %-2V.

6.4.3 Combined Data from 16 % Tests

Table 5 provides summary data for the 16 % tests. All of the 16 % tests burned down to the 0.38 m level with the majority of the hydrogen reacting. The ion probes did not trigger for the 16 %-1 test, and flame speed is not available. All of the non-vehicle tests generated small, gradual pressure rises that generated a pushing effect that resulted in the dislodgement of the front wall. The radiant energy measurements for each of these tests were very consistent with low readings at the floor level and higher levels at the wall. The major difference between the with-vehicle tests and no vehicle tests appears to be the pressure generated and the damage done to the garage. Higher intensity, shorter duration pressures are generated in the with-vehicle tests resulting in destruction of the ceiling as well as the front wall and greater projection distances for wall fragments. The rapid fall off of hydrogen concentration in the engine compartment for the 16 %-2V test resulted in much less damage than that seen in test 16 %-1V, where the engine compartment was at 28 % hydrogen at time of ignition.

Table 5. Summary of 16 % Test Data.

Date / test	Measured Inward Leakage air exch. /hr (Time to fill)	Actual H_2 Conc. at trigger	Radiometer Readings	Flame Speed	Peak Temp.	Notes
9-14 16 %-1	8.5 $(ACH)_4$ (3306 s)	17.0 %	67.6 mW/ m^2 – wall 2.6 mW/ m^2 - floor	-	444 °C-2.59 m height	Burn down to 0.38 m height 357 °C
9-18 16 %-2	4.5 $(ACH)_4$ (4591 s)	16.3 %	62.6 mW/ m^2 – wall 3.7 mW/ m^2 floor	Avg 7.2m/s Range 3.8 m/s to 12.1 m/s	318 °C-2.59 m height 501 °C-210cm Horizontal array	Burn down to 0.38 m height at 227 °C
9-21 16 %-3	2.9 $(ACH)_4$ (2909s)	16.1 %	67.6mW/ m^2 - wall 3.5 mW/ m^2 – floor	Avg 10.9m/s Range 4.2 m/s to 16.3 m/s	376 °C-2.59 m height 476 °C-150cm Horizontal array	Burn down to 0.38 m height at 443 °C
11-04 16 %-1V	3.1 $(ACH)_4$ (3408 s)	16 % Garage 28 % Engine 9 % Pass. Comp.	-	Avg 10.6m/s Range 8.9 m/s to 13.2 m/s by IR Cam	-	-
11-12 16%-2V	4.6 $(ACH)_4$ (2574 s)	16.0%Garage 18% Engine 16.9% Pass. Comp.	13.0 W/ m^2 wall	-	435°C-1.14 m height 365°C-90cm Horizontal array	Burn down to 0.38 m height at 342°C

6.5 28.8 % Tests

6.5.1 Test without Vehicle

A single test was conducted at 28.8 % hydrogen concentration without a vehicle. The hydrogen concentration in the structure was still mildly stratified with the lowest layers having concentrations above 20 %. Figure 26 shows the measured hydrogen concentration profile. The filling process required 60.8 minutes to reach 28.8 % using 4.9 kg of hydrogen at a flow rate of 983 SLPM. Both high speed and low speed data were successfully collected. The damage to the garage was devastating, requiring rebuilding of the garage concrete block walls. The walls split at the corners, all of the welded rebar snapped at their weld points to the I-beam frame, and the wing walls were moved about 0.2 m from their original position. Roof pieces traveled upward between an estimated 18.2 m to 24.4 m, and front wall pieces were projected up to 45.7 m from the front of the structure. All of the low speed temperature and concentration data abruptly cut off near the time of ignition due to loss of the data cables, so no heat flux or temperature data is available after this time. The ion probes and pressure transducers did capture high speed data before the signals were lost. These results are shown in Figures 27 and 28. For the wall sensor, a gradual build up in pressure was seen to approximately 17.2 kPa (2.5 psi) over a period of 49 ms, with an abrupt rise to 59.3 kPa (8.6 psi) at the wall in a very short 70 μs with an impulse width of 320 μs. The slow rise was consistent with a deflagration. The abrupt rise and narrow impulse are consistent with a transition to detonation (DDT). A DDT normally requires transition to a burn velocity that is greater than the speed of sound, which presumably took place somewhere within the vehicle. Similar pressure behaviors were was also observed by the pressure transducer located on the rail near the ceiling.

