Proceedings of the 2000 DOE Hydrogen Program Review
NREL/CP-570-28890

Dispersion of Hydrogen Clouds

Michael R. Swain
Eric S. Grilliot
Matthew N. Swain
University of Miami
Coral Gables, FL 33124

Abstract

The following is the presentation of a simplification of the Hydrogen Risk Assessment Method previously developed at the University of Miami. It has been found that for simple enclosures, hydrogen leaks can be simulated with helium leaks to predict the concentrations of hydrogen gas produced. The highest concentrations of hydrogen occur near the ceiling after the initial transients disappear. For the geometries tested, hydrogen concentrations equal helium concentrations for the conditions of greatest concern (near the ceiling after transients disappear). The data supporting this conclusion is presented along with a comparison of hydrogen, LPG, and gasoline leakage from a vehicle parked in a single car garage. A short video was made from the vehicle fuel leakage data.

Simplification of the Hydrogen Risk Assessment Method to reduce the need for CFD modeling.

A method is being developed that can be used to determine the potential health and safety implications of a hydrogen release. The method allows the user to establish changes to venting in buildings and home refueling areas to minimize or eliminate any serious threats. Additionally, the method can be used to determine optimum hydrogen sensor locations for active safety systems. It is the objective of this portion of the work to simplify the risk assessment method to eliminate or reduce the need for computer modeling in the method.

Gaseous fuel escapes can be classified by enclosure geometry and a hydrogen flow quantity description. This is done as follows:

1. Gas escapes into enclosed spaces
    a. Total volume of escaped hydrogen.
    b. Flow rate of escaping hydrogen.
2. Gas escapes into partially enclosed spaces.
    a. Total volume of escaped hydrogen.
    b. Flow rate of escaping hydrogen.
3. Gas escapes into unenclosed spaces.
    a. Total volume of escaped hydrogen.
    b. Flow rate of escaping hydrogen.

General descriptions of the type of risks incurred can be made for each of the above mentioned classifications. For leaks into enclosed (non-vented) spaces, the risk incurred is most strongly affected by the total volume of hydrogen escaping rather than the flow rate of hydrogen escaping. This is because ignition can occur soon after the gas escape begins or be delayed. The overpressure created by the delayed ignition of an accumulating combustible mixture typically produces a greater risk than does early ignition resulting in a standing flame.

Ignition early in the escape results in a burning jet or standing flame. The size of the standing flame is dependent on hydrogen flow rate.

If ignition is delayed, the magnitude of the potential overpressure, due to ignition of the accumulating combustible mixture, is a function of the gas motion in the enclosed space. The escaping hydrogen will rise to the ceiling (or any overhead barrier) within seconds and then diffuse back toward the lower section, which takes hours. If the total volume of hydrogen escaping is less than 4.1% of the volume of the enclosure, the resulting risk of combustion will decrease to zero as the hydrogen becomes homogeneously distributed into the enclosure. If the total volume of hydrogen escaping is greater than 4.1% of the volume of the enclosure, the resulting risk of combustion will continue until the enclosure is vented or combustion occurs.

For leaks into unenclosed spaces, the risk incurred is most strongly affected by the flow rate of the hydrogen escape rather than the total volume of hydrogen escaped. Without an enclosure, hydrogen rises and the risk of hydrogen accumulation is removed. For hydrogen escaping into an unenclosed space, steady state combustible gas cloud size is typically reached within 15 seconds. If the hydrogen flow is stopped, combustible mixtures of hydrogen are typically gone in 10 seconds. The risk of large overpressures caused by ignition of the hydrogen-air mixture is small due to the lack of an enclosure to constrain the expanding products of combustion. Additionally, the hydrogen jet produced is very inhomogeneous and the volume of hydrogen-air mixtures that produce high flame speeds is typically small. It is near stoichiometric and rich mixtures of hydrogen and air that burn rapidly enough to produce appreciable overpressures.

For leaks into partially enclosed spaces (buildings with vents) the risk incurred is affected by the total volume of hydrogen escaping and the flow rate of escaping hydrogen. The relative importance of the total volume and flow rate is dependent on the geometry of the partially enclosed space and the location of the hydrogen escape. Proper design of the partial enclosure reduces the risk incurred due to hydrogen escape.

Hydrogen's low density causes it to rise after escaping from a container or conduit. Vents near the top of the enclosure can allow hydrogen to exit the enclosure efficiently, as long as vents are also provided near the bottom of the enclosure. Vents near the bottom of the enclosure allow fresh air to enter and replace the hydrogen enriched mixture exiting from the top vents. If fresh air must enter through the same vent that the hydrogen is exiting, the efficiency of hydrogen removal is substantially reduced.

The design of ventilation in structures, which might potentially produce partial enclosures for escaping hydrogen, can be facilitated by using a risk assessment method that simulates potential hydrogen escape scenarios with helium escapes. Both hydrogen and helium are low-density gases and behave in similar a fashion when released into partial enclosures. Helium concentrations, versus time, can be measured in the partial enclosure during a simulated hydrogen escape scenario. Last year's work has shown that accurate descriptions of hydrogen behavior can be obtained by creating a verified CFD model using the helium escape data and then using the model to predict hydrogen escape behavior.

The method of risk assessment, previously developed, utilizes four steps.

1. Simulation of the accident scenario with leaking helium (measure helium concentration versus time at various locations while leaking helium at the expected hydrogen leakage rate).
2. Verification of a CFD model of the accident scenario (modeling helium) using the helium data.
3. Prediction of the behavior of hydrogen using the CFD model (modeling hydrogen).
4. Determination of risk from the spatial and temporal distribution of hydrogen.

It appears that by determining the manner in which helium and hydrogen behave in various geometries, it will be possible to directly interpret helium release data, thereby replacing steps 2 and 3 with a simple procedure.

The ongoing work deals with gas escapes into partially enclosed spaces. The spaces investigated were defined as simple enclosures (six-sided rectangular structures). The simple enclosures studied were of the single vent and double vent configuration. A single case of two interconnected simple enclosures was also studied.

General findings were as follows:

1. For simple enclosures, whether single or double vented, the concentration of hydrogen and helium were the same for areas of bulk flow near the ceiling but not in close proximity to the leak origin or a vent. This was particularly true when

steady state conditions were reached. These are the same areas of high concentration and large volume that are of the greatest safety concern. Figure 1 is a plot of 20 data sets representing the helium/hydrogen concentration ratio for all the geometries modeled to date. The data sets are from locations near the ceiling of the enclosures modeled. Half of the enclosures were of the single vent type and half were of the double vent type.

2. For areas near a vent the concentration of either gas (hydrogen or helium) may fluctuate wildly due to instabilities in flow. This is most noticeable in flow up a "chimney". Figures 2 and 3 show the instability when pure hydrogen or helium is allowed to enter the bottom of a 1 by 1 foot chimney that is 6 feet tall. The figures show a surface of constant 5% concentration versus time for helium and hydrogen. The low-density gas (helium or hydrogen) rises, entrains air, and forms a flow that attaches itself randomly to the four walls of the chimney. The concentration at a specific point is not predictable. Therefore, the helium to hydrogen ratio fluctuates wildly and rapidly. Fortunately, the volume of gases affected is typically small compared to the volume of the enclosure.
3. For areas near the leak origin the concentration of either gas (helium or hydrogen) may fluctuate wildly due to instabilities in the flow. However, concentration gradients in a horizontal direction are typically large, near the leak, so stable readings of zero percent helium are generally an indicator of zero percent hydrogen.
4. Regarding the simulation of an accident scenario with helium: if helium detectors are properly placed, or if a sufficient number of helium detectors are employed, measured helium concentrations can be used as a direct indicator of hydrogen concentrations for the high concentration, high-volume locations of most concern.
5. For two interconnected simple enclosures, one above the other, there appears to be more hydrogen in the lower enclosure than would be predicted by helium concentration measurements in the bulk flow near the ceiling.

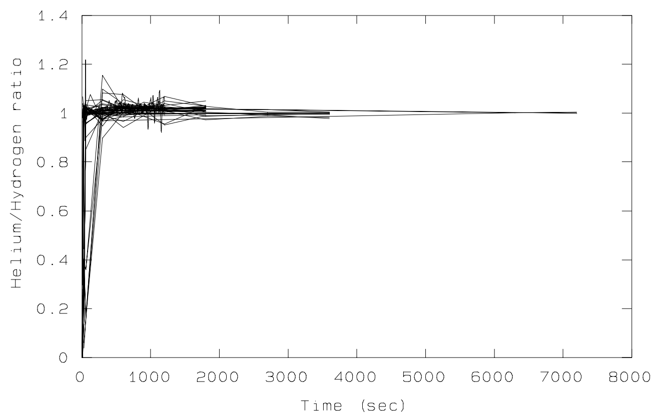


Figure 1 - Data from the 20 enclosures modeled to date. The ratio between helium and hydrogen concentration values near the ceiling are plotted.

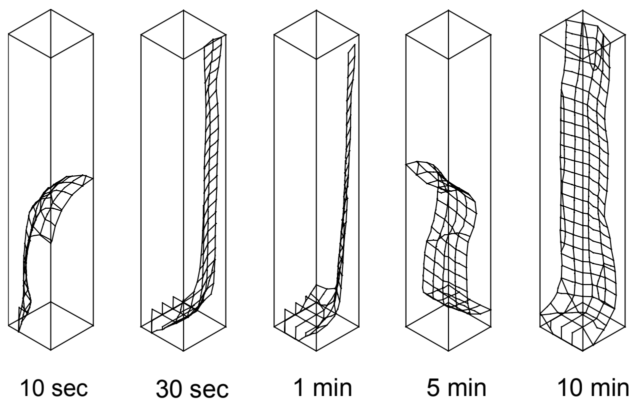


Figure 2– CDF results for helium in chimney

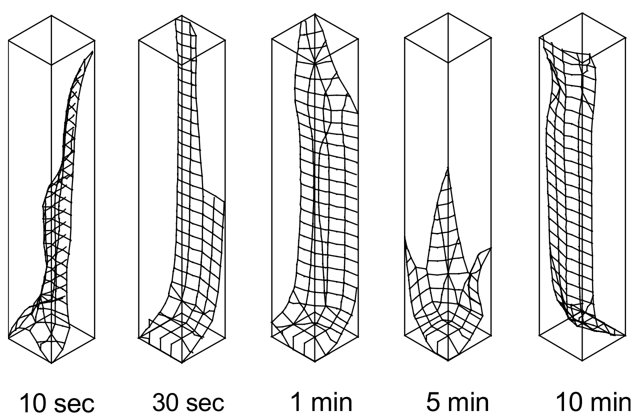


Figure 3 – CDF results for hydrogen in chimney

Explanation of Results

The following experimentally verified computer models of hydrogen leakage into simple enclosures are presented to give examples of the general findings. The results are presented in a schematic of the simple enclosure, and as pairs of graphs: on the left a graph of the ratio of helium to hydrogen concentration at the ceiling and floor, and on the right the percentage concentration of hydrogen at the ceiling and floor. The ratio of helium to hydrogen concentration indicates the accuracy of predicting hydrogen concentrations from measured helium concentrations. Values less than 1.0 indicates under prediction of hydrogen concentrations and would be of greater concern than values greater than 1.0. The graph of hydrogen concentration is presented to show the actual values predicted by the computer model.

The first example is shown in Figures 4 and 5. Fig. 4 shows a single car garage with a single vent in the garage door, and a sheet of plywood mounted above the middle of the floor. The hydrogen is leaking from under the middle of the plywood (all figures are drawn to scale). The hydrogen rose from under the sheet of plywood, and flowed out of the garage door vent while fresh air flowed in the same vent. Hydrogen concentration was higher at the ceiling and lower at the floor. The ratio of helium concentration to hydrogen concentration was approximately 1.0 after 4,000 seconds of leakage. The leakage rate for hydrogen and helium were identical at 7,200 l/hr. As the measured concentration of helium near the ceiling began to stabilize at concentrations above 6%, helium concentration was a good predictor of hydrogen concentration.

