DISPERSION AND BURNING BEHAVIOR OF HYDROGEN RELEASED IN A FULL-SCALE RESIDENTIAL GARAGE IN THE PRESENCE AND ABSENCE OF CONVENTIONAL AUTOMOBILES

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ABSTRACT

Experiments are described in which hydrogen was released at the center of the floor of a real-scale enclosure having dimensions of a typical two-car residential garage. Real-time hydrogen concentrations were monitored at a number of locations. The hydrogen/air mixtures were ignited at pre-determined volume fractions ranging from 8 % to 29 %. The combustion behavior and structural effects were monitored using combinations of high-speed pressure transducers and ionization gauges, standard thermocouples, hydrogen sensors, and digital, infrared, and high-speed video cameras. Experiments were performed both for empty garages and garages with conventional automobiles parked above the hydrogen release location.

1.0 INTRODUCTION

Hydrogen fuel-cell powered automobiles are expected to become commercially available in the next few years. A large fraction of these automobiles will be housed in existing residential garages. The hydrogen is typically stored as a gas in high pressure tanks with maximum pressures between 35 MPa and 70 MPa, and sufficient amounts are present to replace a large fraction of the air present in a typical garage. Since garages are partially enclosed spaces with exchange rates with the surroundings that are relatively slow, unexpected hydrogen leaks have the potential to form flammable hydrogen/air mixtures. Proposed standards for these vehicles are designed to ensure that any hydrogen leaks are sufficiently slow that flammable mixtures can not develop in realistic garages. Nonetheless, concerns about potential accident scenarios that result in larger leak rates have led to numerous studies designed to characterize the mixing behavior of hydrogen (often helium is used as a surrogate) released into partially enclosed spaces typical of residential garages, as well as studies designed to characterize the combustion behavior of hydrogen/air mixtures that can potentially form in these spaces. This paper describes a study designed to characterize the mixing and combustion behaviors of hydrogen when released into a full-scale structure representative of a two-car garage. Experiments were performed within the empty space as well as with conventional automobiles parked over the release location.

A large number of experimental and/or modeling studies of hydrogen (or helium) releases within partially enclosed spaces have appeared over the last fifteen years. An up-to-date summary of these studies is included in a recent National Institute of Standards and Technology Technical Note. [1] Only a limited number with direct relevance to the current work are cited here due to space limitations.

Real-world garages exchange air with their surroundings through generally uncharacterized openings at rates depending on pressure differences due to externally imposed winds and/or temperature differences. As discussed more fully in Pitts et al., leaks are usually characterized in terms of the number of air changes that a garage undergoes during an hour (*ACH*). [1] Code bodies in the United States have recommended that minimum air exchange rates exceed 3 *ACH*. [2,3] While there is evidence that most garages in North America have *ACH* values greater than 0.5 hr^{-1}, Adams et al.

concluded that the vast majority of garages have *ACH*s, with most significantly, less than one. [4] The reason for the different conclusions concerning garage *ACH* values is not fully understood.

Several studies have investigated the effects of having conventional automobiles in the vicinity of a hydrogen (or helium) release. Maeda et al. investigated the build up of hydrogen inside an automobile engine compartment when hydrogen was released at various locations under a vehicle located in the open. [5,6] The built-up hydrogen was ignited, and the authors concluded that the resulting burning did not pose a significant danger to people in the immediate vicinity. Cariteau et al. measured the time and spatial distributions of helium released at three different locations–under the hood, engine, and passenger compartment–of a small van parked in a one-car garage. [7] Measurements were compared with similar releases without a vehicle present. Merilo et al. released hydrogen inside a one-car garage with and without a vehicle present. [8] Hydrogen concentrations were monitored. Hydrogen/air mixtures were ignited and resulting flame spread velocities and overpressures recorded. Tests with a vehicle present showed that explosions occurred in the engine compartment which caused significant damage to the vehicle and resulted in higher overpressures (roughly a factor of 3) than when a vehicle was not present.

2.0 EXPERIMENTAL

The experiments were performed by Southwest Research Institute under contract to the National Institute of Standards and Technology. Brief discussions of the experimental configuration and instrumentation are presented here. Additional details are available in a NIST Grant/Contract Report (GCR). [9]

2.1 Garage Structure

The enclosure was built to have some resistance to the overpressures expected when a large hydrogen/air mixture is ignited, while having characteristics similar to a typical residential garage. The two side and back walls were constructed by stacking (mortar was not used) interlaced rows of 19.4 cm (w) × 38.8 cm (l) × 19.4 cm (h) cinder blocks on top of a foundation formed from steel I-beams. Lengths of 19 mm diameter steel reinforcing bar spaced on 81.3 cm centers were welded to the steel foundation and passed upwards through openings in the cinder blocks to the top of the walls. Vertical openings in the blocks spaced every 20.3 cm were filled with concrete. Additional strength was provided by 114.3 cm wide exterior perpendicular block sidewalls built at the open sides of the block structure. Wall reinforcement was provided by exterior heavy steel I-beam support buttresses placed at the centers of the three walls and corners at the rear.

The three block walls were capped with “2×6” wooden boards on top of which was placed a flat roof supported by fifteen lengths of 2.5 cm wide × 30.5 cm high wooden I-beams that extended between the sidewalls with 46 cm separation. The open ends of the roof frame were capped with vertical “2×12” wooden boards. The roof was formed by 1.6-cm-thick plywood nailed to the tops of the I-beams. No additional weather proofing was used. The roof structure was not directly attached to the walls, but instead was held in place by twelve 2.5 cm diameter, 45 cm long threaded rods capped with washers and bolts and attached to the side and rear walls. Holes were drilled in the roof system such that the entire assembly was free to slide upwards along the rods until it reached the stops. The system was designed to provide some relief from pressure build up inside the garage.