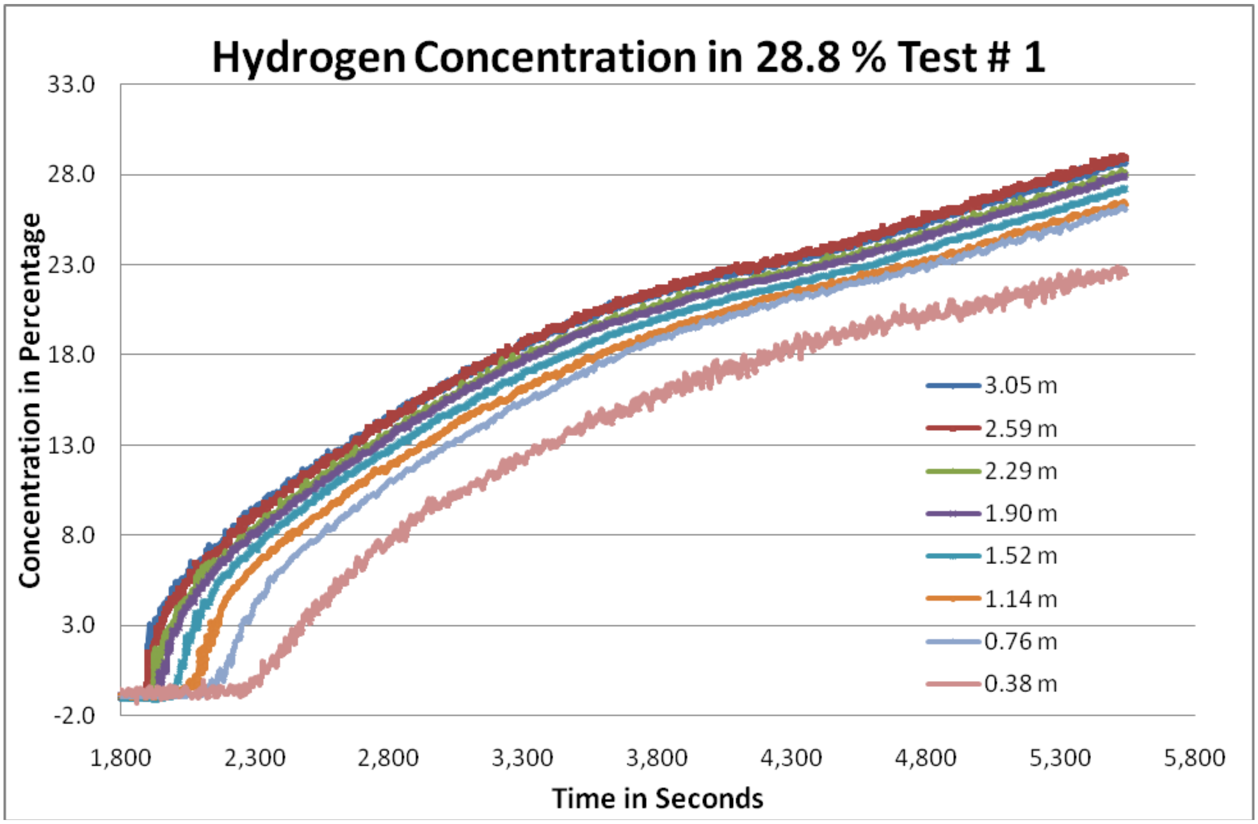

Figure 26. Hydrogen Concentration Profile for Test # 10/1/09, 28.8 %-1 .

The ion probes inidicated that the average flame propogation speed was 25.5 m/s. Four of the six probes registered, and the time difference between probes represents a 0.3 m distance of travel. Three velocities were calculated giving 32.8 m/s, 17.7 m/s, and 25.9 m/s over the distance of 0.9 m with a time resolution of 10 μs.

The degree of damage to the building was catastrophic, as stated previously. The photos included in Figure 29 show the degree of damage and debris projection for this test. High speed video captured the test as a continuous event with no noticeable transitions.

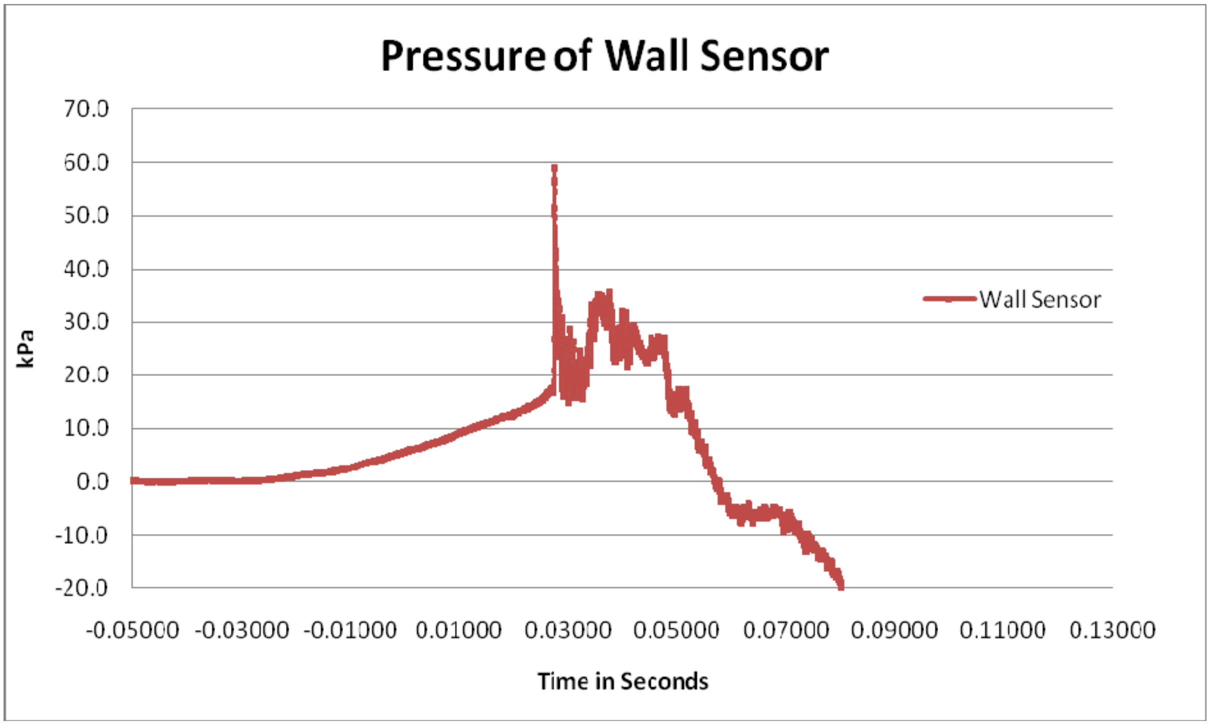

Figure 27. Pressure Sensor Results for the Wall PT for Test # 10/1/09, 28.8 %-1.