Figures 6 through 10 show the effects of increased flow rate on hydrogen concentration and helium to hydrogen concentration ratio, as leakage rate is increased from 7,200 l/hr to 43,200 l/hr. The model shows a home refueling unit leaking in the back of the garage. Note that there were vents at the top and bottom of the garage door to reduce the risks incurred during hydrogen leakage. Separate vents locations, high and low in the room, are more effective than a single vent. Hydrogen concentration increases with leakage rate but doubling the flow rate does not double the concentrations. Helium concentrations near the ceiling are a good predictor of hydrogen concentrations.

Figures 11 through 14 shows the effects of moving a single large vent up and down in the garage door. Though placing the vent low in the garage door increases hydrogen concentrations near the ceiling slightly, little change occurs as long as the vent size does not change. Helium concentrations near the ceiling are a good predictor of hydrogen concentrations.

Figures 15 and 16 show what happens when the leaking unit is placed next to the garage door and the garage door has a single vent across the bottom of the garage door. This is a very inefficient location for a garage door vent. Though hydrogen concentration increases rapidly helium concentrations near the ceiling are still a good predictor of hydrogen concentrations.

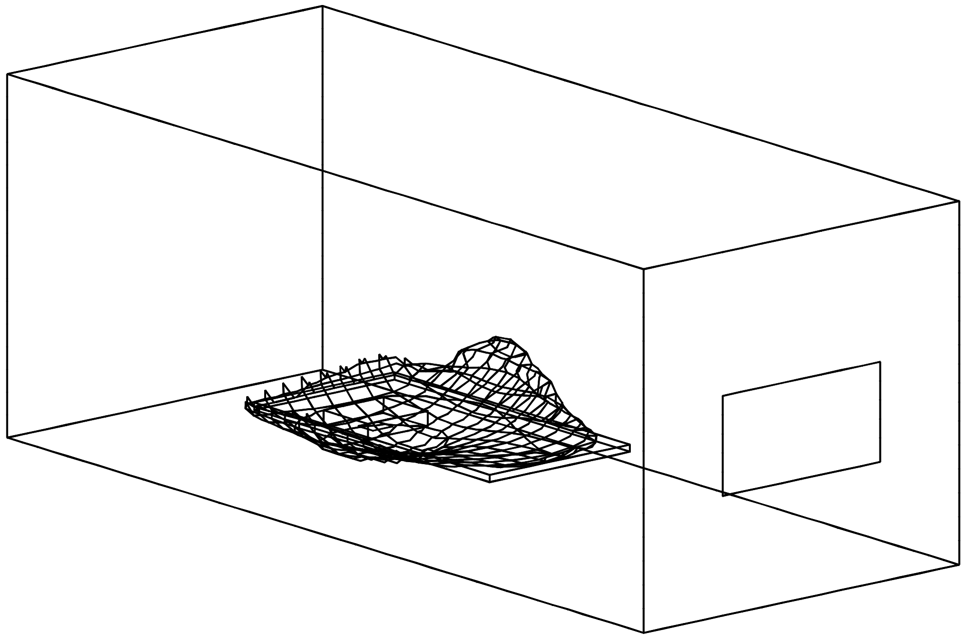


Figure 4 - Surface of constant 6.5% hydrogen concentration after leakage at 7200 l/hr for 25 minutes

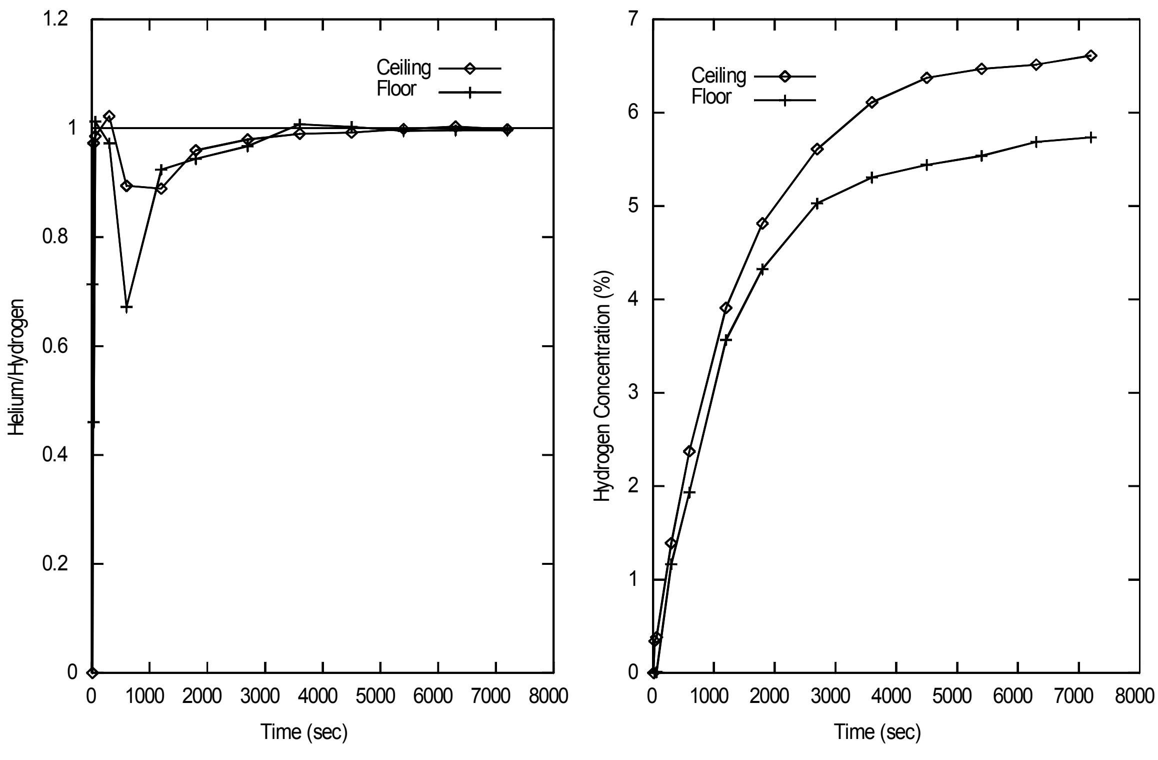


Figure 5 - Leakage in garage. Single vent garage door. Plywood in center of floor. Leakage rate: 7200 l/h

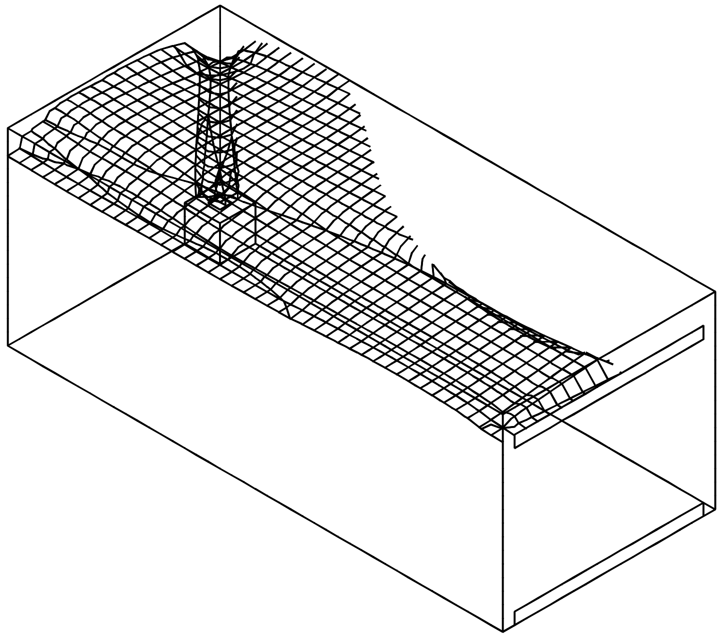


Figure 6 - Surface of constant 1.7% hydrogen concentration after leakage at 7200 l/hr for 10 minutes

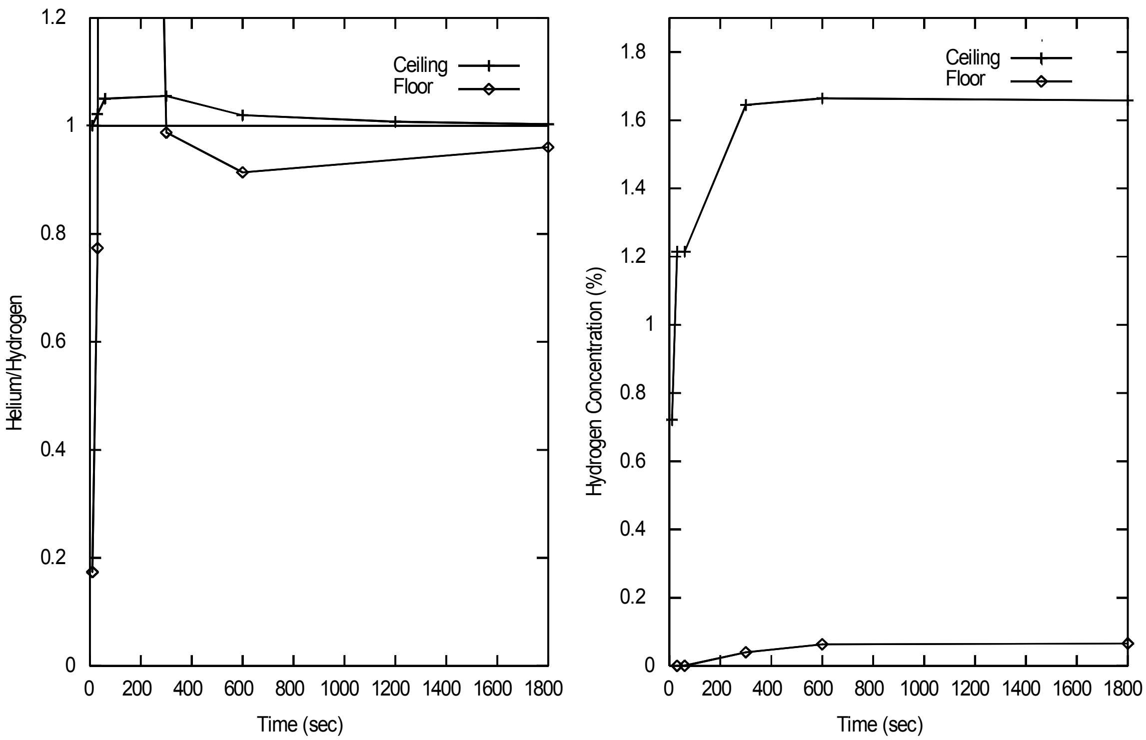


Figure 7 - Leakage in garage. Double vent garage door. Home refueling unit opposite garage door. Leakage rate: 7200 l/hr

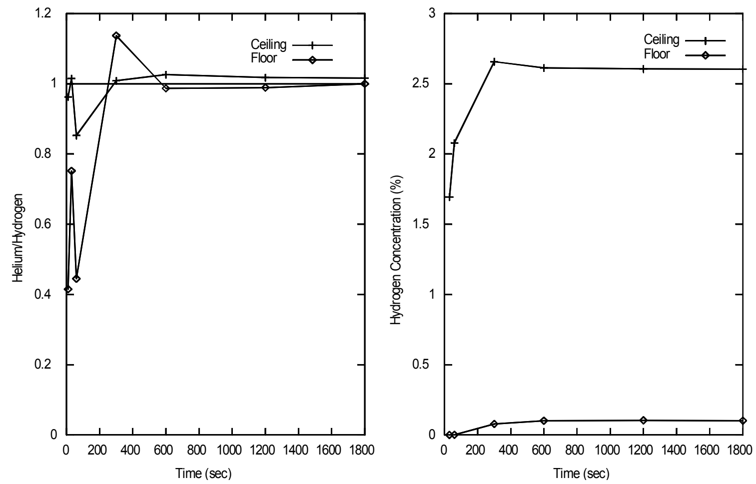


Figure 8 - Leakage in garage. Double vent garage door. Home refueling unit opposite garage door. Leakage rate: 14,400 l/hr