The front wall of the garage incorporated a wooden frame constructed from standard “2×4” lumber. Doubled “2×4s” were used as the bottom and top plates. The vertical studs were 3.7 m long, and the framed wall extended well above the block walls and roof. Doubled vertical “2×4”s and a “2×6” header beam capped with a “2×4” formed an opening for an uninsulated metal panel 2.1 m × 2.4 m roll-up garage door. A second framed area provided an opening for doorway fan tests (see Section 2.3). The inside of the wooden frame was covered by 1.3 cm thick gypsum wallboard extending above the roof. The front wall rested on the steel foundation I-beam and against the block walls, but was only attached to the remainder of the structure by single 7.6 cm long wood screws passing through

Figure 1. Exterior and interior view of garage facility

the wood frame and into the "2×6" boards capping the two side walls. The front wall was effectively hinged and could swing outwards from the bottom to release a modest internal pressure build up.

Two 0.2 m × 0.2 m openings in the right side wall at heights of 2.3 m provided visual access to the interior. Interior lighting was provided by two 0.3 m × 0.3 m ceiling skylights located over the vertical sensor array (see ahead) and center of the ceiling. The four openings were covered with poly(methyl methacrylate) (PMMA) sheets. The interior ceiling was covered by 1.3 cm thick gypsum wallboard. The garage floor was formed by filling the enclosed steel I-beam foundation volume with leveled packed soil. Potential leaks, such as those between the cinder blocks and where the ceiling and front wall met the block walls, were sealed with caulking and/or duct tape. The degree of sealing varied as the tests progressed. Fig. 1 shows exterior and interior photographs of the garage.

2.2 Hydrogen Release System

The hydrogen release scenario assumed a constant leak rate sufficient to release 5 kg (a typical amount for full tanks on current hydrogen-fueled automobiles) in one hour. The mass flow rate of 83.3 g/min corresponds to a volume flow rate of 994 L/min for standard conditions of one atmosphere and 20 ºC. Hydrogen was supplied by a joined bank of twelve cylinders, containing 6.8 kg when full, located a safe distance from the garage. The gas flowed through a pressure regulator and a Matheson Model 8273-0416 mass flow controller.[*] A 3.8 cm diameter line transported the hydrogen to a location near the garage where it passed through a manual safety value before entering the garage through the steel beam foundation and terminating at the hydrogen release-point distributor (a 15 cm high, 30.5 cm square steel box with an open top) located flush with the floor at the center of the garage. The hydrogen entered the box near the bottom and flowed upwards though a wire mesh screen, a 10 cm deep layer of 12 mm crushed stone and a second wire mesh screen before exiting into the garage. Assuming uniform flow, the average upward velocity for the standard flow was 18 cm/s, which indicates that the hydrogen flows that developed in the garage were buoyancy dominated.

2.3 Instrumentation and Video Systems

A global indication of how well the garage was sealed prior to each experiment was obtained using an Infiltec Model E3-A-DM4-110 Blower Door to record the differential pressure (ΔP) as a function of air volume flow rate (Q) for inward flow. The fan was mounted in the front wall to the left of the garage door. The results were least squares fit to the following equation,

$$Q = C(\Delta P)^n, \quad (1)$$

where C is constant and n is the pressure exponent. The leaks were characterized using ACH_{4Pa}, which is the calculated Q for ΔP = 4 Pa, commonly taken as a characteristic value for the pressure difference between a garage interior and exterior, normalized by the interior volume of the garage.

[*] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Real-time hydrogen concentrations were monitored using Xensor Integration Model TCG-3880 thermal conductivity sensors. Individual sensors were calibrated prior to each test by recording their voltage outputs when placed in air and hydrogen and using a model for the sensor response along with recommended values [10] of thermal conductivity as a function of hydrogen volume fraction for hydrogen/nitrogen mixtures at 293.3 K. Additional details concerning the calibration approach are available in [1]. Tests with calibrated hydrogen/nitrogen mixtures of roughly 5 % and 40 % showed that hydrogen volume fractions were accurate to ± 0.1 %. Sensors were mounted on a vertical rod located on the garage centerline 61 cm from the rear wall. The (x,y) coordinates for a system with an origin at the left-front corner and x, y, and z axes oriented along the width, length, and height of the garage were (3.05 m, 5.49 m). Eight sensors were placed at z = 0.38 m, 0.76 m, 1.14 m, 1.52 m, 1.90 m, 2.29 m, 2.59 m, and 3.05 m. Location uncertainties were estimated to be ± 5 cm. During tests with automobiles, the top-most vertical sensor was moved inside the vehicles' passenger compartments, and a ninth sensor was added to monitor concentrations in the engine compartments.

A variety of systems were used to monitor combustion behavior when hydrogen/air mixtures were ignited. Omega Engineering, Inc. 0.159 cm diameter Type K thermocouples (sheathed, grounded) were employed. A vertical-array of thermocouples was mounted at the same (x,y) location and heights as the hydrogen sensors. A horizontal array of seven thermocouples along the garage centerline was mounted on a 5.5 m long "2×4" steel construction stud attached to the rear wall and supported at the opposite end by a rod suspended from the ceiling. Horizontal locations were y = 5.19 m, 4.59 m, 3.99 m, 3.39 m, 2.79 m, 2.19 m, and 1.59 m. An array of six Dynasen Inc. Model CA-1041-C high-speed ionization "pins" were mounted along the same horizontal line at y = 5.19 m, 4.89 m, 4.59 m, 4.29 m, 3.99 m, and 3.69 m. These probes are designed to respond to ions generated by the passage of a shock wave or combustion front. Two PCB Piezotronic, Inc high-speed pressure sensors (either Models 137A21 or 137A23) were placed at coordinates (3.04 m, 5.94 m, 2.59 m) and (6.10 m, 3.04 m, 2.59 m). The manufacturer's specifications indicate that the Model 137A23 can resolve changes of 0.07 kPa and has an uncertainly of less than 1 % over the entire response range. Voltages generated by the various transducers were digitized at two different rates. Signals from the hydrogen sensors and thermocouples were recorded continuously during an experiment at 1 Hz. Additional data recorded at the same rate included the output of the mass flow controller and values of wind speed and direction monitored by a weather system located within 50 m of the garage. The data acquisition system for the high-speed ionization and pressure sensors functioned differently. It was designed to record continuously at 100 kHz into a buffer memory holding 60 000 measurements. An initial signal from any of the ionization gauges triggered the system, which was set to save measurements extending from 50 ms prior to the trigger until 550 ms afterward.

