DETECTION OF HYDROGEN RELEASED IN A FULL-SCALE RESIDENTIAL GARAGE*

Cleary, T.G.[1] and Johnsson, E.L.[2]
[1,2] Fire Research Division, Engineering Laboratory
National Institute of Standards and Technology,
100 Bureau Dr., Gaithersburg, MD 20899, USA
[1] Thomas.Cleary@nist.gov
[2] Erik.Johnsson@nist.gov

ABSTRACT

Experiments were conducted to assess detectability of a low-level leak of hydrogen gas and the uniformity of hydrogen concentration at selected sensor placement locations in a realistic setting. A 5 % hydrogen/95 % nitrogen gas mixture was injected at a rate of 350 L/min for about 3/4 hour into a 93 m^3 residential garage space through a 0.09 m^2 square open-top dispersion box located on the floor. Calibrated catalytic sensors were placed on ceiling and wall locations, and the sensors detected hydrogen early in the release and continued to measure concentrations to peak and diminishing levels. Experiments were conducted with and without a car parked over the dispersion box. The results show that a car positioned over the dispersion box tends to promote dilution of the hydrogen, cause a longer time for locations to reach a fixed threshold, and produce lower peak concentrations than with no car present.

1.0 INTRODUCTION

The reliable and accurate detection of an accidental hydrogen gas release and mitigation of the hazard through engineered safety systems is a key component of hydrogen powered systems in commercial, residential, and transportation applications. A hydrogen-powered vehicle in a garage presents a scenario where a hydrogen leak needs to be detected and mitigated. A low-level leak of hydrogen may portend an imminent catastrophic failure, or at least a wasteful fuel leak, both of which should be detected. A residential garage with doors and windows closed presents a relatively quiescent space with minimal convection flows. Air leakage into and out of the garage space typically occurs at gaps and cracks around doors and windows. To assess whether or not a low-level leak of hydrogen gas can be detected in a space and if detectable, whether or not hydrogen concentration is uniform across the selected sensor placement locations (ceiling and wall), the dispersion of a non-flammable hydrogen-containing gas mixture released in a garage space was studied experimentally.

2.0 DESCRIPTION OF EXPERIMENTS

Experiments were conducted in the NIST Indoor Air Quality test house [1], a double-wide manufactured home with an attached garage. Figure 1 shows the garage with internal dimensions of 6.78 m (L) × 5.59 m (W) × 2.44 m (H). It was instrumented with identical models of catalytic hydrogen sensors as well as a temperature/humidity sensor (data not discussed here) and a two-axis (North-South and East-West) sonic anemometer velocity probe located 10 cm from the ceiling. The anemometer has a velocity resolution of 1 cm/s. The hydrogen detectors, which were previously calibrated in the HyDEE (Hydrogen Detector Environment Evaluator) test facility [2], were installed at four locations, three on the ceiling and one on a wall. The catalytic-type sensors used have a range of nominally 0 % to 2.5 % hydrogen concentration, produce a voltage signal proportional to the concentration, and have a typical 90 % response time (T-90) of 2 s. The manufacturer-reported relative uncertainty for the sensors is ± 3 % (two standard deviations). The data scan rate was 1 Hz. Table 1 lists the positions of the sensors for which results will be discussed in this paper. Figure 2 shows a 3D drawing with the approximate locations of the sensors. Figure 3 is a top view drawing of the garage layout with sensor locations shown.

Forming gas is a readily-available compressed gas mixture containing about 5 % hydrogen with the balance nitrogen. The volume of the garage was approximately 93 m^3, and an A1-size cylinder of forming gas contains approximately 0.32 m^3 (at STP) of hydrogen (6.3 m^3 total volume consisting of 5 % hydrogen and balance nitrogen). Injecting 3 cylinders of forming gas, and assuming injected gas displaces garage air, a well mixed hydrogen concentration of about 0.8 % would be achieved with a reduction in oxygen concentration from 21 % to 17 %. The sensors selected to measure the hydrogen concentration were catalytic-bead type sensors which require oxygen to respond to the target hydrogen gas. These sensors operate properly at oxygen concentrations greater than 5 %, therefore they were appropriate for the forming gas experiments. Metal oxide silicon type sensors were not used because they are sensitive to changes in oxygen concentration and would experience a significant calibration shift due to the oxygen concentration reduction caused by a release of forming gas [3,4].

The forming gas was dispersed by a 0.09 m^2 (30 cm sides × 6.4 cm high) steel open-top dispersion box with a gas inlet at the bottom, and the upper half filled with gravel to evenly distribute the flow over the open top area. The dispersion box was located in the center of the garage on the floor. The purpose of the dispersion box was to provide a defined area source for the gas injection into the garage space. A scoping experiment (#1) was conducted using a different size dispersion box (a so-called sand burner, typically used in fire experiments to produce area flame sources from gaseous fuels). For each experiment, the dispersion box was supplied with forming gas (nominally 5 % H_2, 95 % N_2) from three 1A-size gas cylinders. The forming gas was supplied at 376 kPa (40 psig) at 350 L/min (standard conditions) using two mass flow controllers. For the 0.09 m^2 dispersion box, the average exit gas velocity was 6.5 cm/s which provided a very low level of plume momentum, confirmed by a Richardson number, *Ri*, of about 60 at the top. Gas was released for 43 min in each experiment. Experiments 1 and 4 were conducted with no car in the garage. A car was parked near the center of the garage for experiments 2 and 3. The car was a mid-sized passenger sedan with gross dimensions of 4.86 m long, 2.79 m wide, and 1.39 m high. The car represents a typical source of a hydrogen leak, an on-board hydrogen storage tank. All of the experiments were conducted with the garage door (North), walk-in doors (South and East walls), and windows (South and West walls) closed. The West wall window, which had a fan installed for clearing the garage after experiments, was sealed with a fitted piece of drywall and taped joints.

Figure 1. Photograph of the garage used for hydrogen release studies.

Table 1. Sensor locations.

Sensor Name	Key	Sensor Description	Distance (m) from				
			East Wall	West Wall	North Wall	South Wall	Floor
CCeil	●	H_2, near center of ceiling	2.69	2.69	2.79	3.99	2.44
WCeil	●	H_2, near center of West wall at ceiling	4.47	0.91	2.79	3.99	2.44
SCeil	●	H_2, near center of South wall at ceiling	2.59	2.79	5.87	0.91	2.44
EWall	●	H_2, near center of East wall, on wall	0.0	5.38	2.79	3.99	2.13
VProbe	▼	Velocity, near ceiling at Southwest corner	4.33	1.05	5.98	0.80	2.34
THum	■	Temperature and humidity, near ceiling at Southeast corner	1.22	4.17	5.56	1.22	2.29