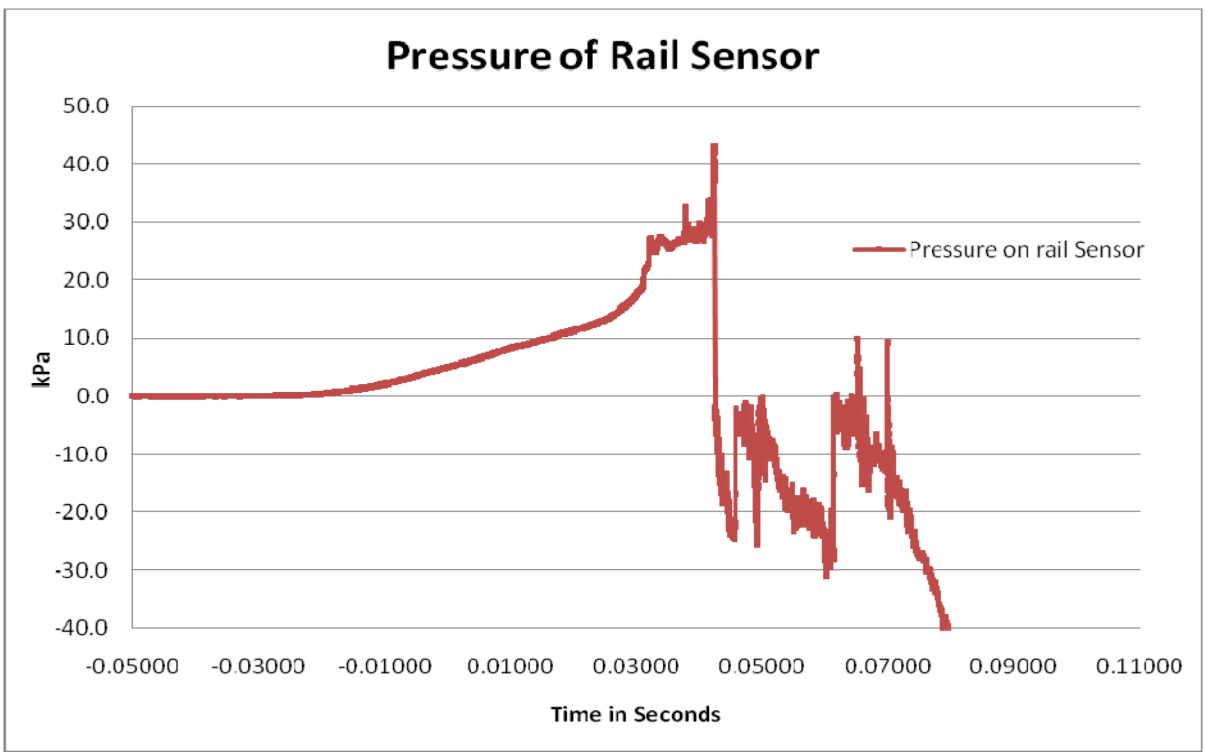

Figure 28. Pressure Sensor Results for the Rail PT for Test # 10/1/09, 28.8 %-1.

Figure 29. 28.8 % Test Damage Photos.

6.5.2 Test with Vehicle

The 17.7 %V test conducted with the vehicle only reached a peak room concentration of 18 % at the ignition point for a fill time of 4738 s (1 h and 19 min). The intent had been to reach a hydrogen concentration of 28 % The lower value was likely due to the higher inward leakage rate of the building with $(ACH)_4$ measured to be 4.1. The burn was ignited at this time due to the slow rate of hydrogen concentration increase and concerns over of loss of daylight required to capture high speed video of the event. The vehicle engine compartment (Ford Explorer) shows a rapid hydrogen concentration rise to 18 % in the first 40 s, with a slow rise to 25 % over the duration of the fill time. Stratification of the hydrogen concentration in the room was completely upset by the inclusion of a vehicle as was seen in all previous vehicle tests. Figure 30 depicts the continuous concentration readings of the room, engine compartment and passenger compartment. The hydrogen sensor at 1.52 m was not operational for this test, but this was not deemed to affect the quality of the data. All concentrations were in a very narrow band, except for the engine compartment which was considerable higher.

Due to the rapid destruction of the building, the post trigger temperatures on the horizontal array were only recorded for a very short time following ignition, and the data are somewhat suspect. The temperature spikes are of very short duration (1 data point) and may correspond to signals generated during the destruction of the sensor array. The temperature profiles for the vertical thermocouple arrays are shown in Figure 31.

Radiometer readings were not obtained due to signal loss during the rapid destruction of the structure. The duration of the event was shorter than the 1 second recording frequency of the low speed sensors. The signal became strongly negative after the trigger event, probably caused by loss of the signal from the probe.

The high speed sensors did capture the event for both the flame propagation speed and the pressure profile. Figure 32 shows the measurements for the pressure sensor mounted on the rail in front of the garage door. The pressure event begins at approximately 0.208 s and the sensor appears to fail at approximately 0.264 s. The pressure peak at 0.261 s has structure (multiple data point pressure rise and fall which is consistent with random noise) and a peak pressure of 28.7 kPa (4.16 psi). The width of the impulse peak is 230 μs (23 data points).