Digital hand-held still cameras with video capability, standard high-definition (HD) video cameras, a Raytheon Model TVS-620U infrared video camera, and a Vision Research Phantom v5.1C high-speed camera operating at 1 kHz were used to record video records of the experiments. At various times, cameras were placed inside the enclosure (protected by a plastic housing) near the floor in the rear right corner (HD camera), at the side windows viewing the ignition area or the center region (HD and/or IR), and at outside positions located at various distances and angles from the garage (HD, high-speed, and digital hand-helds).

2.4 Hydrogen/Air Mixture Ignition

The ignition point was chosen to be near the ceiling along the same vertical line where the concentration and temperature measurements were made, i.e., (x,y,z) = (3.05 m, 5.49 m, 2.59 m). Preliminary experiments using 1 J and 10 J electric sparks indicated that ignition was unreliable for hydrogen volume fractions between 4 % and 8 %. As a result, 80 J squib charges triggered by voltage pulses were employed for all of the tests discussed here.

2.5 Testing with Automobiles

Several tests were run in which conventional automobiles were placed in the garage centered over the hydrogen release position. The automobiles chosen were older models that had reached the ends of their useful lives, but their bodies and interiors were generally intact and appeared to be in good condition. Based on availability, a wide variety of makes and models were used. The cars tested were a 2001 Chevrolet Cavalier, a 1996 Ford Aspire, a 1996 Buick Century Limited, a 1995 BMW 325i, and a 1995 Ford Explorer. No gasoline was on board. All windows and doors were closed.

3.0 EXPERIMENTAL RESULTS

Sixteen experiments without and six experiments with vehicles present in the garage are described in the NIST GCR. [9] During some tests instrumentation failed to function properly, and, as a result, complete data sets are not available for all tests. As an example, the high speed data acquisition failed to trigger or improperly triggered in many tests, and ionization and pressure traces were not recorded. The GCR includes a table listing the various tests and the types of information that were recorded [9] along with results of preliminary data analysis performed by SWRI staff members. Additional data analysis was carried out by NIST staff, and these results are presented here.

3.1 Doorway Fan Test

Doorway fan tests were recorded prior to testing on most days. The target ACH_{4Pa} for the test series was 3 h^{-1}. During early testing, prior to more careful sealing of the garage, ACH_{4Pa} values varied between 4.5 h^{-1} and 9.8 h^{-1} with n values for the fits to Eq. (1) lying between 0.5 and 0.65. These values provide an indication of the type of flow through the leaks with n = 1 and n = 0.5 being characteristic of laminar and turbulent flow, respectively. As the sealing of the garage was improved, measured ACH_{4Pa} values fell, with a value as low as ACH_{4Pa} = 1 h^{-1} observed. The majority of these later tests had ACH_{4Pa} values in the 3 h^{-1} to 4.5 h^{-1} range. For some tests the leakage rate was adjusted by raising the garage door slightly to increase the leak area. For the later tests, n ranged from 0.6 to 0.88, with most greater than 0.72. This suggests that larger leaks had been sealed since the leak flows were more laminar. Note that variations in leak size and distribution were expected because it was necessary to make substantial garage repairs, including one complete rebuild, after many of the tests.

3.2 Volume Flow Rates

Mass flow controller voltages were recorded for most experiments. Voltages were proportional to the volume flow rate in standard liters per minute nitrogen (SLPMN) at 20 ºC. The actual flow rates depended on the pressure, temperature, and a small factor (1.01) to correct for using hydrogen instead of nitrogen. Average SLPMN settings were highly reproducible, with an average of 984 SLPMN ± 5 SLPMN. Actual volume flow rates were somewhat more variable since temperatures and baselines varied during the tests. Corrected values ranged from 894 LPM to 941 LPM. Atmospheric pressures were not recorded, and no corrections for pressure variations were applied.

3.3 Hydrogen Mixture Fraction Distributions in Garage

3.3.1 Experiments without Vehicles in Garage

Hydrogen was released near the floor and flowed until just prior to ignition when the hydrogen sensor at the 2.59 m height reached a pre-set voltage. Initial experiments showed that the hydrogen/air mixtures did not ignite for volume fractions around 4 % (the lower flammability limit [11]), but did ignite for volume fractions near 8 %. Hydrogen/air mixtures were allowed to reach levels around 8 %, 12 %, 16 %, and 29 % (close to the stoichiometric volume fraction [11]) prior to ignition. Fig. 2 shows measured hydrogen volume fractions as a function of time for experiments which reached the indicated hydrogen volume fractions at ignition (increasing from top left to bottom right). Zero time is defined to be when the mass flow controller opened. For each case, the sensor nearest the ceiling was the first to detect hydrogen. Only a few seconds were required for hydrogen to reach this location. As time passed, the hydrogen layer at the ceiling descended, and hydrogen was detected sequentially at the lower sensors. Generally, concentrations decreased with height at all times, but after the initial period, the concentration gradients in the upper half of the garage were relatively small, while those in