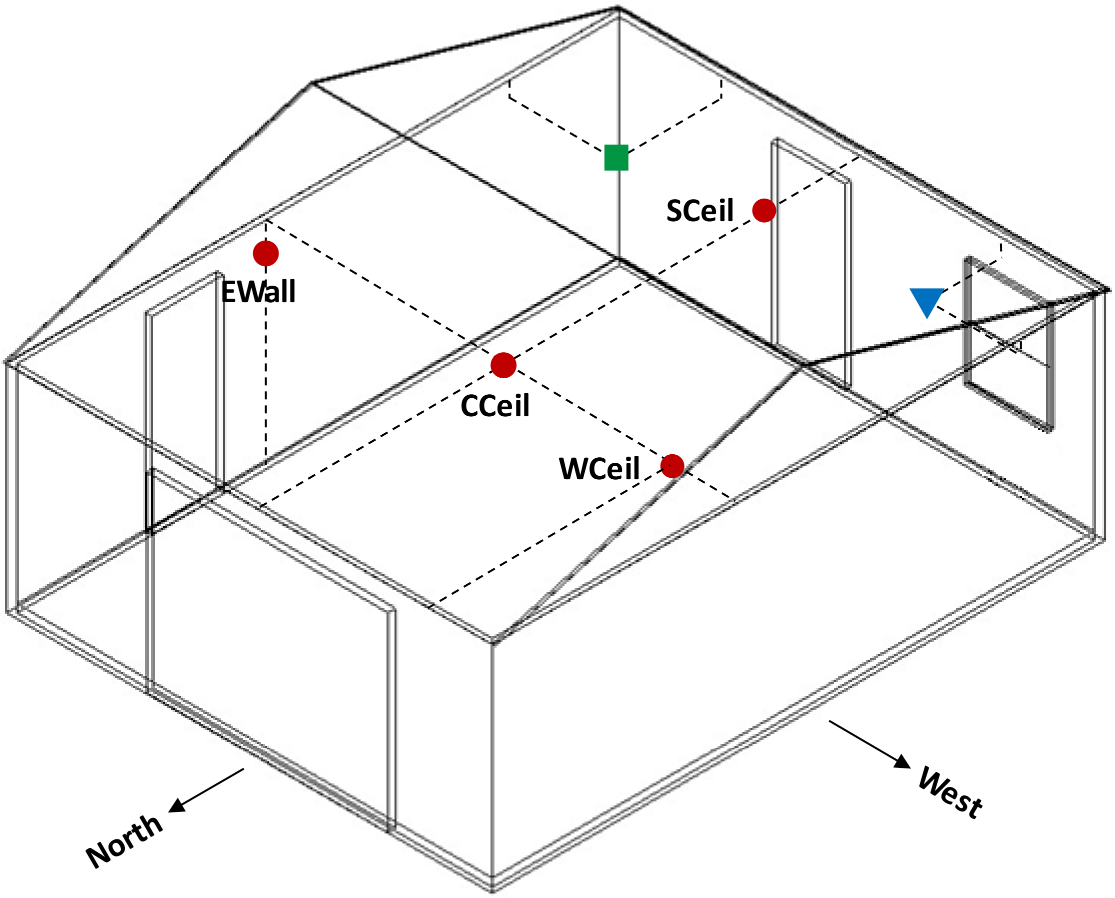

Figure 2. Pictorial drawing of the garage showing doors and sensor locations.

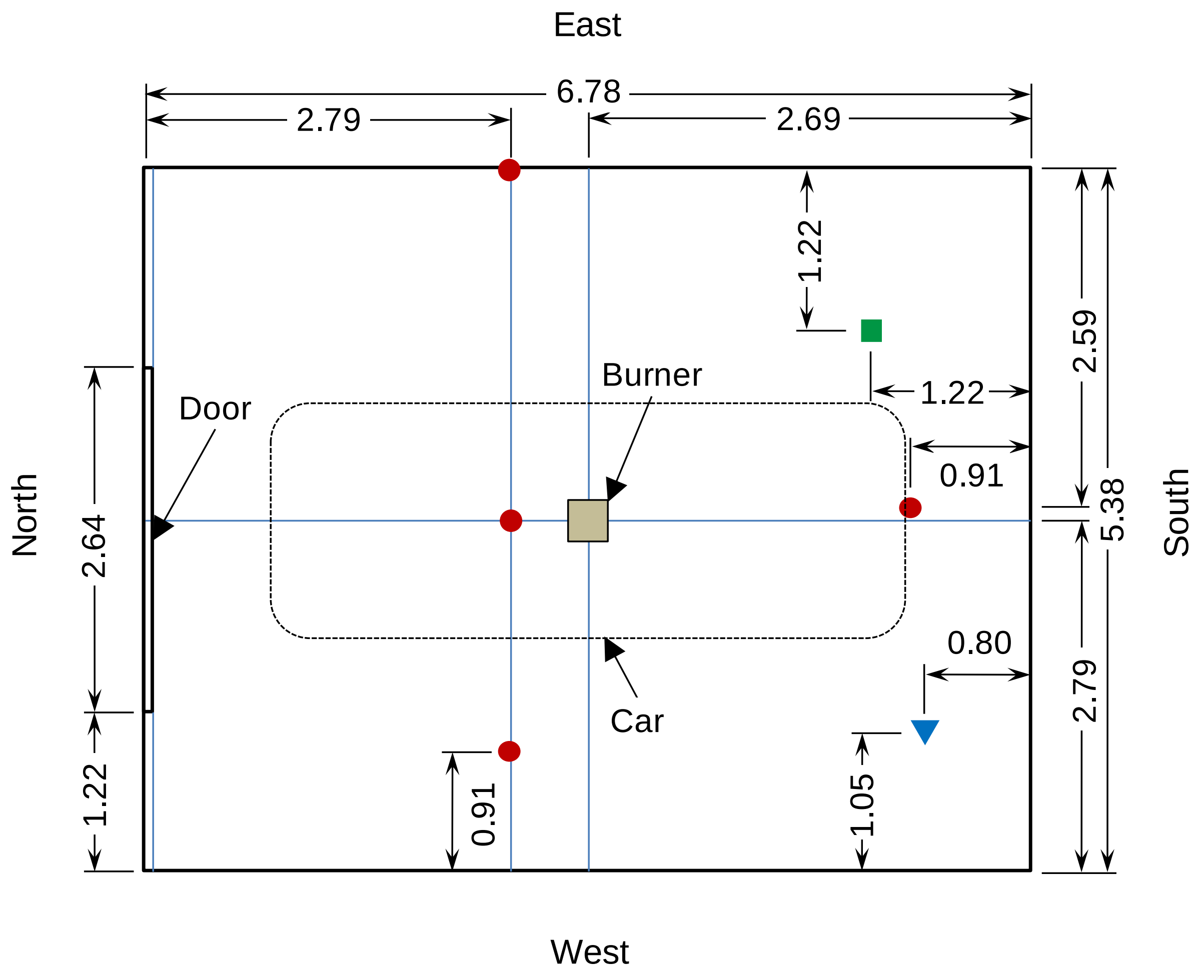

Figure 3. Top view diagram of the garage showing dimensions (m) and locations of the key sensors.