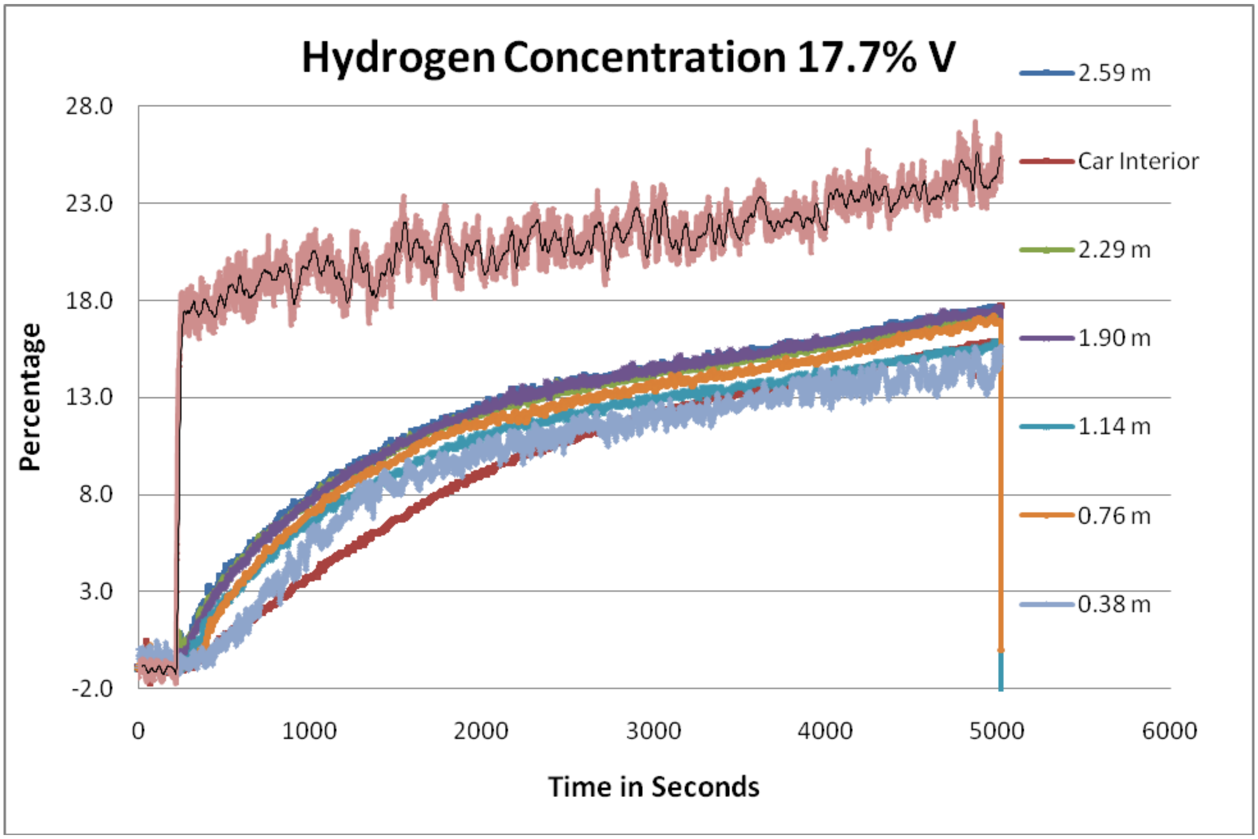

Figure 30. Concentration Profile for Test # 11/23/09, 17.7 %V.

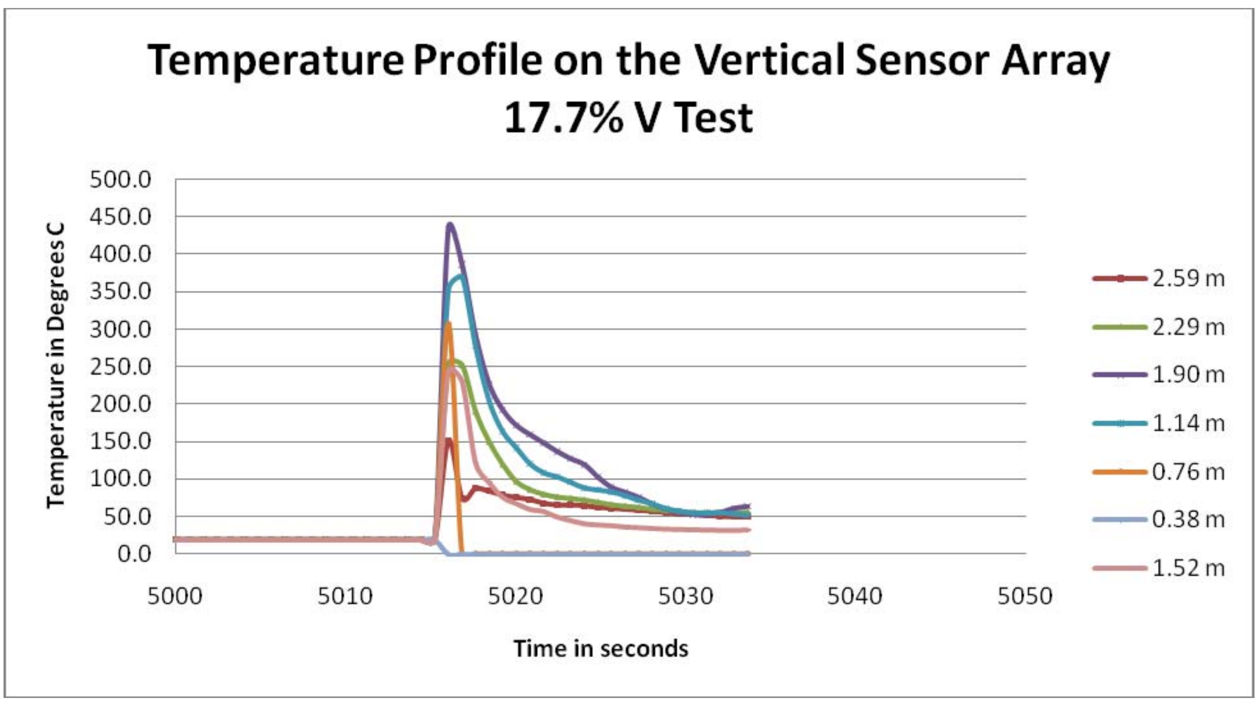

Figure 31. Vertical Array Temperature Profile for Test # 11/23/09, 17.7 %V.