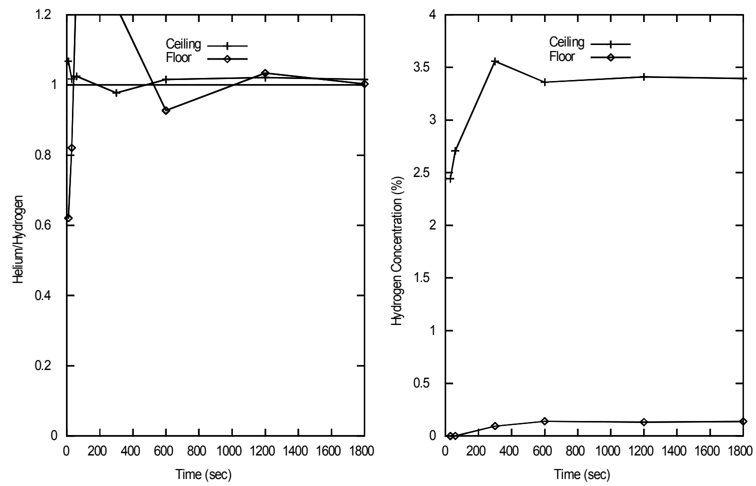


Figure 9 - Leakage in garage. Double vent garage door. Home refueling unit opposite garage door. Leakage rate: 21,600 l/hr

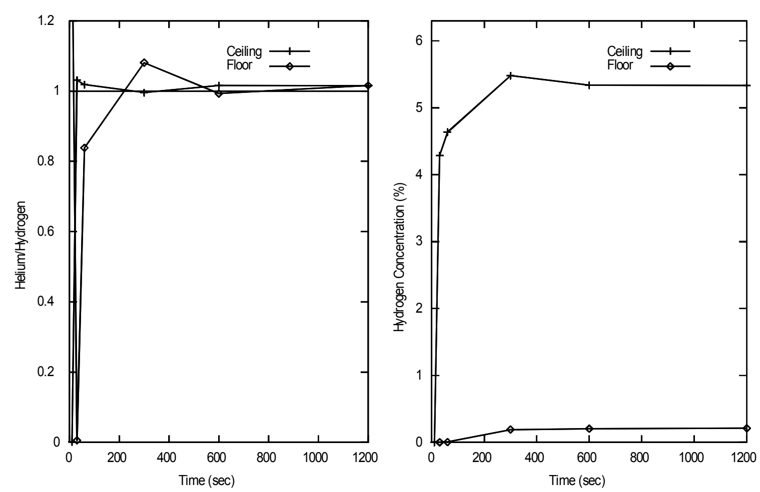


Figure 10 - Leakage in garage. Double vent garage door. Home refueling unit opposite garage door. Leakage rate:

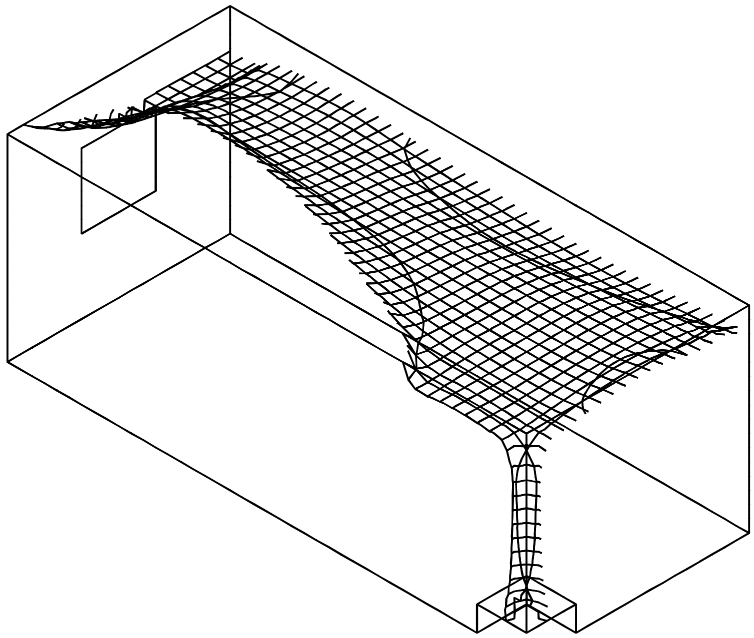


Figure 11 - Surface of constant 7.5% hydrogen concentration after leakage at 6796 l/hr for 20 minutes

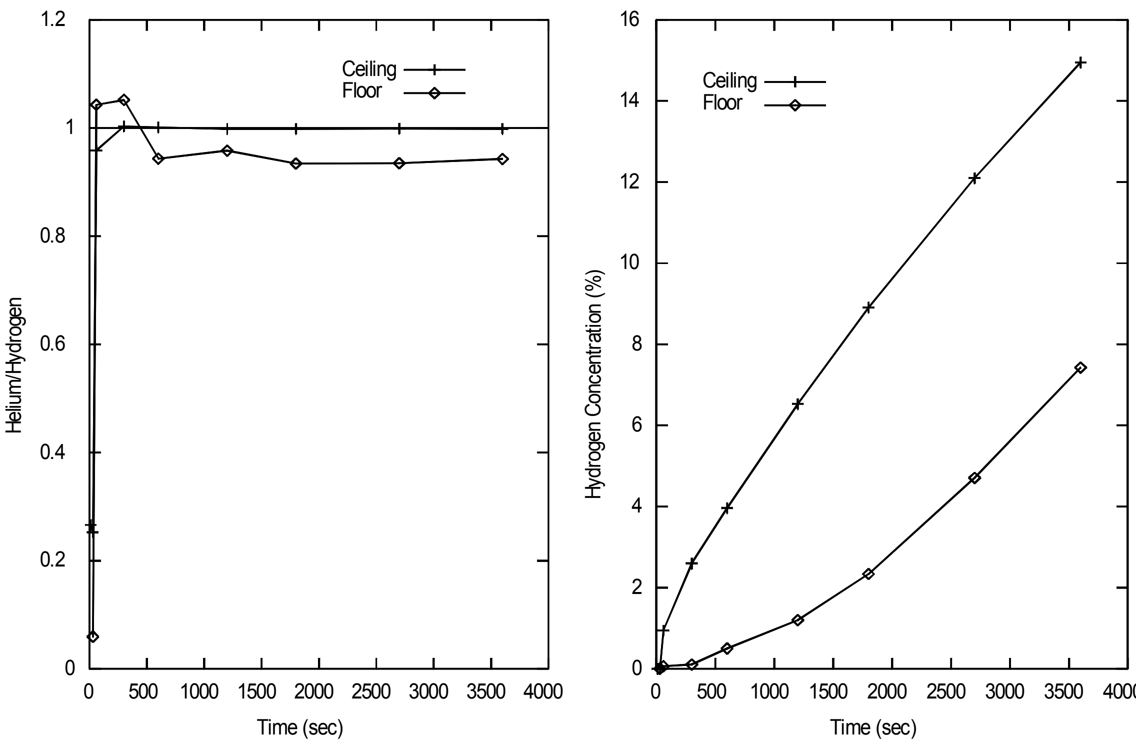


Figure 12 - Leakage in garage. Single vent garage door. Home refueling unit opposite garage door. Leakage rate: 6796 l/hr

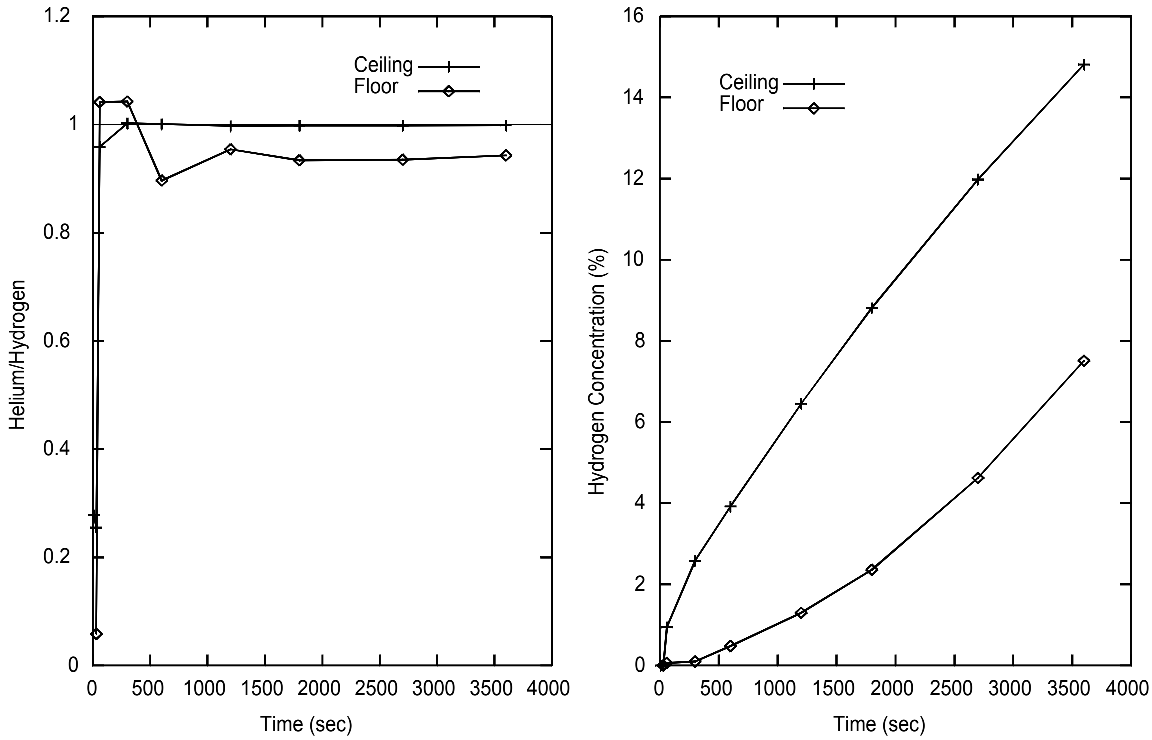


Figure 13 - Leakage in garage. Single vent high in garage door. Home refueling unit opposite garage door. Leakage rate: 6796 l/hr