3.0 EXPERIMENTAL RESULTS AND DISCUSSION

Results from experiments 2 to 4 are shown and discussed here. Experiment 1 differed from experiment 4 only by use of a different dispersion box. The results for those two experiments were not significantly different so experiment 1 is not included in subsequent discussion. The responses of the four hydrogen sensors deployed in each experiment were compared to determine the spread and mixing of the hydrogen by the relative timing and concentrations at the various locations. Also, the results from experiment 4 (no car) were compared with those from 2 and 3 to determine the effect of the parked car. In addition, the results from experiments 2 and 3 were compared for reproducibility of the hydrogen spread under the identical set up (car parked in the garage). All of the times plotted are referenced to the time the forming gas release was started.

Figure 4 is a plot of the hydrogen volume fraction at the four sensor locations plotted versus the time elapsed since the forming gas release was initiated during experiment 4 when there was no car present in the garage. For the no-car case, the expectation was for the buoyancy-driven plume of forming gas to rise uninterrupted to the central ceiling area and then spread outward uniformly toward the garage walls, where the ceiling jets would be directed downward. Some entrainment of air and dilution of the plume was expected as it rose along with further mixing and formation of a ceiling layer as the plume was redirected and divided across the ceiling and down the walls. The data for this experiment shows that the initial hydrogen sensor responses at the different locations were 19 s, 29 s, 40 s, and 49 s for the central ceiling, West ceiling, South ceiling, and East wall, respectively. The central ceiling location hydrogen level peaked at just over 1 % at about 43 min (2580 s). The other sensor locations peaked at lower levels between 0.85 % and 0.88 %, also at about 43 min (2580 s). The sharp drop off in concentration at the central ceiling location at 2591 s was due to the stoppage of the forming gas flow about 30 s earlier. Without the car to divert and mix the plume, the sensor responded sharply to any change in the plume. The hydrogen measurements seemed consistent with the expected behavior of the forming gas release.

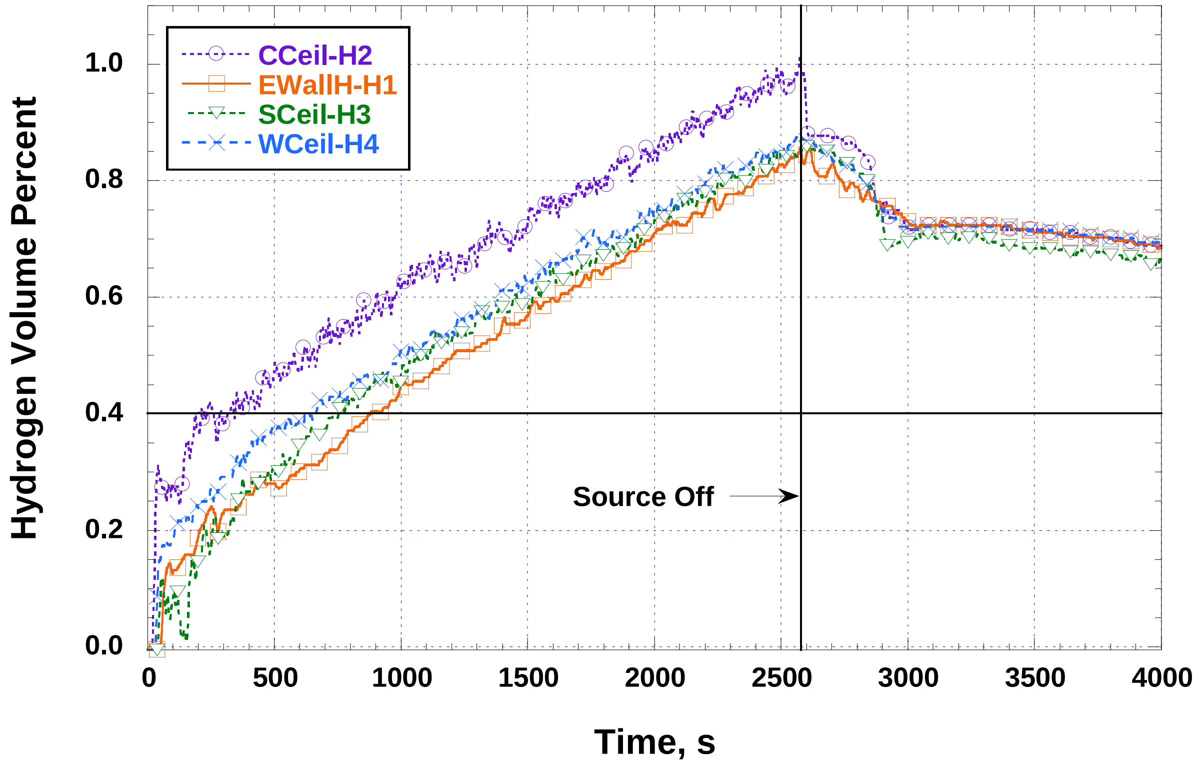

Figure 4. Hydrogen volume fraction at four locations plotted versus time from initial release for experiment 4 with the garage empty (relative uncertainty is 3% of reading).

Figure 5 is a plot of the hydrogen volume fraction at the four sensor locations plotted versus the time elapsed since the forming gas release was initiated during experiment 2 with a car parked in the garage. The West ceiling sensor responded first, within about 10 s. The center ceiling sensor responded at 57 s, followed by the South ceiling sensor at 70 s, and the East wall sensor at 84 s. All three ceiling sensors responded within 1 min of each other while the hydrogen was slightly delayed in reaching the wall sensor due to the time required for the ceiling layer to drop 30 cm from the ceiling. The plot also shows the hydrogen concentration rate of increase to be less at the wall location than at the ceiling locations until about 440 s when it began to match the others. The wall and ceiling locations experienced similar maximum gas concentrations between 0.7 % and 0.74 %. Hydrogen concentrations at the three ceiling locations peaked in the period from 41 min (2500 s) to 50 min (3000 s), while the wall location value peaked at about 55 min (3300 s).

Figure 6 shows the same sensor responses as Figure 5 except the results are for experiment 3. A car was again present in the garage. In this case, the central ceiling sensor was the first to respond at 58 s after the hydrogen release was started. The East wall sensor, South ceiling sensor, and West ceiling sensor responded closely together at 80 s, 85 s, and 90 s, respectively. Hydrogen peaked between 0.6 % and 0.7 % at all of the sensors in the 44 min (2600 s) to 50 min (3000 s) timeframe, except for the South ceiling sensor which peaked at about 59 min (3500 s). While experiments 2 and 3 were supposed to be identical, the results differed slightly in maximum concentration and more so in the order in which the locations initially experienced increases in hydrogen. The results were consistent in that the presence of the car tended to disperse the forming-gas plume such that the central ceiling sensor was not exposed to hydrogen significantly earlier than the sensors at peripheral locations. The diverted and dispersed plume caused additional mixing compared to the no-car case which resulted in