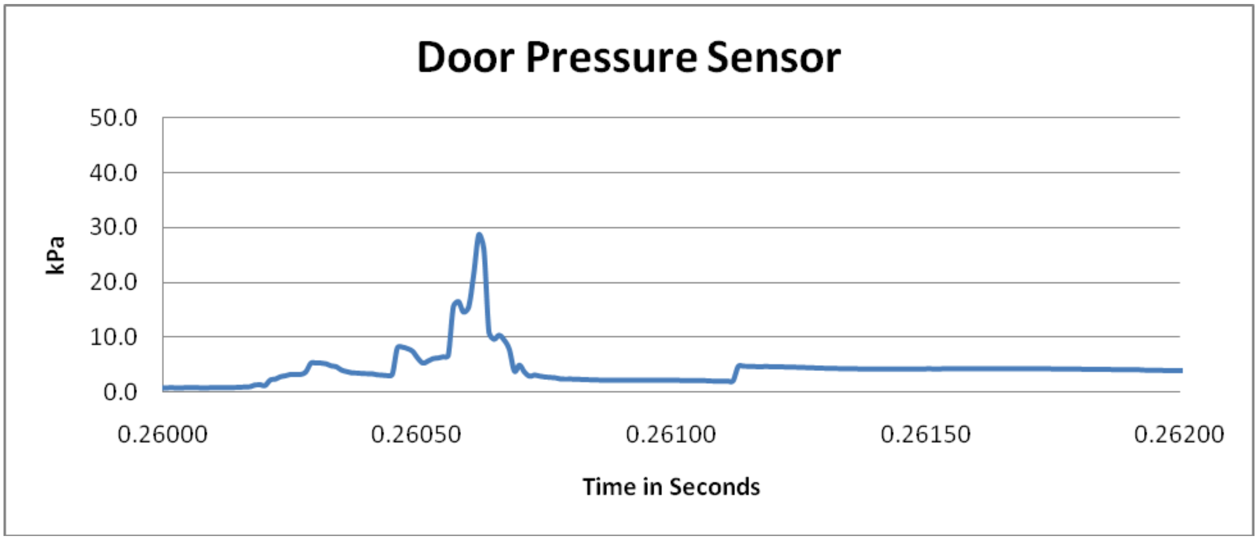

Figure 32. Door Pressure Sensor Data for Test # 11/23/09, 17.7 %V.

The wall pressure sensor gives a very different pressure profile. The pressure appears as a series of broad pressure waves of between 34.5 kPa and 37.9 kPa (5.0 psi and 5.5 psi). It appears that the pressure impulse occurs in waves due to a non-continuous burn or reflective pressure impulses from the three fixed walls or both. Signal shows a gradual decay in wave intensity as would be expected for reflected pressure waves. There are also two, short duration impulses of 47.6 kPa (6.9 psi) and 65.5 kPa (9.5 psi) superimposed on the pressure waves. Figure 33 shows the wall pressure sensor data.

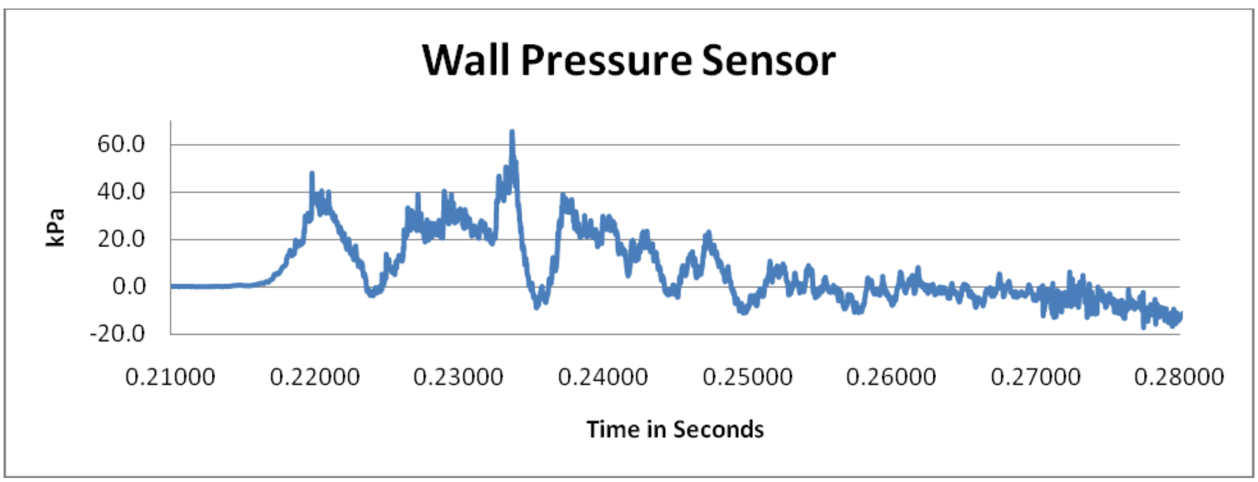

Figure 33. Wall Pressure Sensor Data for Test # 11/23/09, 17.7 %V Time Expanded.

The ion probes captured flame front passage for this test. The average burn velocity is calculated to be 24.0 m/s with individual values of 26.2 m/s, 32. 8 m/s, 21.1 m/s, and 16.0 m/s. The same phenomenon of acceleration and deceleration was noted here as seen in other tests. Figure 34 presents the ion probe data captured during this test. Signal widths of 100 μs (10 data points indicate real peaks).

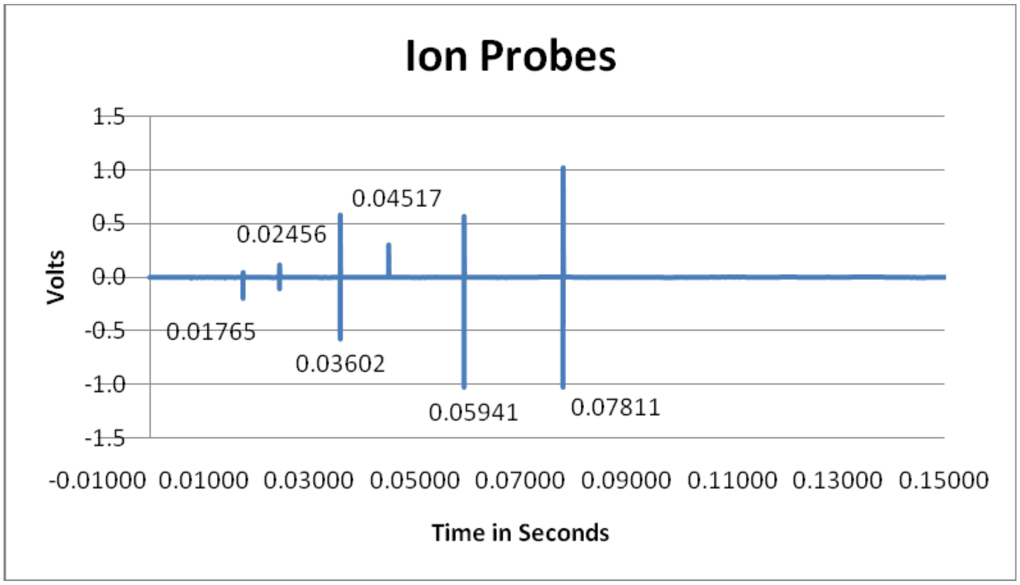

Figure 34. Ion Probe Data for Test # 11/23/09, 17.7 %V with Time Point for Each Peak (negative time is time before trigger of collection, data collected in the buffer).