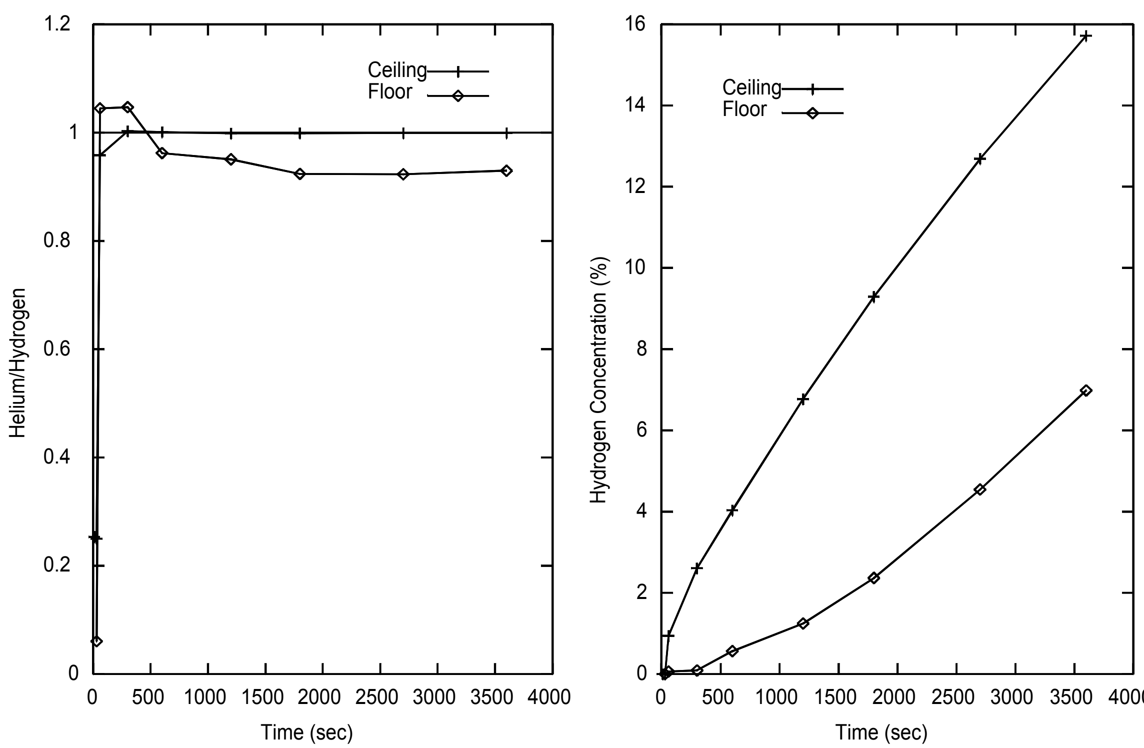


Figure 14 - Leakage in garage. Single vent low in garage door. Home refueling unit opposite garage door. Leakage rate: 6796 l/h

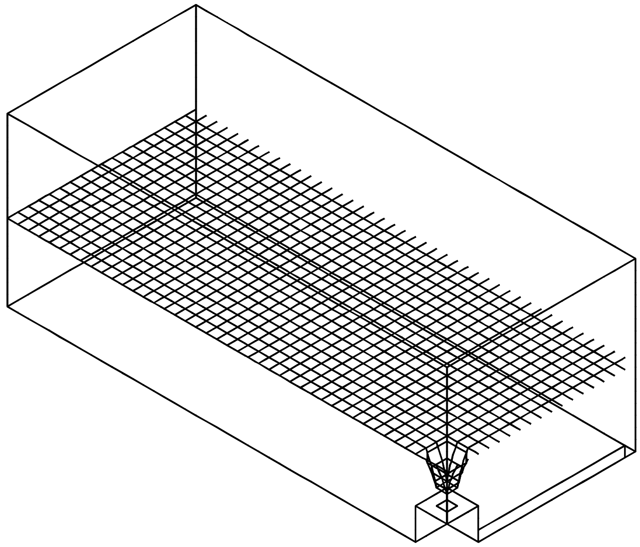


Figure 15 - Surface of constant 34% hydrogen concentration after leakage at 43,200 l/hr for 20 minutes

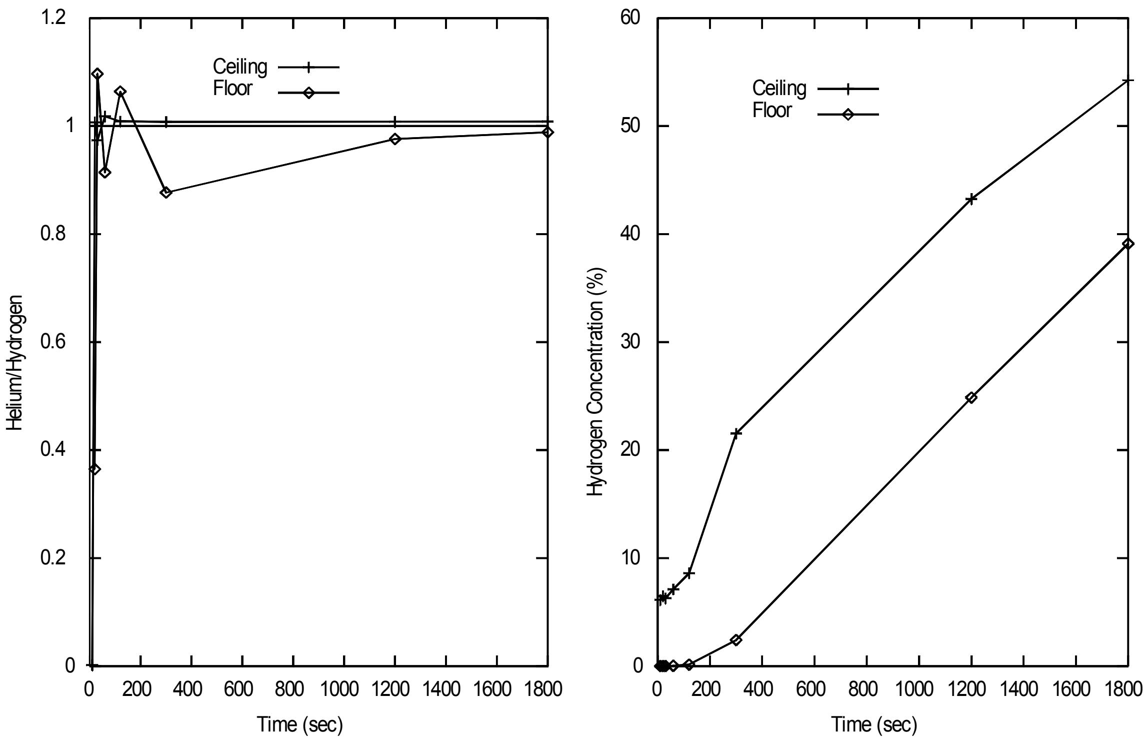


Figure 16 - Leakage in garage. Single vent low in garage door. Home refueling unit opposite garage door. Leakage rate: 43,200 l/hr

Figures 17 through 20 show the results from a van parked in a garage. The effects of moving the single garage door vent location and van position are shown. Moving the van near the garage door or raising the vent location had little effect on hydrogen concentration. Helium concentrations near the ceiling are still a good the predictor of hydrogen concentrations.

Figures 21 and 22 show the effects of hydrogen leakage into a hallway. The hydrogen leaks from the floor at one end of the hallway while two vents exist at the other end the hallway. One vent is in the ceiling and the other vent is in the bottom of the door at the end of the hallway. Because there are lower and upper vents, the enclosure produces a steady state condition after 300 seconds. Helium concentrations near the ceiling are a good predictor of hydrogen concentrations.

Figures 23 and 24 show the effect of adding a "chimney" to the upper vent. Hydrogen concentrations are reduced. Helium concentrations continue to be a good predictor of hydrogen concentrations.

Moving the leak to the middle of the hallway produces slight decreases in hydrogen concentration as the leak is closer to the vents as shown in Figures 25 and 26. Helium concentrations are a good predictor of hydrogen concentrations.

Shortening the hallway but retaining both vents results in large fluctuations in hydrogen concentration near the floor (Figures 27 and 28). This is because the leak and lower vent are in close proximity to the measurement locations. Eddies created at the leak produce large fluctuations in hydrogen concentration. Helium concentrations near the ceiling are a good predictor of hydrogen concentrations.

Figures 29 and 30 show the effects of leakage into a hallway with a single small vent in the ceiling at the opposite and of the hallway. Hydrogen concentrations slowly rise toward 100% because the vent size is small enough, and leakage rate large enough, to prevent flow of air back into the hallway from the single vent. Helium concentrations are a good predictor of hydrogen concentrations.

If a single ceiling vent is increased in size, back flow of air did occur as shown in Figures 31 and 32. Hydrogen concentration levels off at a concentration below 100%. Helium concentrations are a good predictor of hydrogen concentrations. There is a tendency to predict hydrogen concentrations greater than actually existed.

Figures 33 and 34 show that moving the single vent to a lower position in the door does not prevent back flow of air into the room. Helium concentrations were a good predictor of hydrogen concentrations.

The addition of a "chimney" reduces hydrogen concentrations as can be seen comparing Figures 35 and 36 to Figures 31 and 32. The "chimney" does not prevent the back flow of air through the vent. Helium concentrations near the ceiling are good predictor hydrogen concentration.

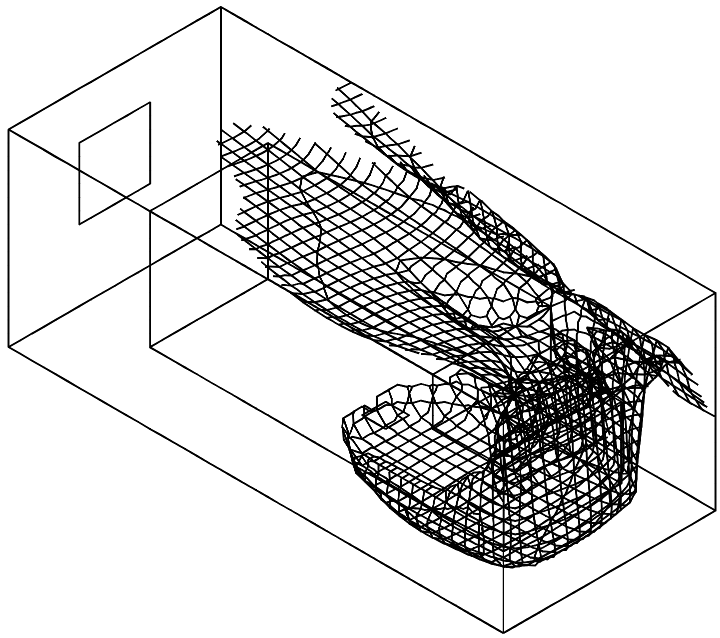


Figure 17 - Surface of constant 6.5% hydrogen concentration after leakage at 6796 l/hr for 20 minutes

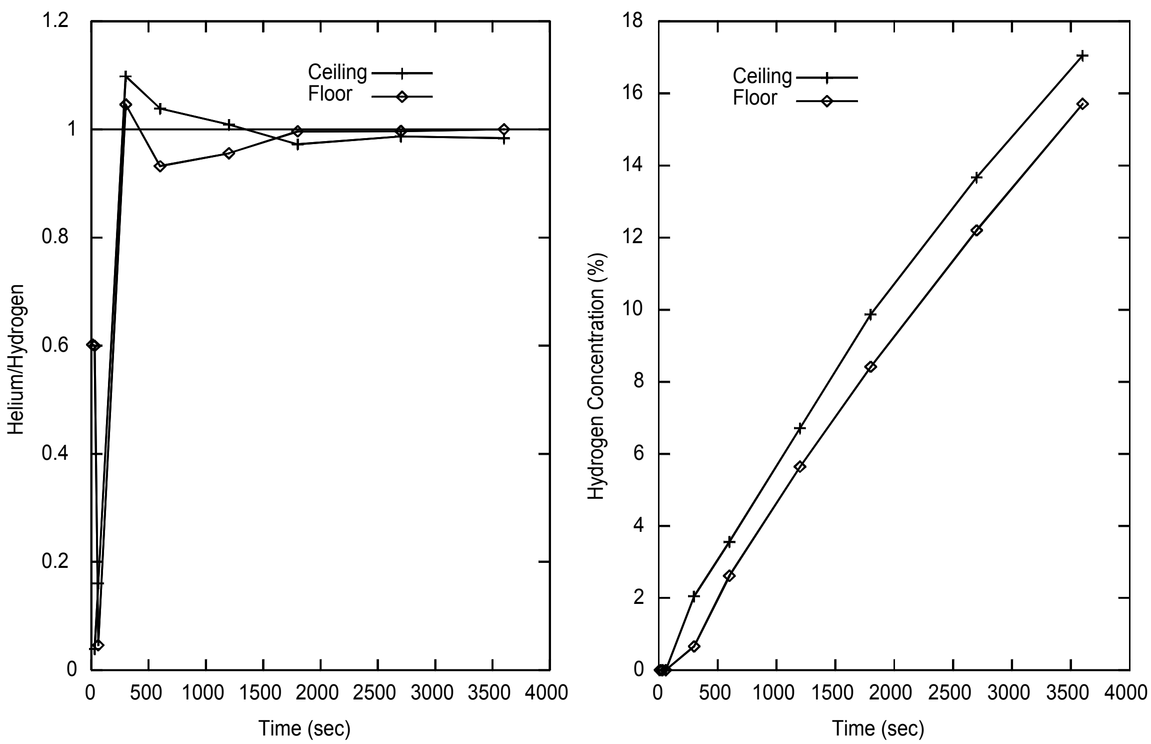


Figure 18 - Leakage in garage. Single vent garage door. Van in standard position. Leakage rate: 6796 l/h