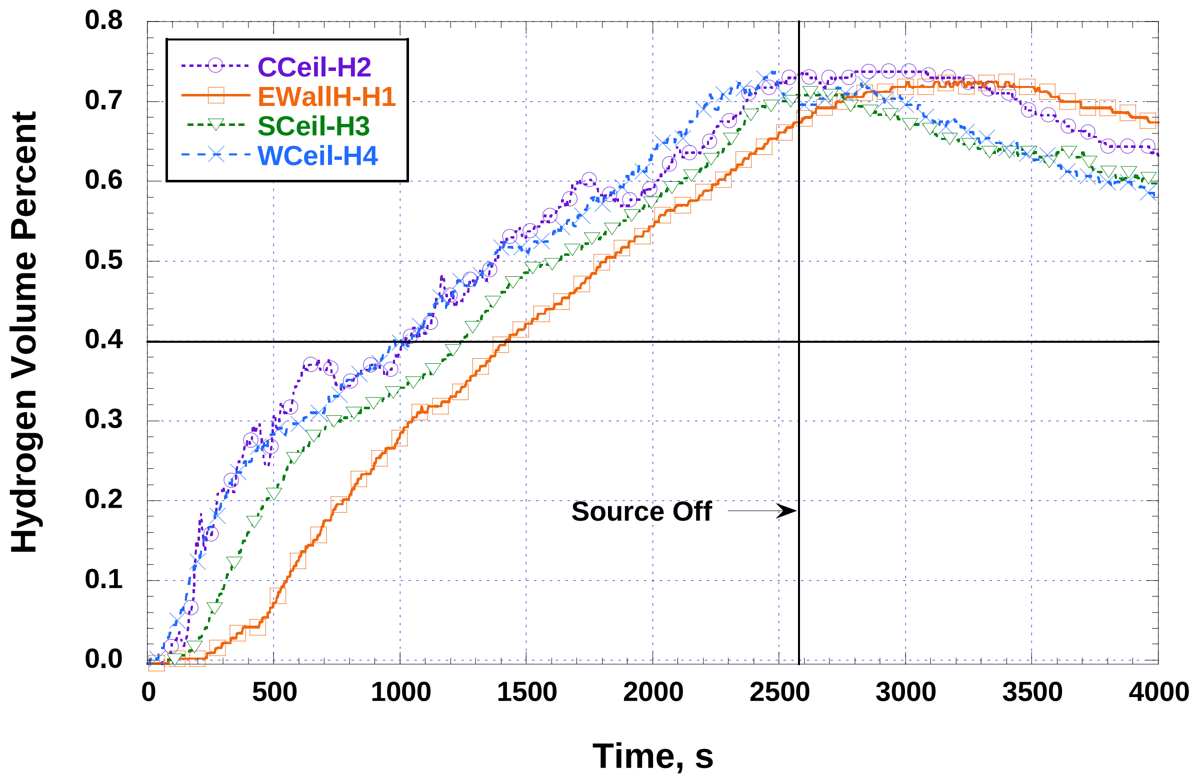

Figure 5. Hydrogen volume fraction at four locations plotted versus time from initial release for experiment 2 with a car (relative uncertainty is 3% of reading).

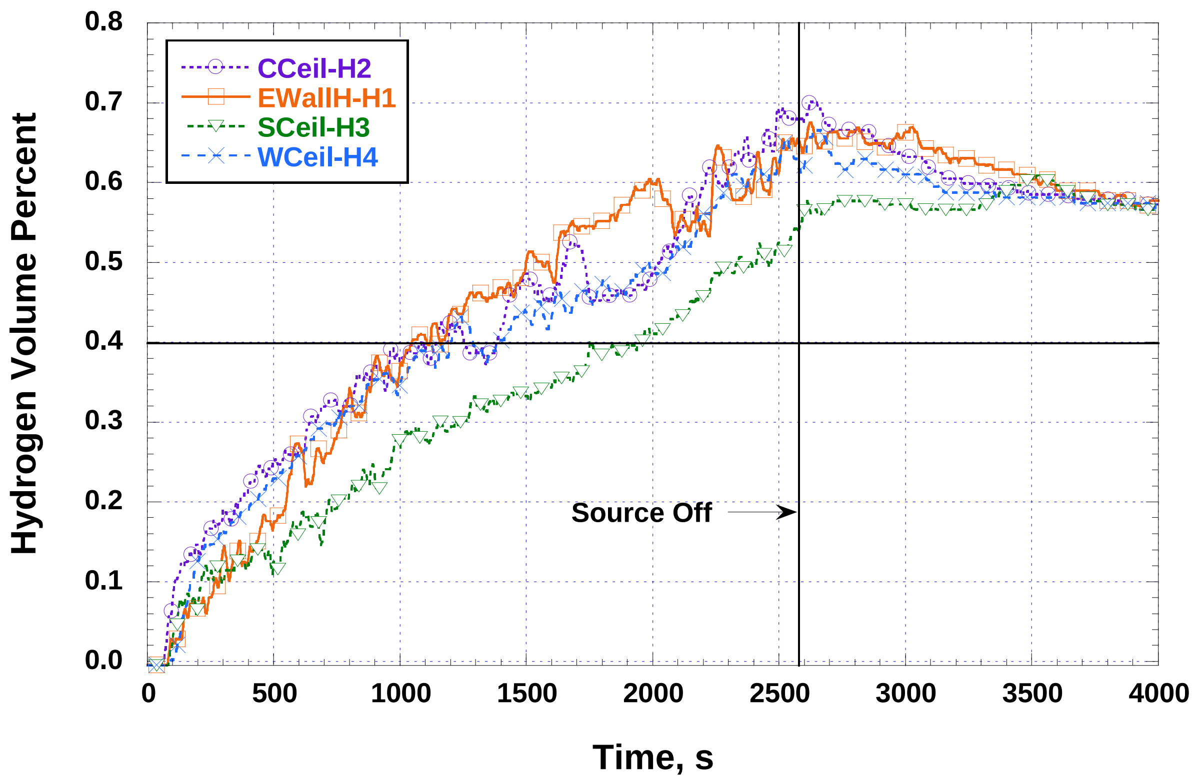

Figure 6. Hydrogen volume fraction at four locations plotted versus time from initial release for experiment 3 with a car (relative uncertainty is 3% of reading).

lower peak hydrogen concentration. The unpredictability of the forming gas spread to various sensor locations could be due to different environmental conditions between the two experiments which were conducted on different days. Variations in wall temperatures due to weather-specific external heating could affect convective currents in the garage. Also, external wind variations could cause differences in forced currents within the garage.

The differences between the experimental results without a car in the garage and those with a car are clear. With the car in place, the flow dynamics are less obvious than without. With the car present, the underside of the car filled with forming gas causing a delay for the gas to reach the ceiling, and then the gas flowed out from the sides causing enhanced mixing by the distributed flow. With no car to block it, the central ceiling sensor experienced the plume earlier than those at the other locations and eventually saw a hydrogen concentration about 15 % higher than the others. The sensors at the peripheral locations sensed dispersed ceiling jets rather than the main buoyant plume, and the greater travel distance provided the forming gas more opportunity to become mixed and diluted with air.