6.5.3 Summary Data for 28 % Tests

Table 6 shows a data summary for the two 28 % tests. Even though the hydrogen concentration in the garage only reached 17.7 % in the test containing a vehicle, the damage is comparable between the two tests. The concrete walls cracked and the welds at the foundation were sheared off. The ceiling and roof were completely destroyed, and fragments of the walls were projected over 30.5 m. Measured burn velocities were similar between the two tests. The longer fill time and lower effective concentration of the 17.7 %V test are attributed to both the higher leakage rate and the disruption of stratification in the room. The displacement volume of the vehicle can be ignored due to the fact that the concentration inside the vehicle was close to that seen in the room. The similarity in the damage seen is likely attributable to the trapped hydrogen in the engine compartment resulting in a more energetic event.

Table 6. Summary of 28 % Test Data.

Date / test	Measured Inward Leakage air exch. /hr (Time to fill)	Actual H_2 Conc. at trigger	Radiometer Readings	Flame Speed	Peak Temp.	Notes
10-1, 28 %	2.2 ACH_4 (3645 s)	28.8 %	Data lost	Avg 25.5 m/s Range 32.8 m/s to 17.7 m/s	Data lost	Blast damage resulted in instant loss of real time signals
11-23, 17.7 %V	4.1 ACH_4 (4738 s)	17.7 % Room 25.2 % in engine compartment 15.9 % in passenger compartment	Data lost	Avg 24.0 m/s Range 32.8 m/s to 16.0 m/s	434 °C-1.90 m height	Impact resulted in loss of 0.38 m sensor, Blast damage resulted in instant loss of most real time signals

Figure 35 shows examples of damage observed for the test with a vehicle included. This vehicle had a leaky passenger compartment with the hydrogen concentration reaching 13.7 %. The engine compartment was well sealed with little or no loss of hydrogen concentration during the period between termination of filling and ignition.

Figure 35. Damage Photos from the 28 %V Test.

7. CONCLUSIONS

The following conclusions are made based on measurements and observations during this testing program:

- The gas introduction system performed very well in providing a continuous flow of hydrogen at between 982 SLPM and 990 SLPM.
- The hydrogen concentration was stratified when a vehicle was not present in the test garage. The stratification was not the result of the hydrogen introduction system.
- Mixtures where the hydrogen concentration was roughly 8 % at the ignition height did not ignite well. The flames burned up to the ceiling and did not consume most of the hydrogen in the room. This is illustrated by the temperature profiles at the 3.05 m thermocouple and all of the IR video footage of the 8 % tests conducted on 10/16/09 and 10/22/09.
- A 100 mJ spark did not ignite hydrogen/air mixtures at 8 %, and increasing the energy to 1-J and 10-J sparks also failed to ignite these mixtures. As a result, an 80-J electric match was used for all later tests. The higher concentration tests might have ignited with a spark, but this was not attempted.

- The hydrogen concentration does not stratify when a vehicle is placed in the garage. All of the hydrogen sensors gave readings in a very narrow band during the filling of the garage.
- Higher concentrations of hydrogen were observed in the engine compartments than in the garage space outside of the vehicles. This higher concentration results in a significant increase in structural damage at moderate hydrogen concentrations (12 % and 16 %). A two-stage event was seen for all of the vehicle tests with concentrations of 12 % or greater. This observation is indicative of a similar ignition and early burning to cases without a vehicle, with burn down to the bottom of the car with subsequent ignition of higher concentration hydrogen trapped in the engine compartment and other recesses. The effects of this two-stage process are clearly visible in the high speed videos for the 12 % and 16 % vehicle tests conducted from 10/22/09 to 11/12/09.
- The size of the vehicle and the degree to which the engine compartment was sealed appeared to affect the degree of damage seen in the garage test facility. Five different vehicles were used in the vehicle tests. The Chevy Cavalier, Buick Century, and Ford Explorer had well sealed and larger engine compartments, and the garage ceilings were completely destroyed in all of these tests. The Ford Aspire had the smallest engine compartment, but was sealed well which resulted in the build up of a high hydrogen concentration. Even so, the ceiling survived this test with most of the gypsum board cladding remaining intact. In the test using the BMW, the engine compartment did not seal well resulting in a drop in hydrogen concentration in the engine compartment before ignition. In this test the ceiling survived, but the gypsum board cladding was lost.
- The model TCG-3880 hydrogen sensors manufactured by Xensor Integration were very robust and reliable. The sensors survived rigorous conditions over multiple tests. The sensors need to be calibrated before each test because of their temperature dependence, but this was easily done by calibrating the sensors at 0 % and 100 % hydrogen.
- Ion probes proved to be less than ideal for this application. They often failed to respond to hydrogen flames burning in lower concentrations of hydrogen. Weather conditions impact the sensors with rain and dripping water triggering the sensors. Because of the relatively slow flame propagation speeds, millisecond response thermocouples, may have worked well in these tests.
- The IR camera illustrated that at lower hydrogen concentrations (8 %) the burning event can take place for extended periods of time (from a few seconds). In the 8 %V test the vehicle slowly leaked hydrogen from the engine compartment and sustained combustion for up to 400 s.
- The inclusion of a vehicle in the garage disrupted the stratification of hydrogen concentration with localized high concentrations seen in entrapping spaces like the engine compartment. Shelving and other disruptive clutter in the garage should be explored to measure impact on stratification and the further potential for DDT. Because of the highly variable results of using multiple vehicle types of varying conditions, engine compartment size, and leakage rates, a mock-up with controllable configuration might be used to characterize the impact of engine compartment size and entrapment. This would allow for better comparison of results from test to test.