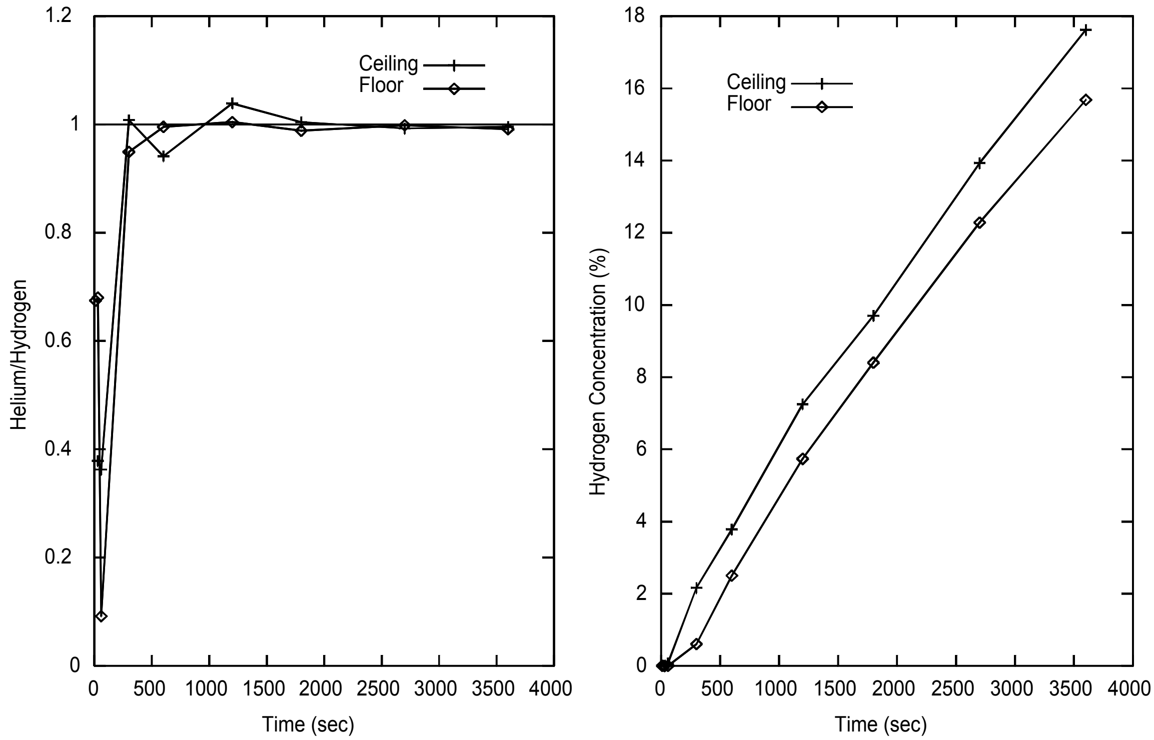


Figure 19 - Leakage in garage. Single vent garage door. Van near garage door. Leakage rate: 6796 l/h

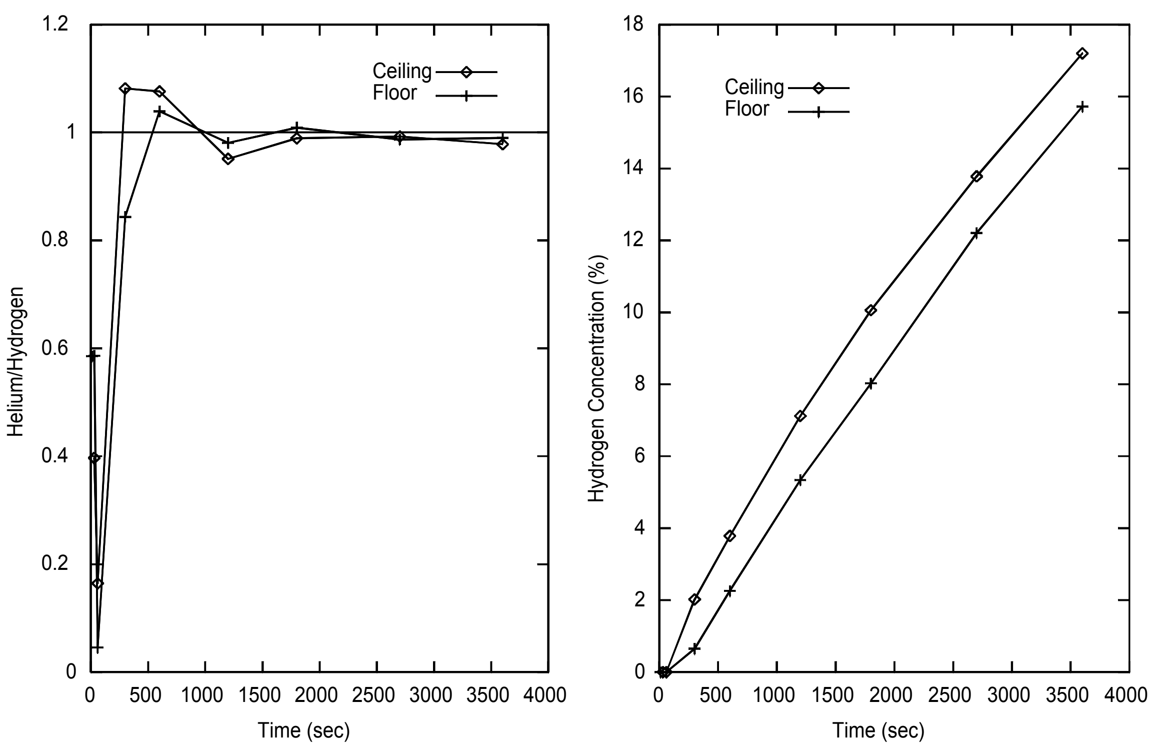


Figure 20 - Leakage in garage. Single vent high in garage door. Van in standard position. Leakage rate: 6796 l/h

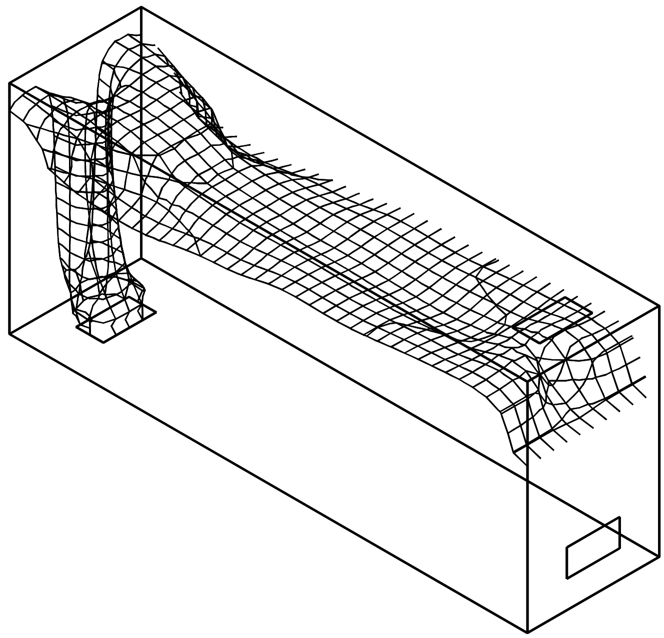


Figure 21 - Surface of constant 3.0% hydrogen concentration after leakage at 27,184 l/hr for 1 minute

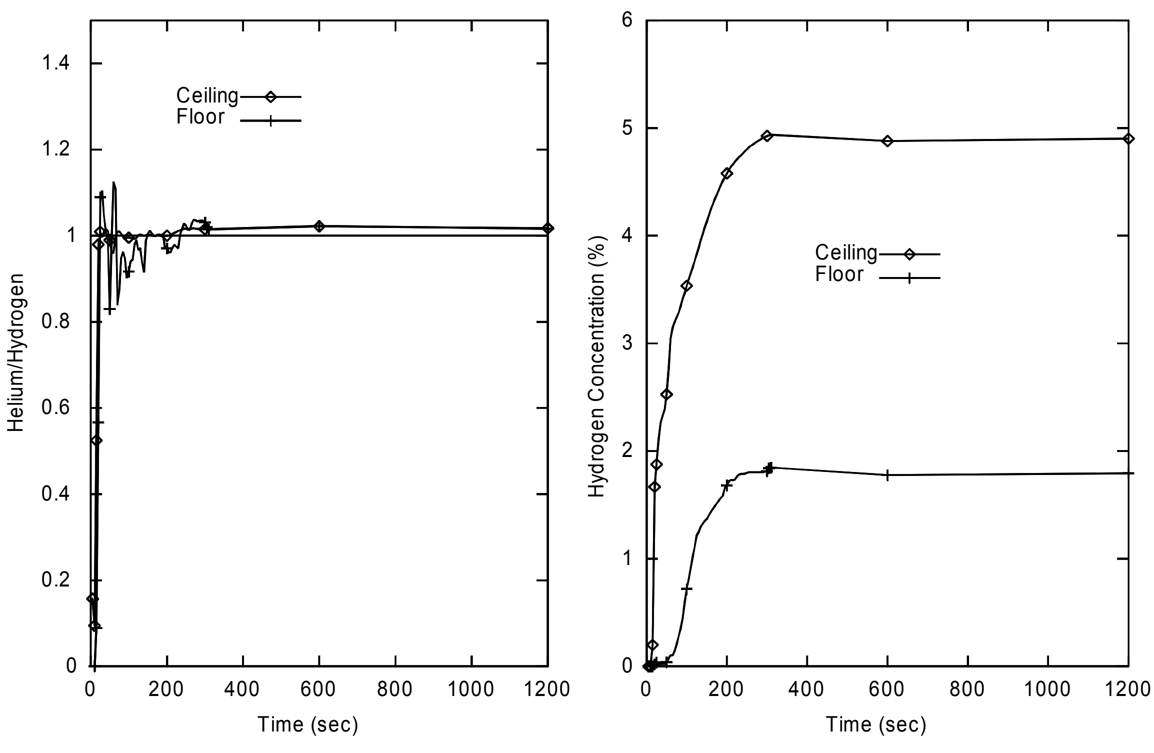


Figure 22 - Leakage at end of hallway. Double vent opposite leak. Leakage rate: 27,184 l/hr