Figure 7 is a plot of the hydrogen volume fraction at the central ceiling sensor location as a function of time from release for experiments 2 to 4. This plot shows consistency at that location for the two experiments with the car present. The absence of the car allowed a much higher hydrogen concentration to be produced at the central ceiling position. Figure 8 is a similar plot to Figure 7, but for the West ceiling position. It shows a little less consistency for the hydrogen concentrations at the West ceiling location for the two experiments with the car, but the concentration without the car was still higher than with the car. Figure 9 shows similar hydrogen behavior at the South ceiling position to that at the West ceiling position for the three experiments. Figure 10 shows the relative concentration trends with time for the three experiments at the East wall location. The plot shows lower concentrations and smoothed peaks due to mixing for the two experiments with the car compared to higher concentration and sharp response for the experiment without the car.

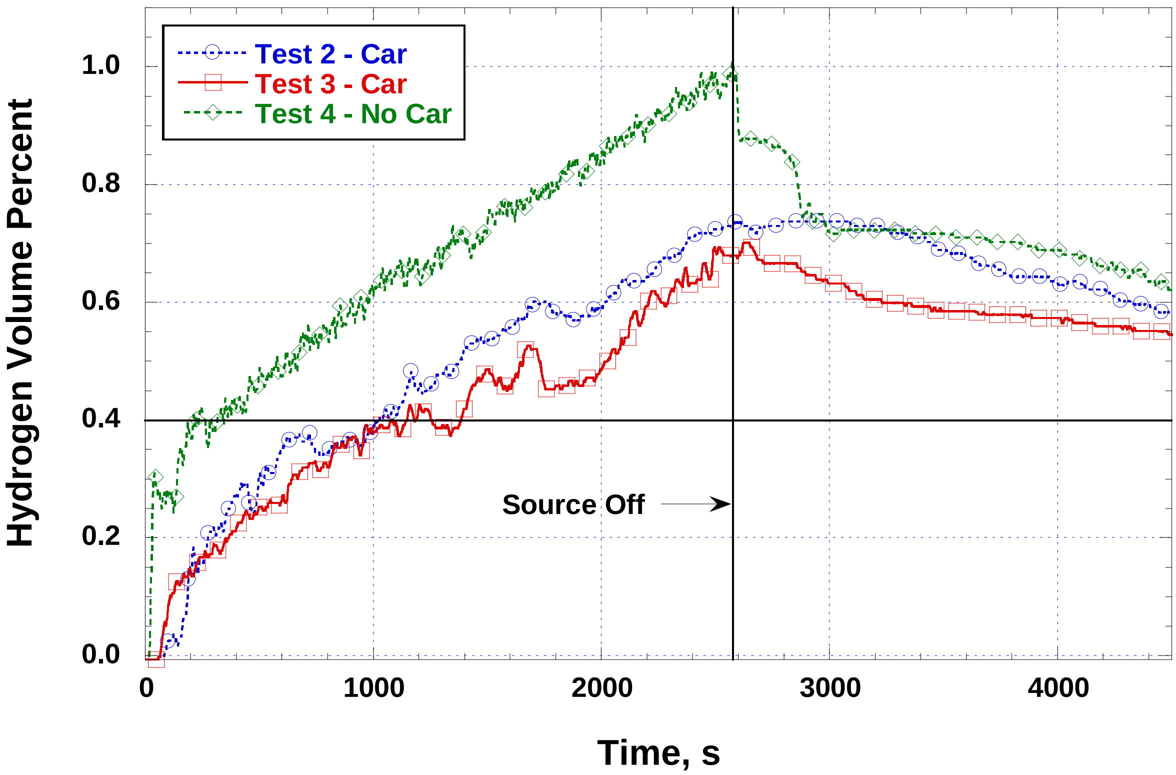

Figure 7. Hydrogen volume fraction at the central ceiling location plotted versus time from initial release for experiments 2 to 4 (relative uncertainty is 3% of reading).

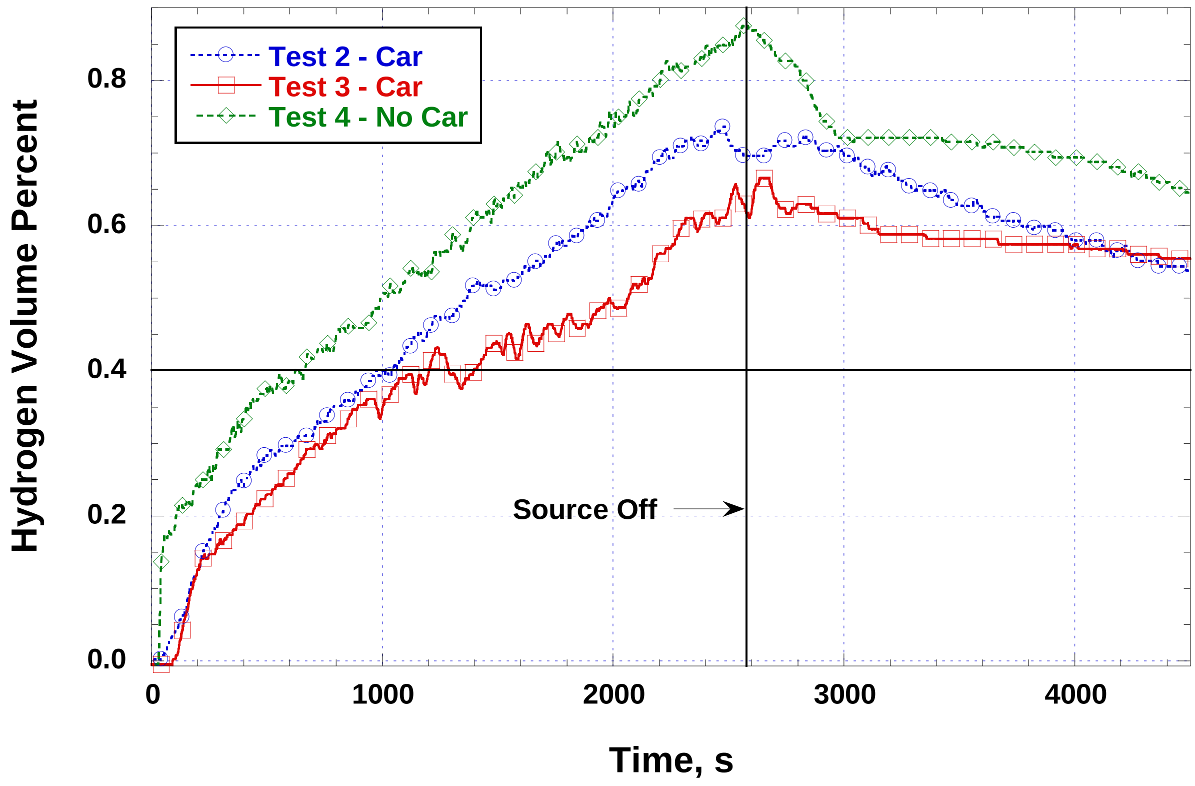

Figure 8. Hydrogen volume fraction at the West ceiling location plotted versus time from release for experiments 2 to 4 (relative uncertainty is 3% of reading).