APPENDIX A

H_2 Garage Test for NIST

Hazard / Risk Assessment

Introduction

With the advent of increased emphasis on alternative fuels, hydrogen has become an attractive option because of its availability and non-polluting combustion. Extremely wide combustion percentage range of hydrogen and its high tendency to leak create serious safety concerns for its use in vehicles. Small leaks in homes may present flammability hazards with the potential for large scale destruction. For this reason the National Institute of Standards and Technology (NIST) has embarked on a testing program to gather data on the combustion potential of hydrogen in realistic garage settings in support of the development of a predictive model of the hazards associated with this fuel.

A test facility simulating a garage will be constructed and instrumented to measure the combustion temperatures, pressures and combustion velocities of hydrogen at four concentrations. The garage will be constructed of concrete-filled, rebar-reinforced concrete block walls on three sides. The front of the building will be stick built with drywall and a garage door. The ceiling will consist of wood I joists protected with gypsum board. The inner dimensions of the garage will be 20×20×10ft.

Hydrogen will be released at floor level in the center of the room. The triggering concentration will be measured at 8.5 ft above the floor, with the measurement taken outside of the buoyant plume. The test concentrations will be between 4 and 43% of hydrogen by volume at the 8.5 ft sensor.

Safety Considerations

Construction: normal precautions during construction will be observed – appropriate PPE for the task being performed, fall protection for above-grade work, use of guides and barrier for heavy equipment, and safety briefings will be periodically conducted by the Construction Supervisor for tasks being performed. Construction is considered a high risk operation and all of the expected safety precautions will be observed. In addition this operation will be conducted out of doors in high heat conditions so hydration will be critical. Hydration stations will be established before construction operations commence and replenished regularly.

Visitors: NIST personnel will visit the SwRI test facilities and explosive range before and during testing. All NIST visitors will comply with the requirements of this Risk Assessment, Standard Operating Procedure (SOP) for Ammunition, Explosive and Energetic Materials (A&E) Operations, August 2005, and SOP 15071-01-003 for this test.

Testing: Hydrogen will be released within the garage at the center of the floor and allowed to rise to ceiling height. The concentration will be measured away from the plume. Inward leakage will be controlled and measured. At a height of 8.5 ft a hydrogen sensor and spark igniter combination will be installed. Hydrogen will be introduced at a rate of 933 LPM. When the concentration reaches the desired percent composition at the 8.5 ft level, the spark igniter will be initiated. The hydrogen net explosive weights in TNT equivalents are shown below for each explosive scenario:

4% H_2 = 0.04 equiv. lbs TNT, Fragmentation hazard distance <80 ft., Noise impulse distance for <110 dB is <80 ft., Over pressure distance < ½ psi <80 ft.

8% H_2 = 0.17 equiv. lbs TNT, Fragmentation hazard distance <80 ft., Noise impulse distance for <110 dB is <80 ft., Over pressure distance < ½ psi <80 ft.

16% H_2 = 0.63 equiv. lbs TNT, Fragmentation hazard Distance <80 ft., Noise impulse distance for <110 dB is <80 ft., Over pressure distance < ½ psi <80 ft.

29.2% H_2 = 2.38 equiv. lbs TNT, Fragmentation hazard distance <80 ft., Noise impulse distance for <110 dB is <80 ft., Over pressure distance < ½ psi <80 ft.

43% H_2 = 3.49 equiv. lbs TNT, Fragmentation hazard distance <80 ft., Noise impulse distance for <110 dB is <80 ft., Over pressure distance < ½ psi =80 ft.

Risks identified by analysis of scenario

1. Premature ignition of hydrogen form heat, spark or flame source.
2. Ignition of hydrogen in hydrogen supply line from blast effects of the test.
3. Projection of fragmentation from building construction materials impacting personnel or facilities.
4. Overpressure from detonation impacting personnel.
5. Impulse noise affecting personnel or alarming the community.
6. Ion probe voltage may be high enough to trigger ignition of Hydrogen vapors by dielectric breakdown (Sparking) in the hydrogen rich atmosphere.

Risk Matrix used to analyze impact of risk items is shown in Figure 1.

Figure 1

RISK MATRIX								
POTENTIAL CONSEQUENCES		**PROBABILITY**						
		VERY UNLIKELY	**UNLIKELY**	**MAY HAPPEN**	**LIKELY**	**CERTAIN OR IMMINENT**		
		1	**2**	**3**	**4**	**5**		
No Hazard of injury	**1**	1	2	3	4	5	**LOOK UP TABLE**	
Minor Injury	**2**	2	4	6	8	10	Low	1 to 6
Major Injury	**3**	3	6	9	12	15	Moderate	7 to 10
Single Fatality	**4**	4	8	12	16	20	High	11 to 16
Multiple Fatality	**5**	5	10	15	20	25	Very High	17 to 25

Risk Item 1. Premature ignition of hydrogen form heat, spark or flame source.

Rating is 5 for potential consequences and 1 for probability. Only explosive-proof sensors will be used in this testing. Hydrogen will not be introduced into the system until the test ignition and will only be allowed after checking to make sure the test site is clear. This will be captured in the SOP for the operation.

Risk Item 2. Ignition of hydrogen in hydrogen supply line from blast effects of the test.

Rating is 3 for potential consequences and 1 for probability. Any hydrogen in the supply line is free of air and will not detonate. The supply line will be flushed with air between tests, before allowing construction or cleanup operations to commence. The flushing operation will be added to the design and SOP.

Risk Item 3. Projection of fragmentation from building construction materials impacting personnel or facilities

Rating is 5 for potential consequences and 5 for probability. This risk will be mitigated by employing the safe separation distance required by the TNT equivalent explosive weight. Test site will be cleared before the addition of hydrogen to the test facility. The supply line will be flushed with air between tests, before allowing construction or cleanup operations to commence. The flushing operation will be added to the design and SOP. Mitigated risk is 1 for potential consequences, 5 for probability.

Risk Item 4. Overpressure from detonation impacting personnel.