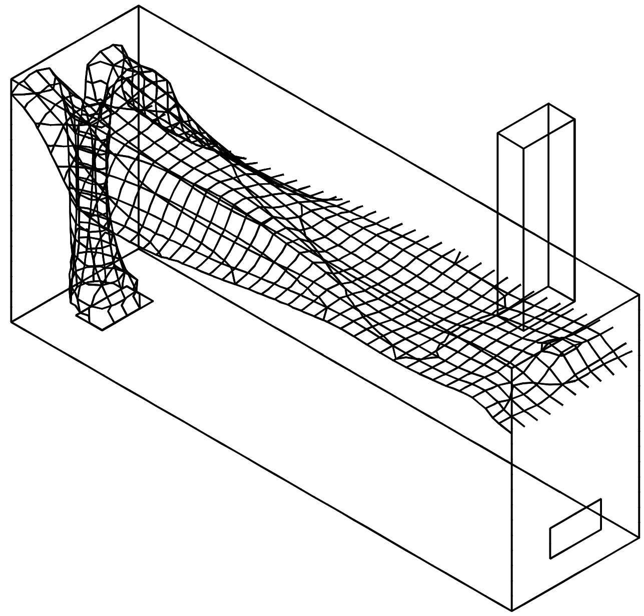


Figure 23 - Surface of constant 4.0% hydrogen concentration after leakage at 27,184 l/hr for 20 minutes

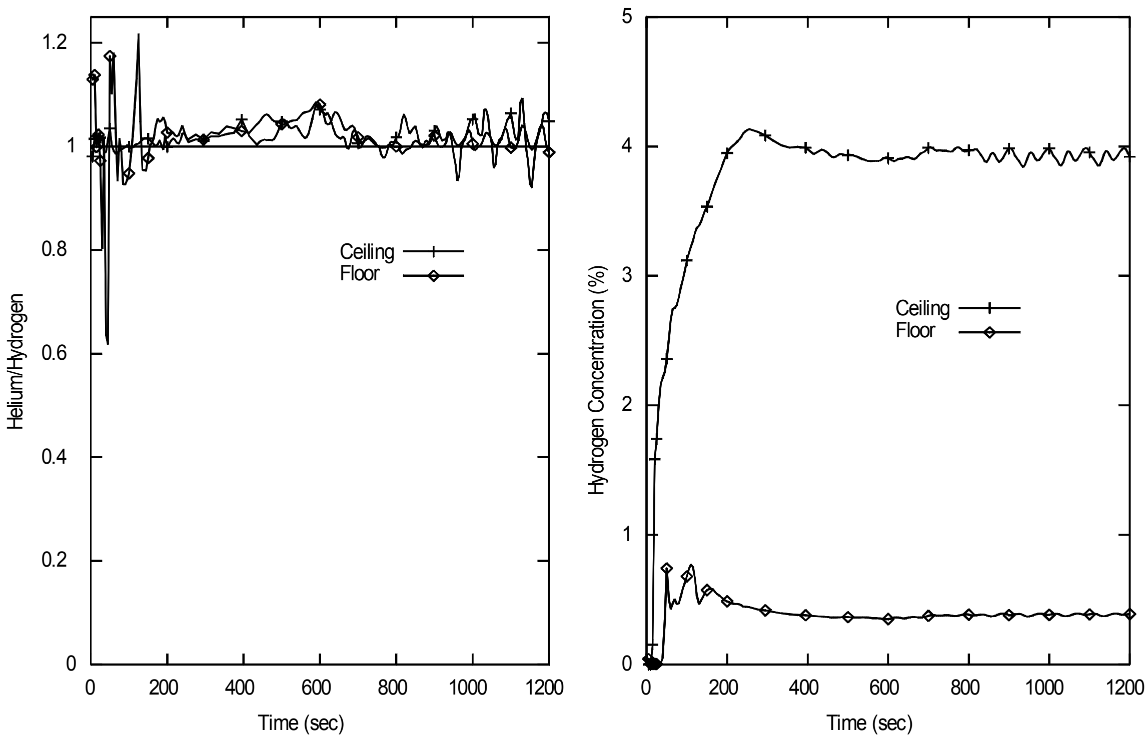


Figure 24 - Leakage at end of hallway. Double vent opposite leak. Chimney on roof vent. Leakage rate: 27,184 l/hr

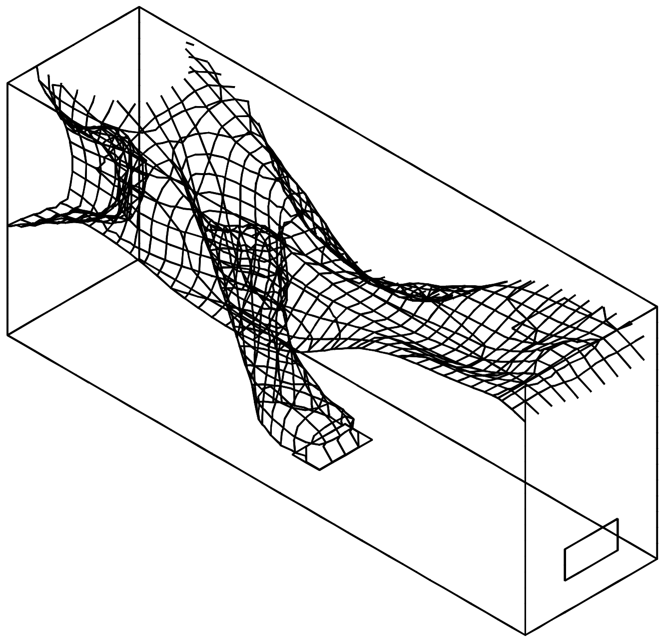


Figure 25 - Surface of constant 4.8% hydrogen concentration after leakage at 27,184 l/hr for 20 minutes

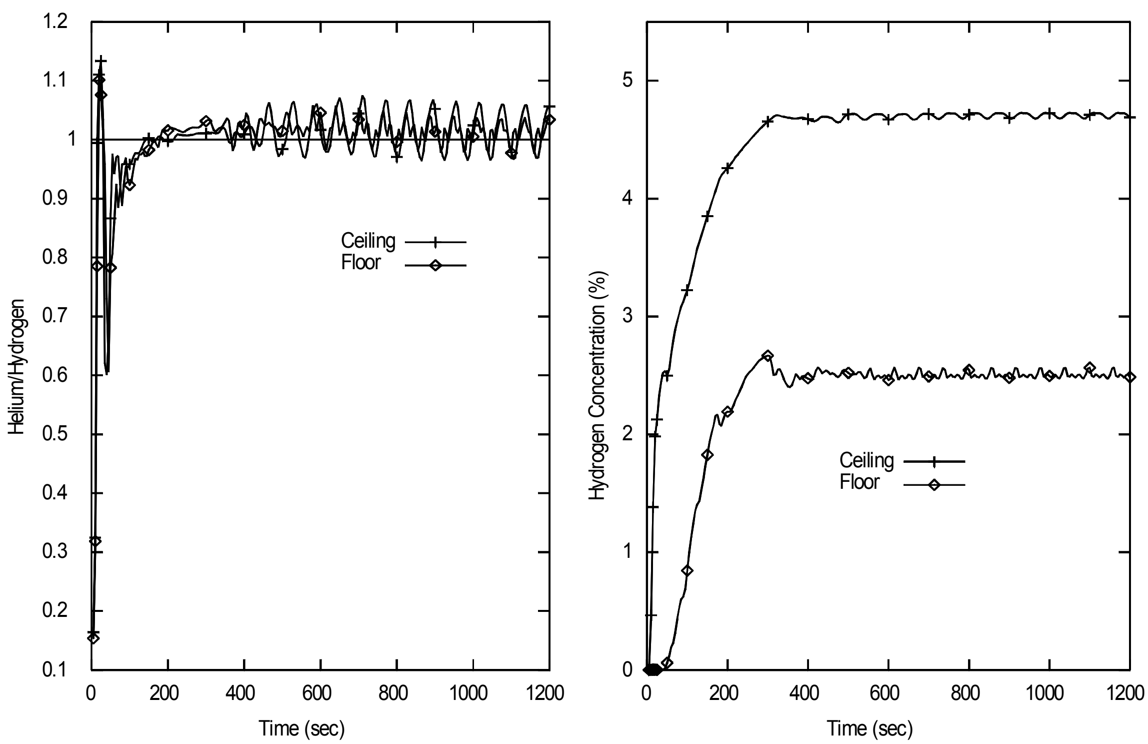


Figure 26 - Leakage in middle of hallway. Double vent at end of hallway. Leakage rate: 27,184 l/hr

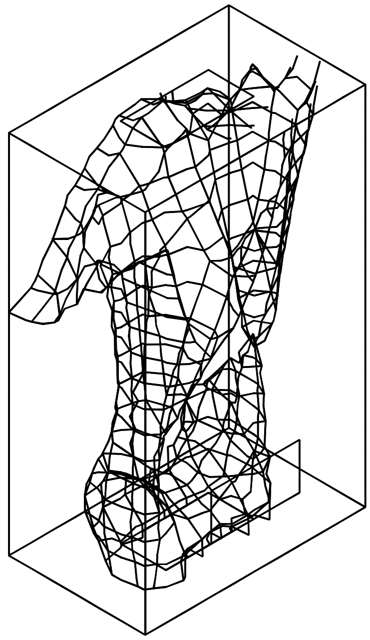


Figure 27 - Surface of constant 4.1% hydrogen concentration after leakage at 27,184 l/hr for 20 minutes

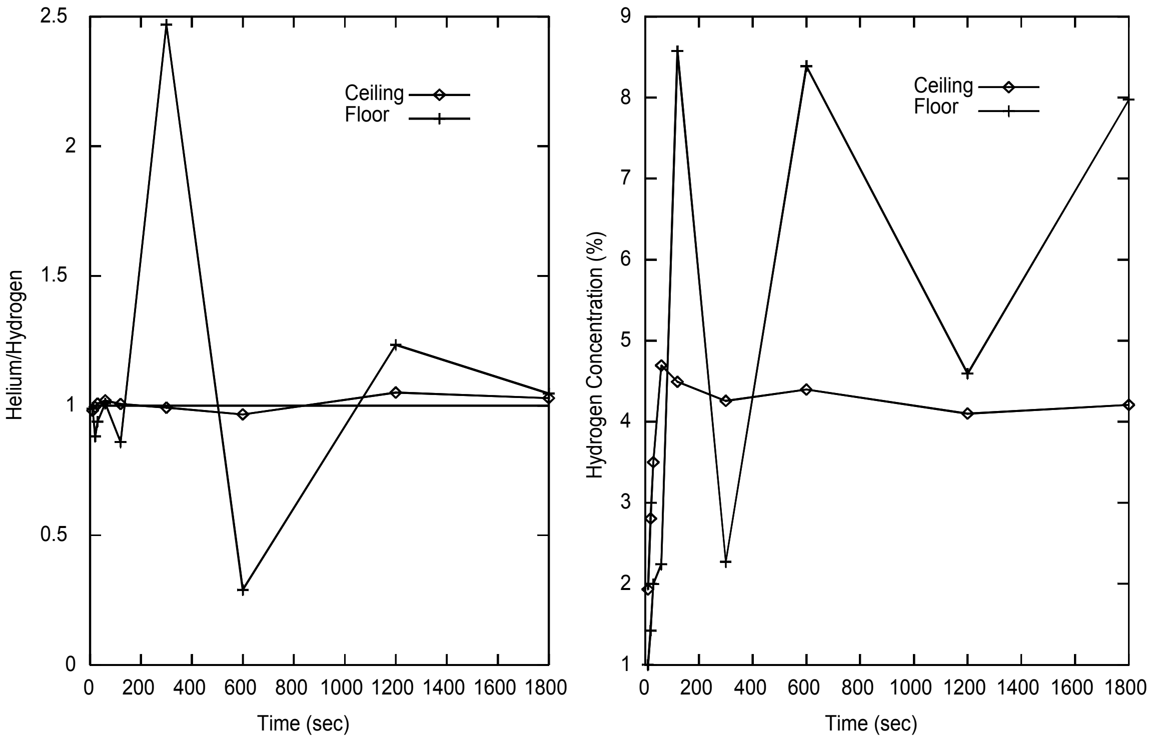


Figure 28 - Leakage in middle of hallway. Double vent at end of hallway. Leakage rate: 27,184 l/hr