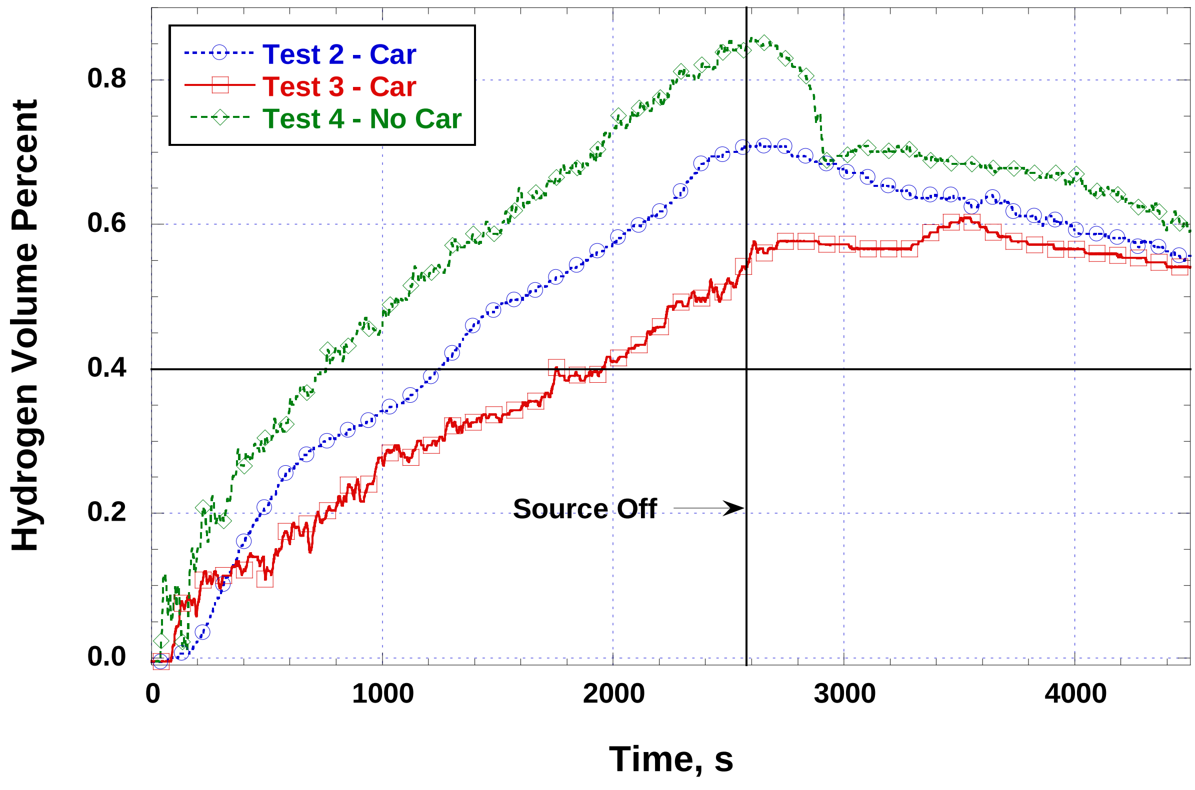

Figure 9. Hydrogen volume fraction at the South ceiling location plotted versus time from initial release for experiments 2 to 4 (relative uncertainty is 3% of reading).

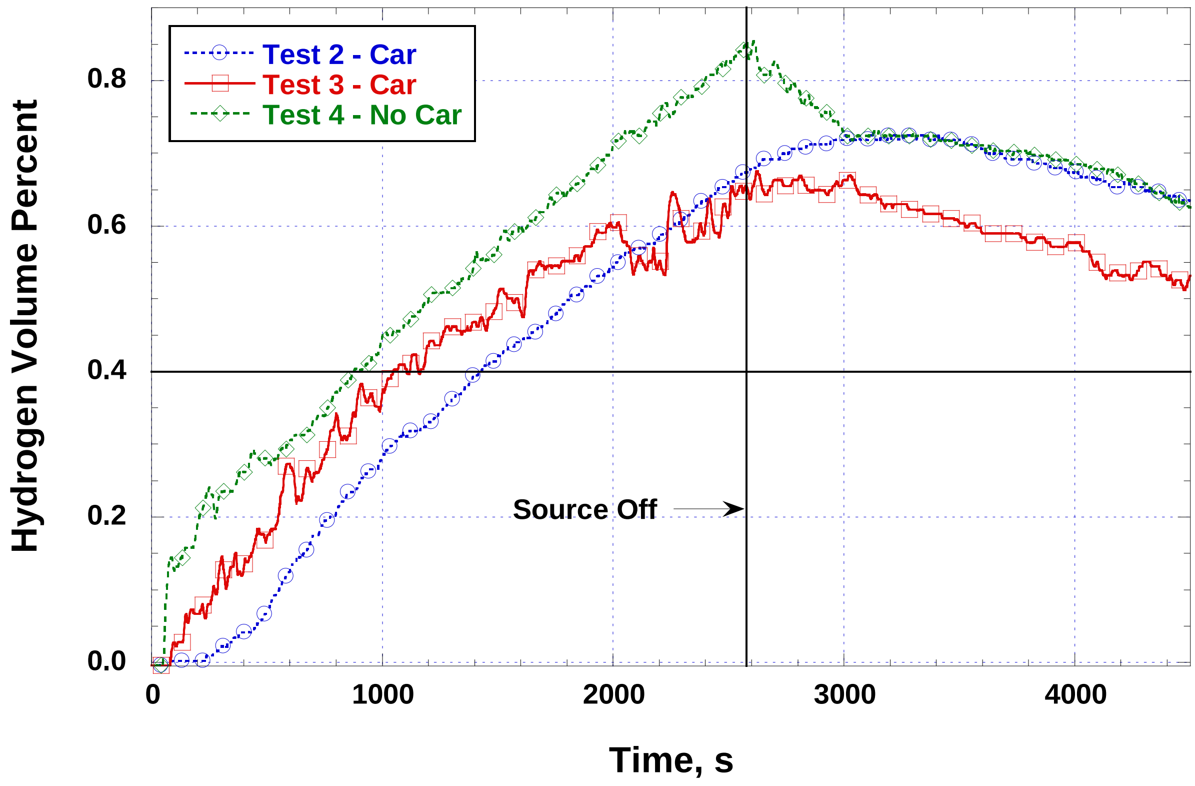

Figure 10. Hydrogen volume fraction at the East wall location plotted versus time from release for experiments 2 to 4 (relative uncertainty is 3% of reading).

Figure 11 is a plot of the total (combined directions) air speed measured at the Southwest ceiling location velocity probes. The speed is the square root of the squares of the two velocity components (North-South and East-West). A 57 point (about a 1 min window) smoothing algorithm (locally weighted least squares regression) was applied to the data to show the trends amidst frequent large fluctuations. The plot shows that there is a negligible effect of the forming gas release on the ambient flows near the ceiling of the garage. There appears to be a slightly higher ceiling flow speed during experiment 4, with no car, but the flow speed persists after the gas flow to the dispersion box stops, suggesting external forces (such as wind) during this experiment were producing this larger background flow.