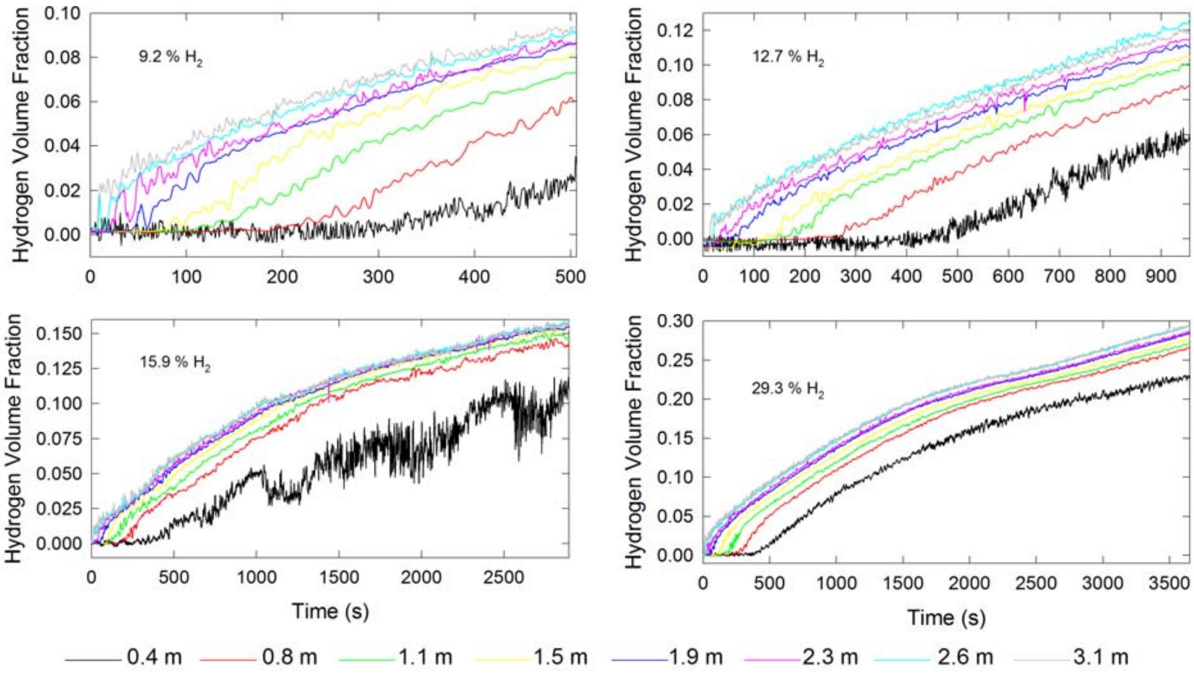

Figure 2. Examples of hydrogen volume fraction temporal profiles measured in garage without a vehicle during the period between hydrogen flow initiation and hydrogen/air mixture ignition.

the lower half were somewhat larger. The concentration gradients and the volume fraction differences between the highest and lowest sensor positions decreased as the flow time increased. Comparison shows that the temporal profiles differ somewhat from test to test. This is attributed to differences in the leak areas and distributions, varying weather conditions, and variations in construction as the garage was repaired following damage incurred when the hydrogen/air mixtures were ignited.

3.3.2 Experiments with Vehicles in Garage

Fig. 3 shows similar temporal concentration profiles for experiments in which vehicles were centered over the floor hydrogen release location. As above, the concentrations just prior to ignition increase from the upper left to the lower right. Targeted hydrogen volume fractions at ignition were 8 %, 12 %, 16 %, and 29 % at the sensor located 2.59 m above the floor. Note that it was not possible to reach the highest targeted hydrogen concentration since the hydrogen volume fraction approached an asymptotic value at a lower concentration. This was not the case for the similar experiment without a vehicle, which emphasizes the significant variations in hydrogen losses from the garage observed between nominally similar experiments.

For the lowest hydrogen volume fraction ignition experiment (upper left in Fig. 3), the sensor nearest the ceiling was moved to the interior of the passenger compartment (P. C.) of the 2001 Chevrolet Cavalier used for this test and placed near the rear-view mirror attached to the center of the windshield. The measurements along the vertical array indicated that the hydrogen volume fractions were nearly uniform from top to bottom. The measurements revealed that hydrogen entered the passenger compartment, but that the build up of hydrogen was much slower than in the surrounding garage. For the nominal 12 % hydrogen ignition test a ninth hydrogen sensor was placed inside the engine compartment (E. C.) near the top between the engine and bulkhead separating the engine and passenger compartments of the 1996 Ford Aspire. The hydrogen volume fraction at this location jumped to roughly 20 % immediately after the flow started and then increased slowly as the hydrogen concentration in the surrounding garage rose, reaching 27 % when the 11.4 % mixture located 2.59 m above the floor was ignited. The concentrations recorded along the vertical direction indicate nearly uniform mixing within the surrounding garage. These concentrations increased smoothly with time. Apparently, the passenger compartment for the vehicle used in this test was leakier than that of the

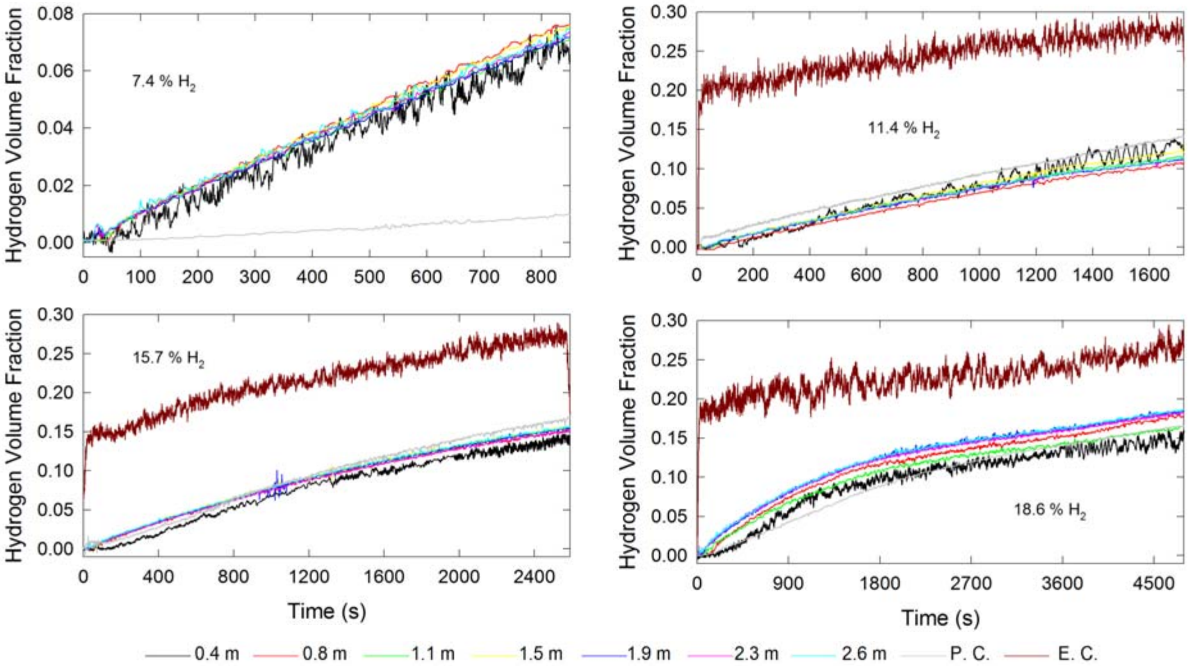

Figure 3. Examples of hydrogen volume fraction temporal profiles measured in garage with vehicles during the period between hydrogen flow initiation and hydrogen/air mixture ignition.