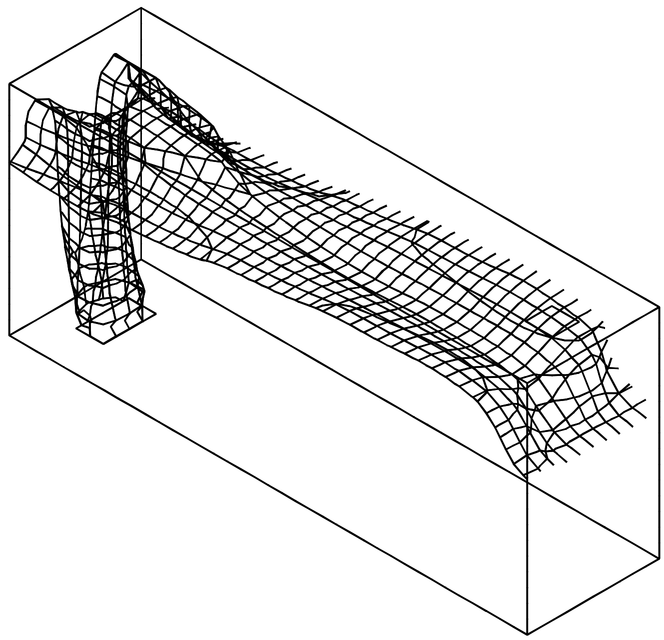


Figure 29 - Surface of constant 36% hydrogen concentration after leakage at 27,184 l/hr for 20 minutes

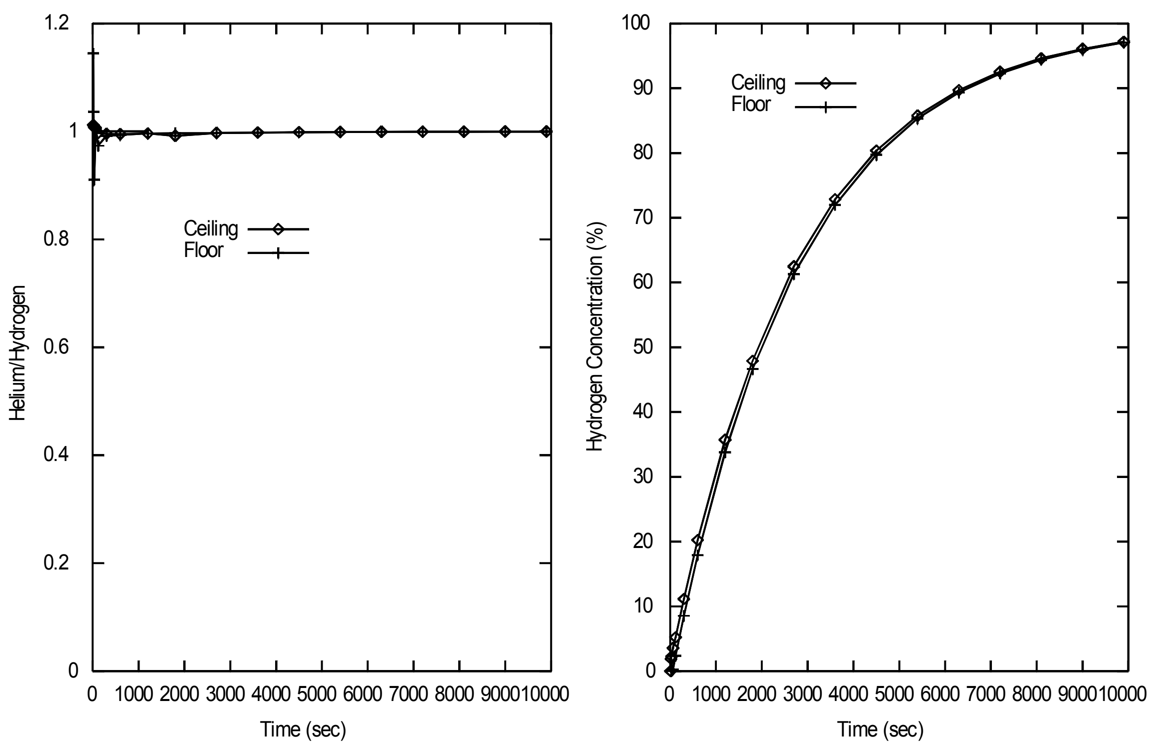


Figure 30 - Leakage at end of hallway. Single vent high at opposite end of hallway. Leakage rate: 27,184 l/hr

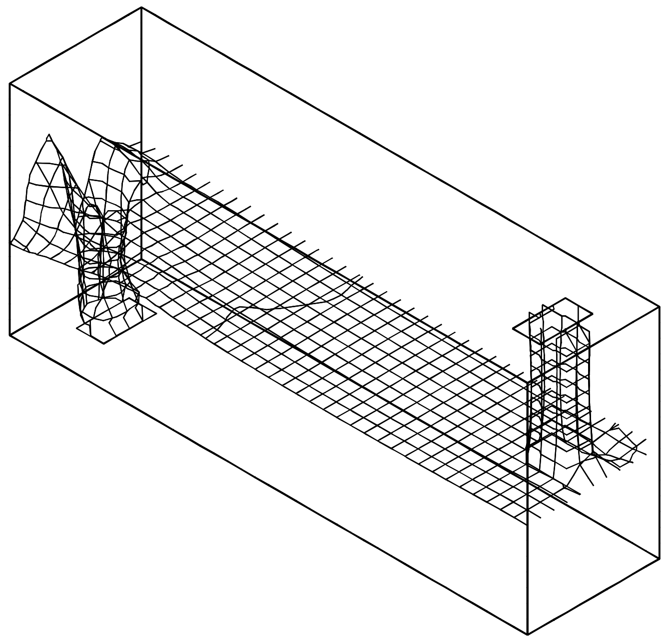


Figure 31 - Surface of constant 22% hydrogen concentration after leakage at 27,184 l/hr for 20 minutes

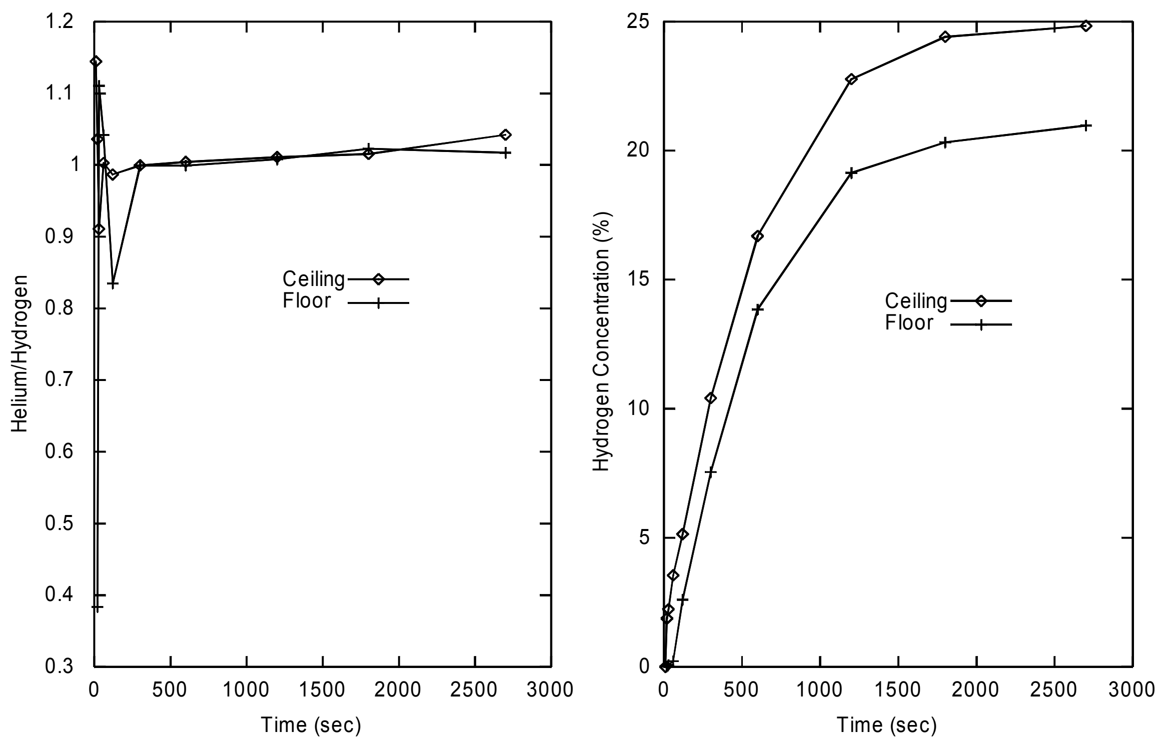


Figure 32 - Leakage at end of hallway. Single vent high at opposite end of hallway. Leakage rate: 27,184 l/hr

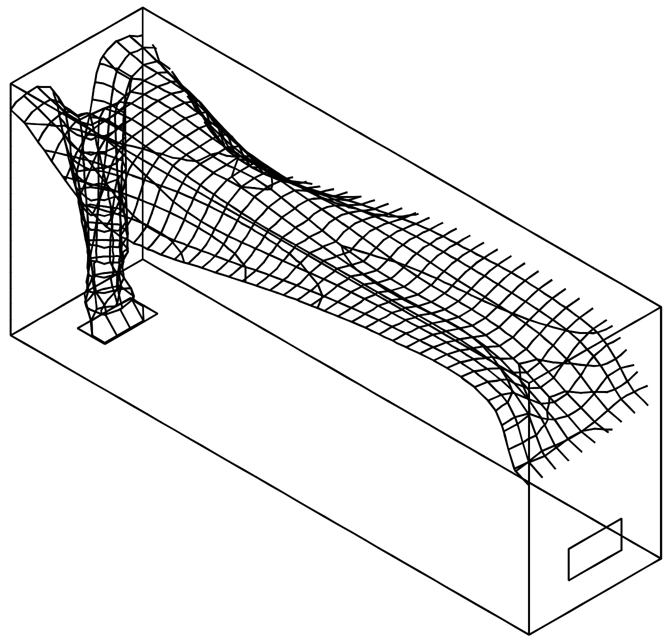


Figure 33 - Surface of constant 24% hydrogen concentration after leakage at 27,184 l/hr for 20 minutes