Rating is 3 for potential consequences and 5 for probability. This risk will be mitigated by employing the safe separation distance required by the TNT equivalent explosive weight. Test site will be cleared before the addition of hydrogen to the test facility. The supply line will be flushed with air between tests, before allowing construction or cleanup operations to commence. The flushing operation will be added to the design and SOP. Mitigated risk is 1 for potential consequences, 5 for probability.

Risk Item 5. Impulse noise affecting personnel or alarming the community.

Rating is 3 for potential consequences and 5 for probability. This risk will be mitigated by employing the safe separation distance required by the TNT equivalent explosive weight. test site will be cleared before the addition of hydrogen to the test facility. The supply line will be flushed with air between tests, before allowing construction or cleanup operations to commence. The flushing operation will be added to the design and SOP. Mitigated risk is 1 for potential consequences, 5 for probability.

Risk Item 6. Ion probe voltage may be high enough to trigger ignition of hydrogen vapors by dielectric breakdown (Sparking) in the hydrogen rich atmosphere.

Rating is 1 for potential consequences and 4 for probability. No mitigation is required but Ion probes approved for use in a hydrogen atmosphere will be used in this series of tests.

APPENDIX B

Data Files Available on DVD, Associated with Each Test

Date and Test #	Data Files – All files are Excel Spreadsheets located in folders :\Data\Date	Video Files located in folders :\Videos\Date	Still Photographs located in folders :\Hs Garage Photos\ Sub folders listed for each test where photos are available
9/11/09, 8 %-1	09-11nist processed data test no 1		\Hs Garage Photos Initial set-up photos – 20 photos
9/11/09, 8 %-2	09-11nist-01 8 percent test 2 data		
9/11/09, 8 %-3	09-11nist-8 percent test no 3 data1		
9/14/09, 16 %-1	09-14nist-01 hs Processed Data 09-14nist-01 Processed Data	9-14-09.DivX HS Video door view 9-14 HD Video Igniter HD Video Interior 9-14 HD Video	\9-14 16 % Test 1 18 photos
9/18/09, 16 %-2	09-18-nist-1-2 Calibration run 09-18-nist-1-2a H2 concentration 16-2 high speed processed data 9-18	High-Speed.DivX Igniter Interior Small camera	\9-18 16 % Test 2 10 Photos
9/21/09, 16 %-3	09-21-processed data Cocentration temp 09-21-nist-hs-Processed valid	9-21-09.DivX Igniter Interior Exterior	\9-21 16 % Test 3 25 photos
9/23/09, 12 %-1	09-23-nist-Processed data 12-1 09-23-nist-hs-processed data	9-23-09.DivX Igniter Interior	
9/24/09, 12 %-2	09-24-nist-calibration of h2 09-24-nist-12 percent run no2 processed data	9-24-09.DivX Igniter Interior	
9/28/09, 8 %-4	09-28-nist-1-1a00001 8percent rerun calibration 09-28-nist-1-2a00002 actual run 8 percent processed	Highspeed-A.DivX Igniter-A Interior-A Small camera-A	
9/28/09, 12 %-3	09-28-nisthydsenstest12-3 calibration 09-28-nist-test12-3 actual run processed data	Highspeed-B.DivX Igniter-B Interior-B Small camera-B	
10/1/09, 29.2 %-1	10-1-nist-1 processed data 29.2-1 10-1-nist-hs processed high speed data for 29.2 run 1	High Speed.DivX	\28.8 %V Test Photos and vids\100K6490 16 photos \NIST (Abel's Camera) 73 photos
10/16/09, 8 %-5	10-16-nist-1-8percent	10-16-09 8-1.DivX 10-16-09 IR 8-1.DivX	
10/16/09, 8 %-6	10-16-nist-2 8percent	10-16-09 8-3.DivX 10-16-09 IR 8-3.DivX	
10/16/09, 8 %-7	10-16-nist-3 8 percent	10-16-09 IR 8-1.DivX	
10/16/09, 12 %-4	10-16-nist-12 percent 10-16-nist-hs-400000 12 percent	10-16-09 12-1.DivX 10-16-09 IR 12-1.DivX	

Date and Test #	Data Files – All files are Excel Spreadsheets located in folders :\Data\Date	Video Files located in folders :\Videos\Date	Still Photographs located in folders :\Hs Garage Photos\ Sub folders listed for each test where photos are available
10/19/09, 12 %-5	10-19-nist-12-2 processed 10-19-nist-hs-12 a percent 10-19-nist-hs-12 percent	10-19-09 12-2.DivX 10-19-09 IR 12-2.DivX	
10/22/09, 8 %V	10-22-nist-8-1v processed data	10-22-09 IR8v 1	
10/22/09, 12 %V	10-22-nist-12v Processed data 10-22-nist-hs-12v00094	10-22-09 IR12v-1	\NIST PICS 10-1 thru 10-22\additional photos from 12 % run 18 photos \NIST PICS 10-1 thru 10-22 25 Photos
10/30/09, 12 %V2	10-30-12V processed 10-30-12-hs100000processed 10-30-12-hs100001 processed 09-303-12-hs100002 processed 09-303-12-hs100003 processed	10-30-09 HS 10-30-09 ignition 10-30-09 Int 10-30-09 IR	\10-28-09 Vehicle and Garage before photos 18 photos \12 %V Photos after initiation 29 photos
11/4/09, 16 %1V	11-4-Nist-16- Cal-processed 11-4-Nist-02hs00058 processed data Calculated velocity from IR video	11-4-09 HS 11-4-09 ignition 11-4-09 Interior 11-4-09 IR	\11-04-2009 Abel's Camera 55 photos \Photos 16 % V Files 679-698 (20 photos)
11/12/09, 16 %2V	Nov-12-01 Calibration Nov-12-09 16-2V RT Data processed	Hi Speed Ignition Interior	\11-12-2009 Abel's Camera 61 photos \Photos 16 % V Files 699-728 (29 photos)
11/23/09, 17.7 %V	test11-23 processed data NIST-11-23hs00001 processed	MOV001 Sequence 03 View 2	\11-23-2009 Abel's Camera 40 photos
Inward Leakage Rate Measurements and Calcs for all tests	Inward Leakage calculator		