Chevrolet Cavalier, and measured hydrogen concentrations were slightly higher than observed in the surrounding garage. The hydrogen volume fraction profiles shown in the lower-left panel of Fig. 3 were recorded with a 1995 BMW 325i in the garage. The hydrogen volume fraction at the ignition point reached 15.7 %. The time profiles have similar appearances to those for the nominally 12 % hydrogen test, but the initial concentration rise measured in the engine compartment was lower, approximately 14 % versus 20 %, and, for a given exterior hydrogen volume fraction, remained lower than observed with the Ford Aspire. Hydrogen volume fractions in the garage were vertically uniform. Concentrations in the passenger compartment tracked those inside the garage. The last panel of Fig. 3 was recorded with a 1995 Ford Explorer in place. The sensor at 1.52 m did not function during this experiment. The rapid increase in hydrogen concentration inside the engine compartment is once again evident, and its initial magnitude was intermediate between those for the Ford Aspire and the BMW 125i. Unlike for the other tests shown, the hydrogen volume fraction measurements along the vertical array in the garage did not fully collapse, and a small concentration increase with height is evident. The concentration gradient was likely a result of larger amounts of air entering the garage during this test. This is consistent with the failure to attain the target hydrogen concentration at the 2.59 m height.

3.4 Hydrogen/Air Combustion Behavior and Resulting Damage

The primary means of characterizing the combustion behavior were flame spread rate, temperature, and over-pressure measurements. Damage to the structure and vehicles resulting from ignition of the hydrogen/air mixtures was qualitatively characterized from photographs and videos. As expected, the strength of the combustion and resulting damage increased with increasing hydrogen concentration.

3.4.1 Experiments without Vehicles in Garage

Ignition was achieved using 80 J squib charges. Videos showed these devices expelled small burning fragments that ignited the hydrogen/air mixtures along their trajectories. Nonetheless, after combustion became established, a well-defined flame front moved away from the ignition location. Fig. 4 shows infrared views from a video of a flame shortly after squib firing and after the flame had begun propagating near the ceiling to the left in a 6.6 % hydrogen/air mixture. By using similar infrared images or ionization gauge signals, flame front positions as a function of time were measured

Figure 4. Two frames taken from an infrared video show the flame 90 ms (left) and 1.7 s (right) after the squib fired in a 6.6 % hydrogen/air mixture.

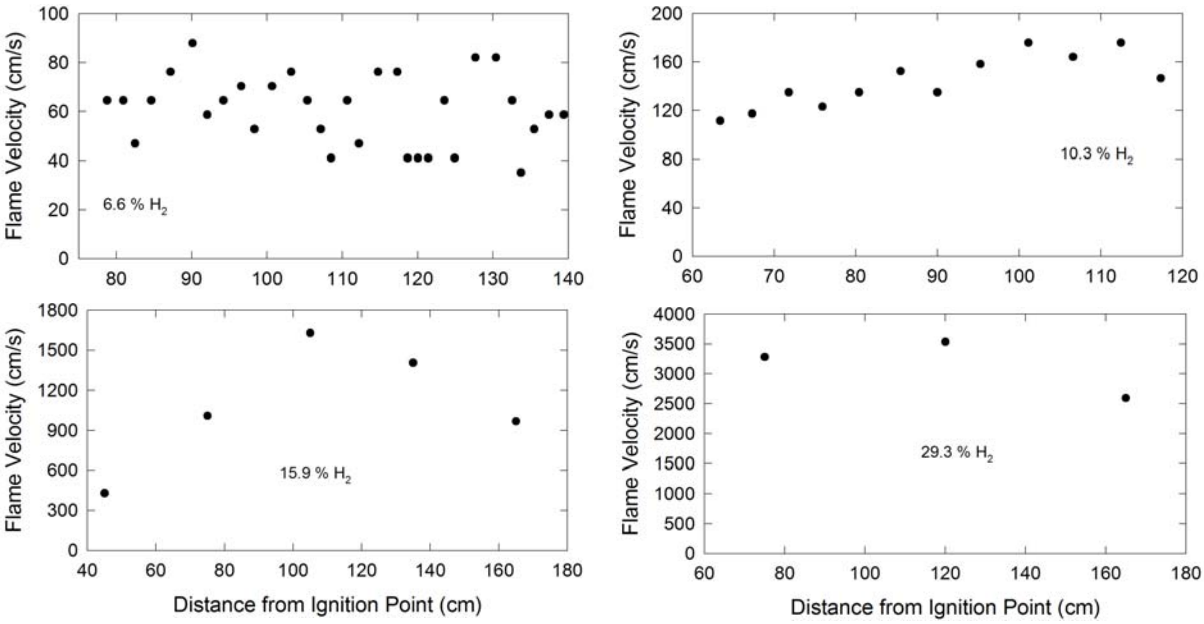

Figure 5. Flame spread velocities measured following ignition of hydrogen/air mixtures having indicated volume fractions at the ignition location.

and used to determine the flame spread velocity toward the front of the garage along a horizontal line at the center of the garage.