In order to characterize the relative spread of the hydrogen to the various regions of the garage, the data were analyzed for how long it took for the hydrogen level at each location to reach 0.4 %. While this level is somewhat arbitrary, it is 10 % of the lower flammability limit concentration of 4 % and would be a reasonable alarm threshold. Table 2 lists the time after the gas release was initiated for each sensor to be exposed to 0.4 % hydrogen for the three experiments. Uncertainty on the time values is estimated at ± 1 s (two standard deviations). Figure 12 shows a bar graph of the same timing results. The two experiments with the car present show similar relative timing for the central and South ceiling sensor locations, while the West ceiling and East wall locations have reversed timing. The central ceiling sensor for the experiment without the car reached 0.4 % hydrogen in 21 % of the time required during experiment 2, the first experiment with a car. For the experiment without the car, the other sensor locations attained 0.4 % hydrogen between 43 % and 84 % of the time required during either experiment with the car present. The ranges of times for any sensor to arrive at this threshold were about 3.5 min to 14.5 min without the car and about 16 min to 29 min with the car. This shows a dramatic effect of the presence of a car above a low-level leak on hydrogen dispersion within a garage.

Table 2. Timing for sensors to reach 0.4 % hydrogen.

Test No.	Car?	Time to Reach 0.4 % Hydrogen, min:s (s)			
		Central Ceiling	South Ceiling	West Ceiling	East Wall
2	Yes	17:01 (1021)	20:53 (1253)	16:12 (972)	23:39 (1419)
3	Yes	19:08 (1148)	29:11 (1751)	20:02 (1202)	17:28 (1048)
4	No	3:31 (211)	12:34 (754)	10:23 (623)	14:38 (878)

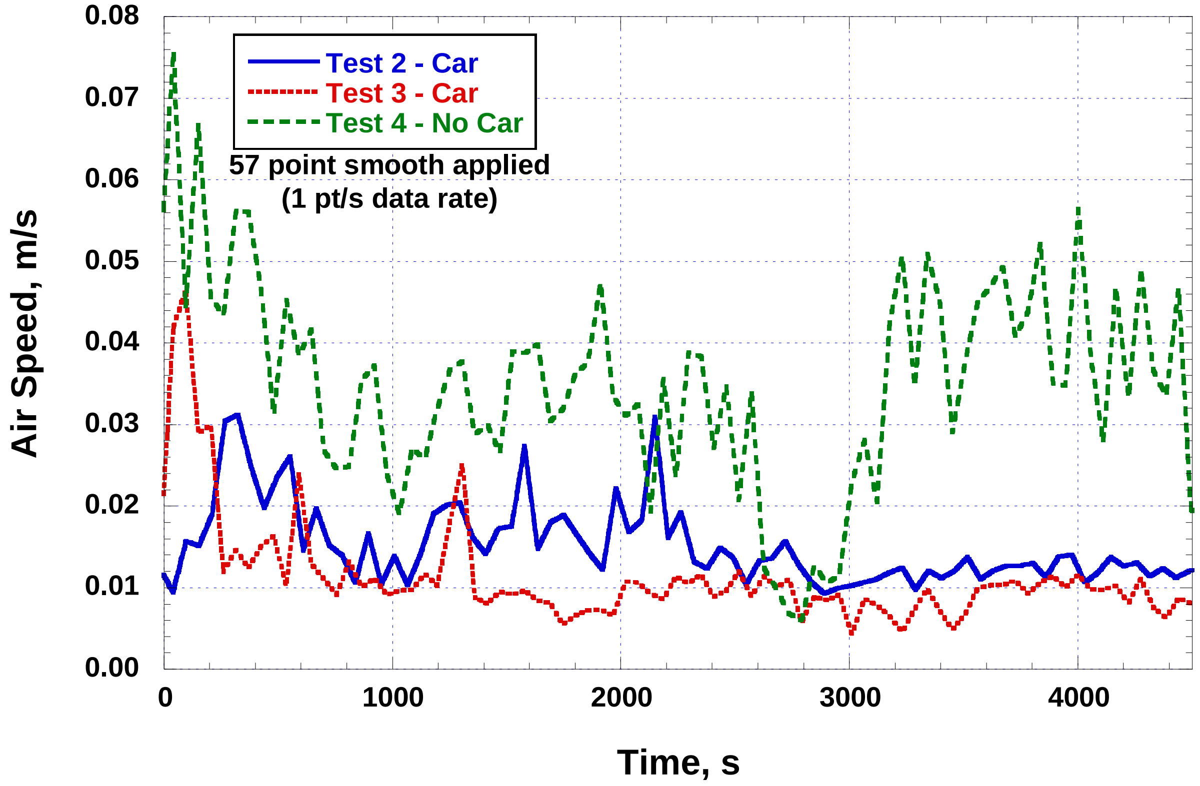

Figure 11. Air speed at the Southwest ceiling location plotted versus time from initial release for experiments 2 to 4. (Standard uncertainty in the speed is 0.01 m/s with a coverage factor of 2).

The data acquisition system continued to collect data for experiment 2 for almost 16 h overnight. During that time, the garage was undisturbed, thus hydrogen leaked out small openings around doors, and diffused through the walls and ceiling. Figure 13 shows that the hydrogen concentrations measured by the sensors over this period decayed in an exponential manner. An analysis of the sensor data using regression fits of the form e^{-kt} where k is the number of air changes per hour resulted in a range of 0.31 h^{-1} to 0.43 h^{-1}, depending on which sensor was used [5]. The average air change rate for all of the sensors was 0.37 h^{-1} for the garage. The differences could be related to diurnal temperature changes, changing garage boundary conditions, the effects of external wind magnitude and direction, and mild stratification.