Fig. 5 shows flame spread velocity measurements as a function of distance from the ignition plane for cases with the indicated hydrogen volume fractions at the ignition point. The measurements for the two lower concentrations were made from IR videos, while those for the two higher values were taken from ionization measurements. Note that for the 29.3 % case only four of the six ionization gauges triggered. As expected, flame spread velocities increased rapidly with hydrogen concentration, going from 0.6 m/s for very lean conditions to a value of roughly 35 m/s close to the stoichiometric concentration. [11] For the 6.6 % hydrogen case the spread rate appeared to be constant, while it was clearly increasing for the 10.3 % case. The limited number of flame spread rate measurements for the higher concentrations did not allow an assessment of how the rate varied with distance. Uncertainties for the flame spread rate measurements are difficult to estimate. On one hand, uncertainties in rates determined based on the period required for flame movement from one point to another were relatively small since distance and period measurements had small uncertainties. These are negligible as compared to variations in the flame spread rates evident in Fig. 5. The larger variations were likely the result of changes in the average flame spread rate as well as fluctuations due to induced turbulence.

Interesting phenomena were observed for flames ignited with hydrogen concentrations around 8 %. In the infrared video from which the frames in Fig. 4 were taken, a weak flame front was observed near

Figure 6. Three frames from high-speed videos showing the effects of igniting hydrogen/air mixtures having volume fractions of 13.3 %, 15.2 %, and 29.3 %. The photograph at right shows block-wall damage due to ignition of the 29.3 % hydrogen mixture.

the ceiling moving from the front towards the rear of the garage, returning to the ignition plane 16.5 s after ignition. Similar oscillations were observed in other tests with ignition in mixtures with hydrogen levels around 8 %, but the details varied substantially. In one test, the returning wave moved across the width of the garage instead of from front to rear. In another, multiple cycles of temperature and concentration variations were observed that lasted over 2 minutes. A characteristic of these weak flames was that associated overpressures were small. An exterior high-speed video and an interior video showed that the effect of igniting an 8.7 % hydrogen/air mixture was to slightly bow the metal garage door and push the bottom of the front wall a small distance outward (recall that it was hinged at the top). The roof was not lifted, and no permanent damage to the structure was evident.

When the hydrogen concentration at the ignition location was increased to around 12 % the overpressure generated by the combustion was sufficient to blow the front wall away from the enclosure, as can be seen in the frame on the left side of Fig. 6. There was no apparent lifting of the roof, and the interior gypsum wallboard ceiling was not dislodged. For ignition of hydrogen concentrations around 16 % the combustion became more vigorous, and the resulting overpressures caused additional building damage. The second frame in Fig. 6 shows a test in which a 15.2 % hydrogen/air mixture was ignited. The resulting overpressure dislodged the front wall and propelled it several meters away. In the video, it was evident that the roof also moved upward several cm before settling back down. Several whole sheets of gypsum wallboard were dislodged from the ceiling, suggesting that combustion occurred in the space between the wallboard and the plywood roof.

By far, the largest explosion and most extensive structural damage were observed for the test in which the 29.3 % hydrogen/air mixture was ignited. The third panel in Fig. 6 shows a frame from the high-speed video. The front wall, garage door, and roof have been shattered and are moving away from the block walls at high rates. Most of the roof disappeared from view, before falling to earth over three second later. Portions of the front wall were propelled tens of meters from the site. Unlike the tests with ignition at lower hydrogen levels, orange flames are clearly visible, providing an indication of the higher flame temperatures present for this condition. The block walls remained standing after the test, but as can be seen in the photograph at the right of Fig. 6, large cracks developed through the blocks, and inspection revealed that the force of the explosion had sheared off the internal reinforcing steel rods at the wall base and had shifted the walls several centimeters on the foundation.

Fig. 7 shows measured overpressure as a function of time for experiments where ignition occurred in mixtures with 15.6 % and 29.3 % hydrogen. Note that the triggering did not correspond with squib firing. For the lower hydrogen volume fraction the trigger occurred well after the pressure had begun to rise. The pressure rose smoothly to a value of just over 0.6 kPa, before smoothly decaying. For the higher hydrogen concentration, the pressure initially increased smoothly to a value around 20 kPa before there was an abrupt pressure increase followed by a period of rapid fluctuations with sharp spikes approaching 60 kPa. The time period shown is shorter at the higher hydrogen concentration.

3.4.1 Experiments with Vehicles in Garage

The effects on burning behavior of placing a conventional vehicle over the hydrogen release location depended on the ignition concentration. For an experiment with a hydrogen concentration of 7.3 %,

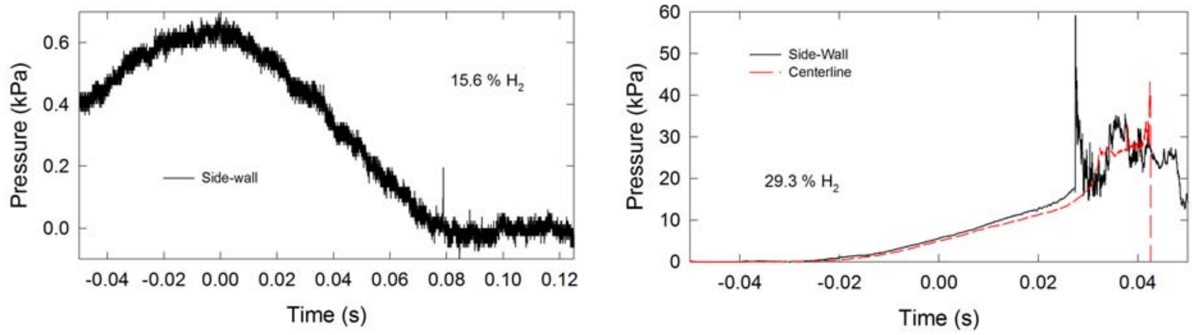

Figure 7. Overpressure time histories for experiments without a vehicle and ignition with indicated hydrogen concentrations at the ignition location.

the observed initial combustion behavior and effects on the structure were very similar to those with similar hydrogen concentrations when no vehicle was present. One difference was that burning continued in the area for many seconds after ignition. The likely explanation for this was that higher hydrogen concentration gas was escaping from the nearby engine compartment of the vehicle and forming a plume that rose into the viewed region where it was burned.

For the ignition of an 11.4 % hydrogen/air mixture the initial flame velocity was estimated from an infrared video to be 2 m/s, which is slightly higher than the values shown in Fig. 5 for an ignition concentration of 10.3 % hydrogen concentration without a vehicle. A high-speed video showed that the initial response of the structure to the overpressure was also similar, with the front wall being pushed out at the bottom and some bowing of the garage door, with no apparent lifting of the roof. However, the video indicated a dramatic increase of combustion intensity starting 2.6 s after ignition. The garage door started rapidly deforming and was broken and pushed out of its frame. The front wall was detached and pushed several meters from the structure and the roof was lifted roughly 20 cm above the block walls. Infrared and HD cameras viewing the interior showed bright flashes of yellow flames at the same time. The HD camera captured the sheet metal from the vehicle's hood being propelled upwards and striking the construction beam supporting the horizontal array of sensors.

The evidence indicates that the spreading flame outside of the 1996 Ford Aspire ultimately ignited the higher concentration hydrogen trapped underneath the vehicle (measured to be 27 % at the top of the engine, see upper-right panel of Fig. 3). This was confirmed by an interior HD video which showed that ignition first occurred at the rear of vehicle and rapidly spread underneath the vehicle to the engine compartment (≈ 0.1 s), where it created an intense, visible flame. The left side of Fig. 8 shows a frame from the interior video at the instance the engine compartment ignited. The right side is a photograph of the vehicle after the test. In addition to the hood being blown off, the body was bulging, the hubcaps were blown off, and much of the trim was damaged. The resulting increase in overpressure also shattered the PMMA protecting the interior camera, broke one of the skylight coverings, and brought down two sheets of ceiling gypsum wallboard. This damage was more severe than observed for similar hydrogen concentrations when a vehicle was not present.

The combustion behavior for a case where a 15.7 % hydrogen/air mixture was ignited in the presence of a 1995 BMW 325i was similar to that for the 11.4 % experiment with a vehicle, but more intense. Following ignition, there was a short period when the combustion behavior was similar to those tests with comparable hydrogen concentrations at the ignition location without an automobile present, but after 0.5 s higher hydrogen concentrations inside the vehicle ignited near the front end and caused a considerably more vigorous event. Fig. 9 shows two frames from a high-speed video taken from outside of the garage. In the left panel the overpressure inside the garage has started to push the front wall outwards. The ignition of the hydrogen trapped in the vehicle had occurred a few milliseconds earlier, and flames are visible on and in the vehicle. Overpressures were substantially increased, and the garage door was blown apart and the front wall was accelerated and shattered (right panel). The entire roof was lifted. Following the test, parts of the front wall were found tens of meters from the garage. The roof settled back down on the block walls, but sustained considerable damage. Most of

Figure 8. Frame from HD video showing moment of hydrogen ignition in engine compartment of 1996 Ford Aspire (left) and resulting vehicle damage (right).

Figure 9. Two frames from a high-speed video recorded approximately 0.5 s and 0.6 s following ignition with a hydrogen concentration of 15.7 % in a garage containing a 1995 BMW 325i.

the interior ceiling gypsum wallboard sections fell. The vehicle was heavily damaged. As before, the upper part of the hood sheet metal was blown off. Additionally, the trunk was blown open, both bumpers were blown off, passenger compartment glass was shattered, and large sections of sheet metal were peeled away from the car body.

The final test was ignited at a hydrogen concentration of 18.6 % with a 1995 Ford Explorer in the garage. This was a much larger vehicle than used in the earlier tests. The garage was completely destroyed. Fig. 10 shows views of the explosion from two DV video cameras. Flames are visible. The front wall has been shattered, and the roof has been blown off and is falling apart. There was a 0.15 s period between when the garage first began to respond to the ignition and when the intense orange flames suddenly appeared. Fig. 11 shows differential pressure traces from the sidewall transducer over two time periods. The first is similar to that shown in Fig. 7 for ignition of a 15.6 % hydrogen mixture with no vehicle present. It represents the overpressure generated by the initial flame spread. The second curve developed when the higher concentration hydrogen trapped in the vehicle ignited. The delay between the two curves is consistent with the time derived from the videos. The overpressures increased substantially and became highly variable with time. Pressure magnitudes were similar to those recorded (Fig. 7) when a 29.3 % hydrogen/air mixture was ignited without an automobile present. Recall that the garage was also destroyed during this test.

The Ford Explorer was heavily damaged during the test as can be seen in Fig. 12. As seen in the test when 29.3 % hydrogen was ignited without a vehicle present, the overpressure generated during the test resulted in the formation of long cracks in the block walls. An example is shown in Fig. 12. Examination showed that the block walls were also shifted on their foundation as observed earlier.

Figure 10. Frames from front- (left) and side-view (right) videos of a test where an 18.6 % hydrogen/air mixture was ignited with a 1995 Ford Explorer located in the garage.

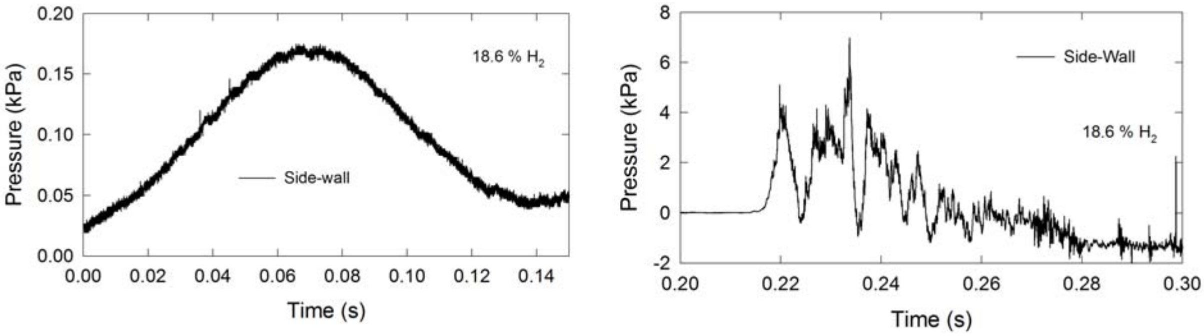

Figure 11. Differential pressure traces recorded over two times during an experiment in which an 18.6 % hydrogen/air mixture was ignited with a vehicle present.