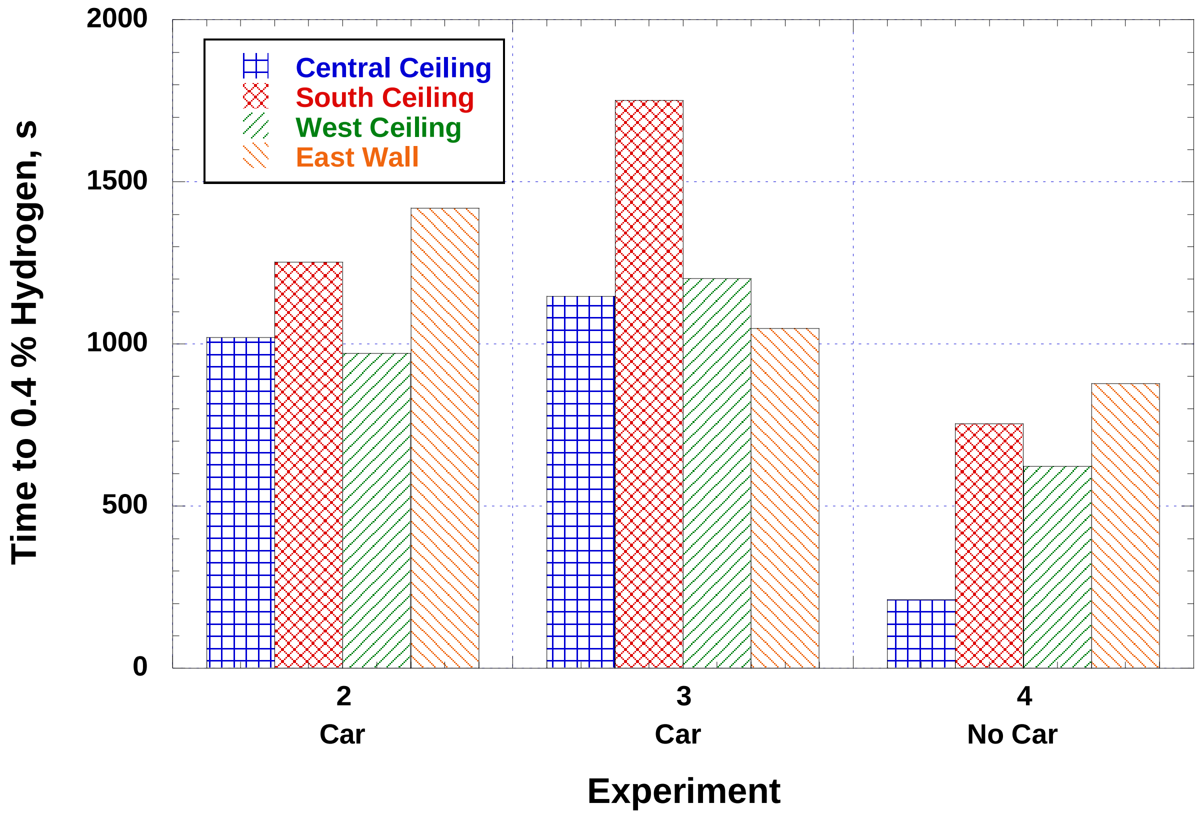

Figure 12. Time for hydrogen levels to reach 0.4 % at each sensor location for each experiment.

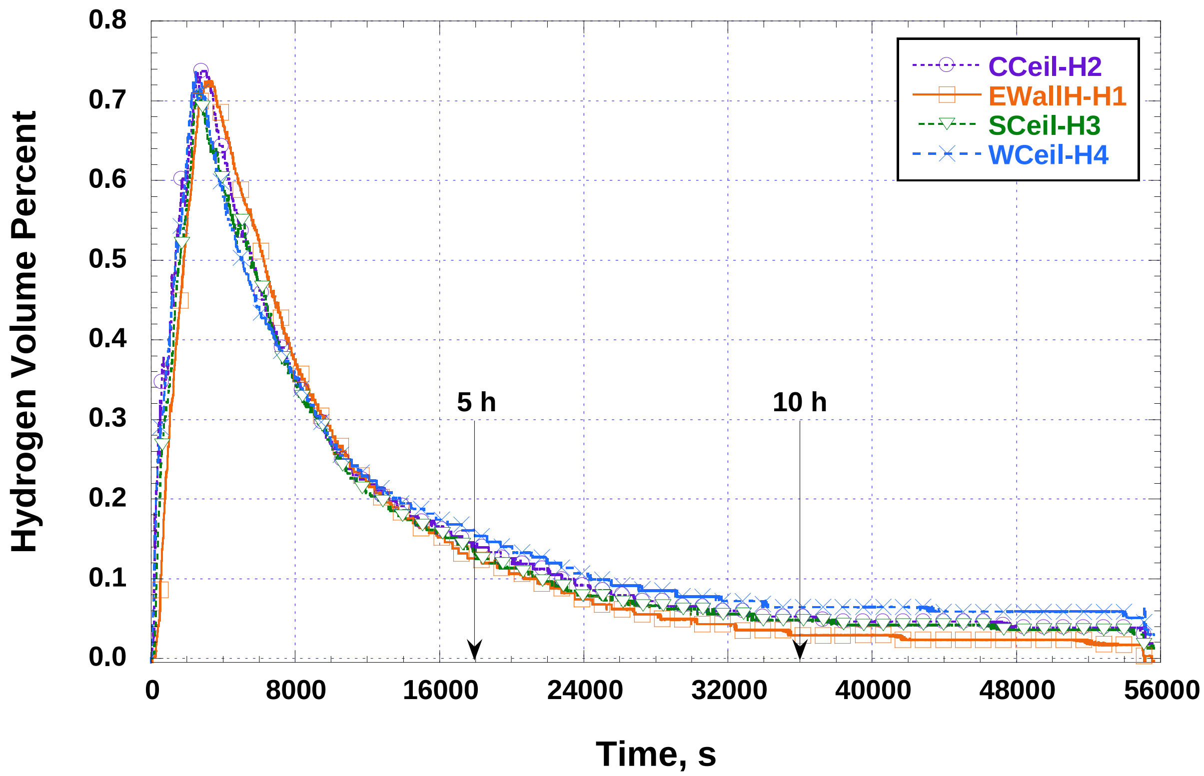

Figure 13. Hydrogen volume fraction plotted versus time from initial release for experiment 2 with a car (relative uncertainty is 3% of reading).

4.0 CONCLUSIONS

The experiments conducted showed that a low level hydrogen leak can be detected in a typical unventilated garage space. The main effects of a car placed over the dispersion box releasing forming gas were to decrease the peak concentration of hydrogen measured by 25 %, produce a less predictable distribution of hydrogen at the sensor locations, and take considerably more time to reach a threshold of 0.4 % hydrogen compared to the no-car case. The time to reach a threshold of 0.4 % hydrogen for experiments with a car in place varied between about 1000 s to 1800 s. The central ceiling sensor location is definitely preferable in the no-car case and seems to be marginally preferable with the car present as well. Generally in a given space, a sensor should be placed directly above a location where there is a potential hydrogen source which could form a localized plume similar to the no-car case. There appears to be no obvious or consistent advantage in sensor placement between the other (non-central) ceiling and wall locations. Based on these experiments, if only one sensor is to be deployed to alarm for a vehicle-based hydrogen leak, the ceiling area above the parked vehicle seems to be slightly preferable, while a sensor located lower than the ceiling would lead to delayed detection of hydrogen.

5.0 ACKNOWLEDGMENTS

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6.0 REFERENCES

1. Nabinger, S.J. and Persily, A.K., “Airtightness, Ventilation, and Energy Consumption in a Manufactured House: Pre-Retrofit Results,” NIST Technical Note 7478, U.S. Department of Commerce, Washington DC, May 2008.
2. Marsh, N.D., and Cleary, T.G., “Testing the Performance of Hydrogen Sensors,” AUBE ‘09, 14th International Conference on Automatic Fire Detection, Duisburg, Germany, September 8-10, 2009.
3. Coles, G., Williams, G., Smith, B., “The Effect of Oxygen Partial Pressure on the Response of Tin (IV) Oxide Based Gas Sensors,” J. Phys. D: Appl. Phys., **24**, pp. 633-641, 1991.
4. Cukrov, L., McCormick, P.l, Galatsis, K., Wlodarski, W., “Gas Sensing Properties of Nanosized Tin Oxide Synthesised by Mechanochemical Processing,” Sensors and Actuators B, **77** pp.491-495, 2001.
5. Sherman, M. H., “Air Infiltration Measurement Techniques,” LBL-27656, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, 1998.