Figure 12. Photographs of the garage interior and vehicle (left) and exterior block wall damage (right) following ignition of 18.6 % hydrogen/air mixture

4.0 DISCUSSION

Concentrations were tracked in real time during experiments in which hydrogen was released into a two-car-garage. It was shown that vertical concentration gradients developed when no vehicle was present, and since the hydrogen release rate was held constant, the gradients were more pronounced when ignition occurred at lower concentrations. When vehicles were placed over the hydrogen release location the mixing was more complete, and vertical concentration gradients were virtually eliminated. The latter finding is consistent with the results of Cariteau et al., who found nearly uniform vertical concentration profiles when helium was released under a small commercial vehicle parked in a single-car garage. [7] No definitive explanation was identified for substantial variations in build-up rates of hydrogen concentration inside the garage observed between experiments during this test series.

Tests with vehicles parked over the release location showed that high concentrations of hydrogen collected inside engine compartments when the release was initiated. This indicated that significant mixing with surrounding air took place and that the engine compartments acted as partially enclosed spaces capable of trapping high hydrogen concentrations. Initial hydrogen concentrations were similar to those observed by Maeda et al. who studied hydrogen release under a vehicle in the open. [5,6] The trapped hydrogen concentrations increased with time as hydrogen in the surrounding garage increased. Prior to ignition inside the garage, hydrogen concentrations in the engine compartments were close to stoichiometric values. [11] Hydrogen was also found to enter the passenger compartments, with the rate of build up varying substantially between the different older vehicle models tested.

A wide variety of burning behaviors were observed depending on the hydrogen volume fraction at the point of ignition and whether or not a vehicle was present. Burning was only observed near the ceiling following ignition of mixtures with hydrogen volume fractions around 8 % and no vehicle present. Measured flame spread velocites were around 80 cm/s and were sufficiently slow that the resulting overpressures had few effects on the structure. A variety of slow oscillatory flame behaviors were observed which varied depending on the hydrogen concentration. Increasing the hydrogen concentration to near 12 % resulted in a rough doubling of the flame spread velocity. For these cases the overpressures were sufficient to push the garage front wall outwards at the bottom, which helped limit the pressure buildup. For ignitions of hydrogen volume fractions around 16 %, the measured flame spread velocities increased to roughly 10 m/s. Maximum observed overpressures were on the order of 0.2 kPa to 0.6 kPa. These were sufficient to break the front wall of the garage from its attachment points and propel it several meters away. The roof was also lifted several centimeters and sheets of ceiling sheet rock were dislodged. When the hydrogen concentration at the ignition point was increased to near the stoichiometric value, 28.6 %, observed flame spread velocities reached as high as 35 m/s. The burning generated bright orange flames and sufficient overpressure inside the garage to shatter the front wall and roof and considerably damage the cinder block walls. Overpressure measurements indicated a transition in burning behavior 50 ms after ignition that generated spikes in excess of 50 kPa. Note that this transition likely occurred after the flame spread velocitie measurements were completed. Merilo et al. reported similar flame spread velocities and overpressures following the ignition of 23 % hydrogen mixtures inside a structure sized as a single-car garage. [8]

The addition of a vehicle had little effect on observed burning behavior for experiments where hydrogen concentrations around 8 % were ignited. The flames did not spread into the vehicle where higher hydrogen concentrations were present. In contrast, when hydrogen concentrations at the ignition point were 12 % and higher, the flames reached and ignited the trapped hydrogen. The periods between initial ignition and the ignition of the trapped gases decreased from a few seconds for an ignited concentration of 12 % hydrogen to 0.2 s for 18.6 % hydrogen. The burning of trapped hydrogen created conditions that were more severe than observed for comparable ignition concentrations without a vehicle present. For ignition concentrations around 12 % hydrogen, the damage was similar to that observed for cases without a vehicle with 16 % hydrogen. The experiment with 16 % hydrogen caused considerably more damage than the corresponding case without a vehicle. When the hydrogen concentration at the ignition point was 18.6 %, and a large vehicle was used, the resulting explosion caused damage to the garage that was comparable to that observed with a near-stoichiometric hydrogen concentration in the empty garage. Overpressure measurements for both of these tests showed strong temporal fluctuations with spikes of significantly higher pressure. The increased burning intensities of the trapped hydrogen were likely due to a combination of the higher concentrations present and the cluttered environments present under the automobiles. The presence of obstacles is known to increase turbulent flame speeds for premixed combustion. [11] Observed vehicle damage indicated that in some cases hydrogen inside the passenger compartments was also ignited.

A few experiments in which hydrogen was trapped inside and under vehicles have been reported. Maeda et al. measured the hydrogen concentration at several locations during experiments in which hydrogen was released under vehicles at several different locations. [5,6] These measurements were performed in the open. Observed concentrations inside the engine compartment were comparable to those observed following the start of hydrogen release in the current experiments. When Maeda et al. ignited the mixtures, the resulting fires were relatively weak and did little damage to the vehicle. Various measurements indicated that a person in the immediate vicinity would not have been harmed significantly. [5,6] This was not the case for the current experiments. In all cases where trapped hydrogen ignited, the hood was blown off and significant damage occurred to the vehicle and surrounding garage. These differences in burning behavior are likely due to the buildup of higher trapped hydrogen concentrations in the vehicles when housed inside a garage. Merilo et al. ignited hydrogen inside a single-car sized volume containing an automobile. [8] Even though the concentration of the trapped gas was not measured, they did observe ignition of the trapped mixture and an enhancement of burning rate similar to those reported here. Overpressures generated by this burning were also comparable. These findings indicate that hydrogen trapped in the partially confined spaces of conventional automobiles can lead to enhanced burning rates and increased damage inside a residential garage.

5.0 REFERENCES

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