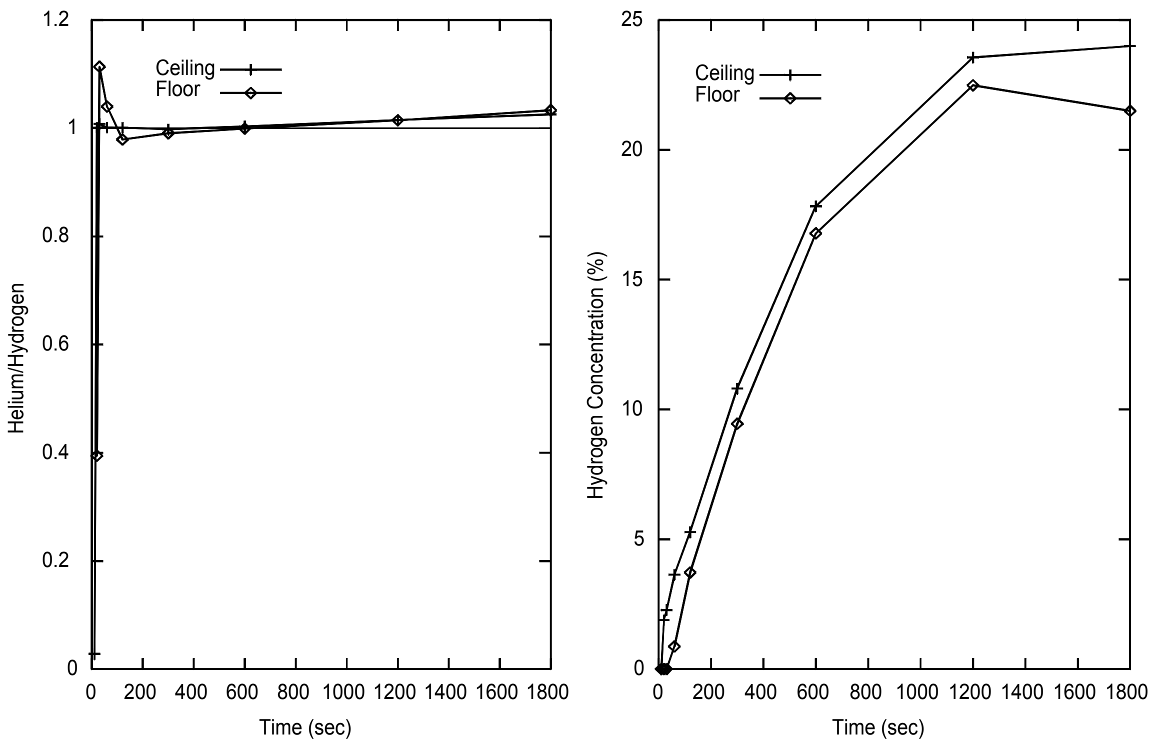


Figure 34 - Leakage at end of hallway. Single vent low at opposite end of hallway. Leakage rate: 27,184 l/hr

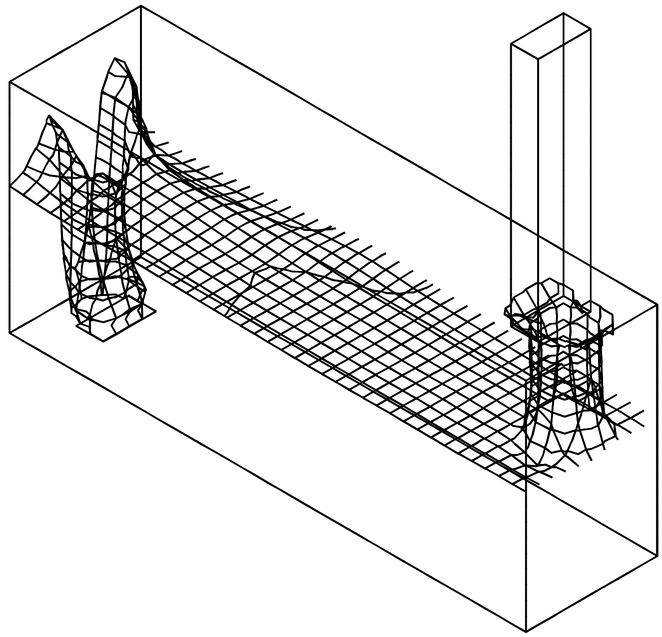
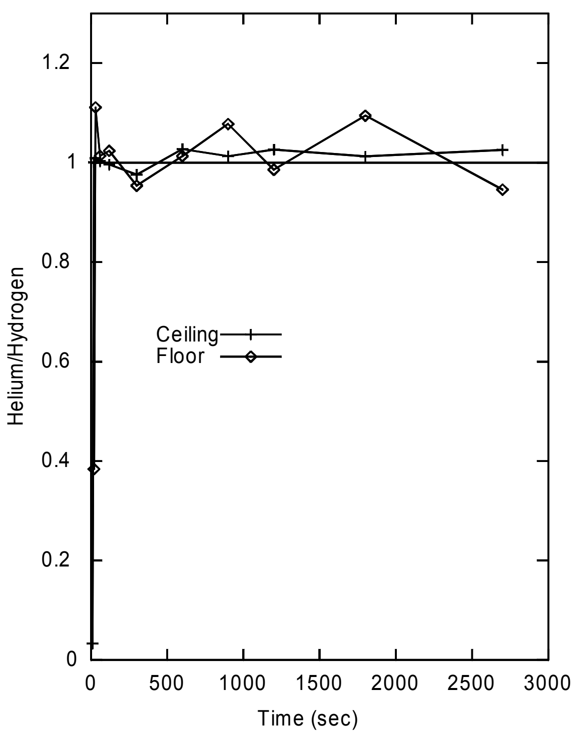


Figure 35 - Surface of constant 12% hydrogen concentration after leakage at 27,184 l/hr for 20 minutes



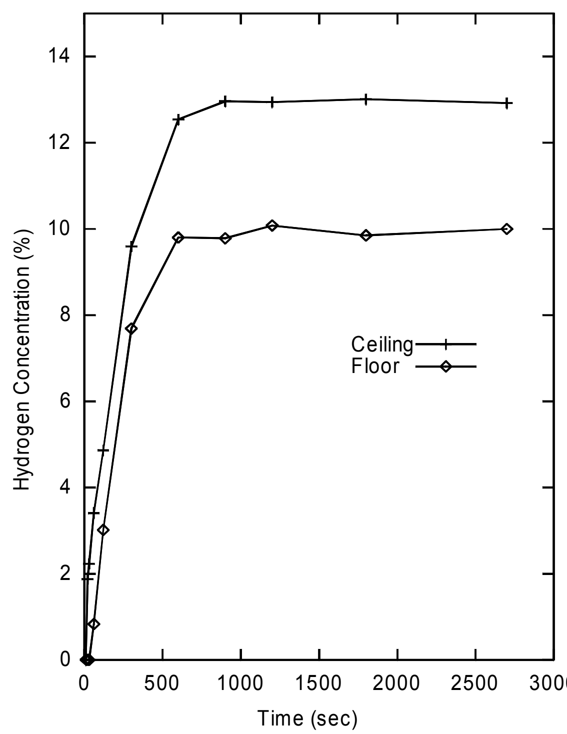


Figure 36 - Leakage at end of hallway. Single vent, with chimney, at opposite end of hallway. Leakage rate: 27,184 l/hr

Interconnected simple enclosures do not necessarily show a one-to-one relationship between helium and hydrogen concentration. Figures 37 through 40 show two interconnected hallways, one above the other in a two-story structure. In the downstairs hallway the helium to hydrogen ratio is less than 1.0. This would result in hydrogen concentrations that were 15% higher than predicted if the helium values were used has a direct indicator. The method is still an accurate predictor of behavior in the upstairs hallway but since higher hydrogen concentrations are reached in the downstairs hallway, the downstairs hallway is of greater concern.

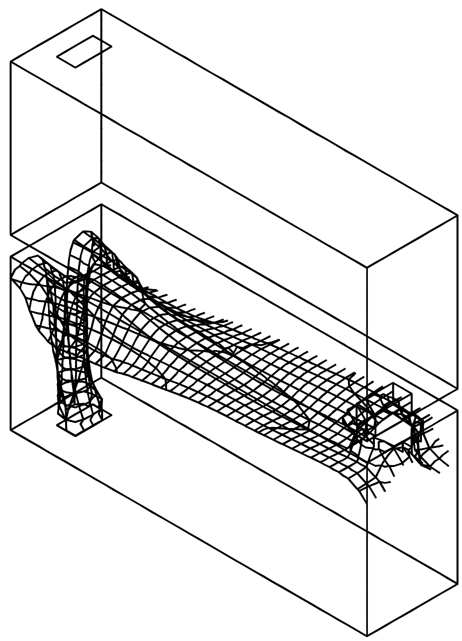


Figure 37 - Surface of constant 25% hydrogen concentration after leakage at 27,184 l/hr for 20 minutes

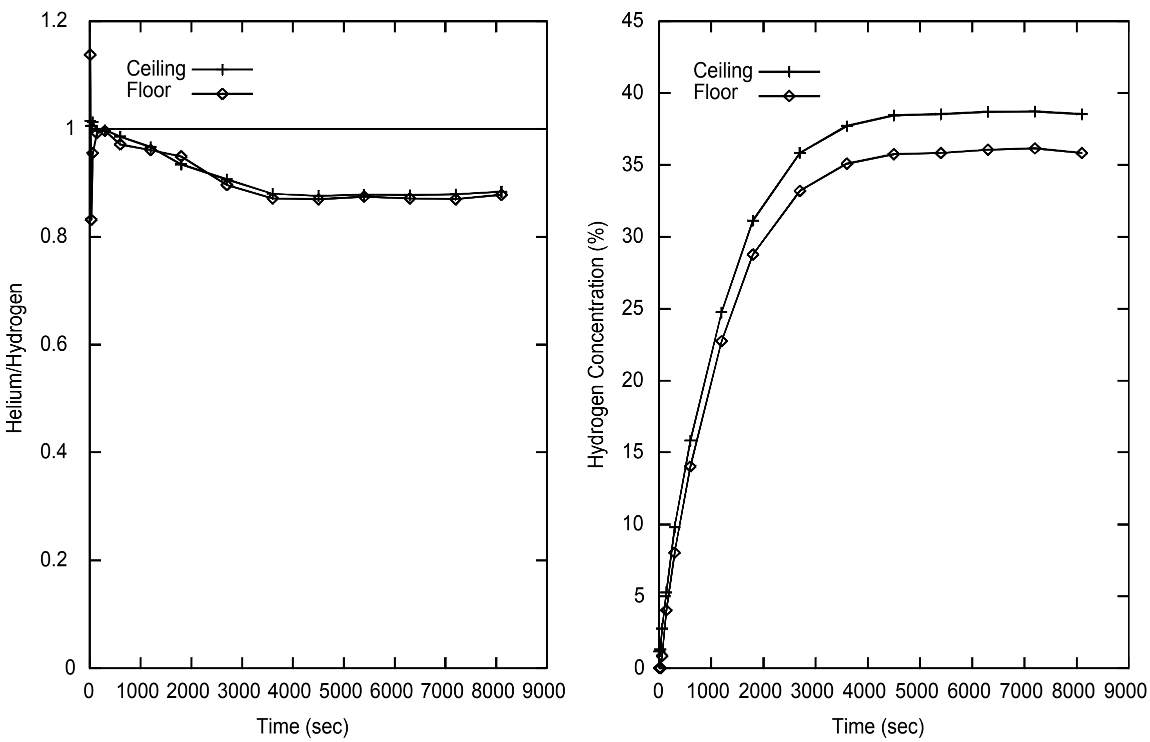


Figure 38 - Downstairs: Leakage at end of hallway (downstairs). Vent at opposite end of hallway (downstairs). Vent in ceiling (upstairs). Leakage rate: 27,184 l/hr

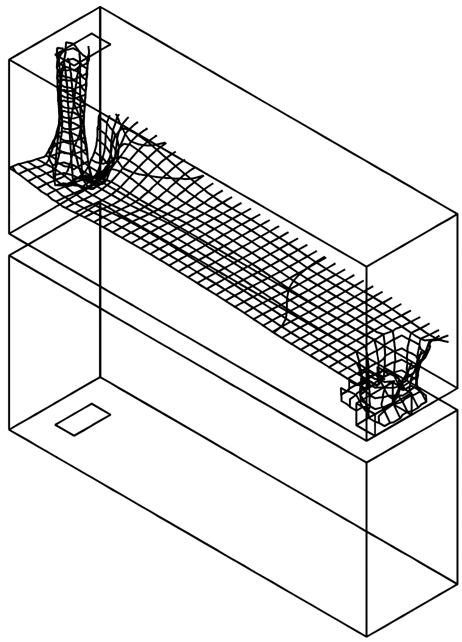


Figure 39 - Surface of constant 13% hydrogen concentration after leakage at 27,184 l/hr for 20 minutes

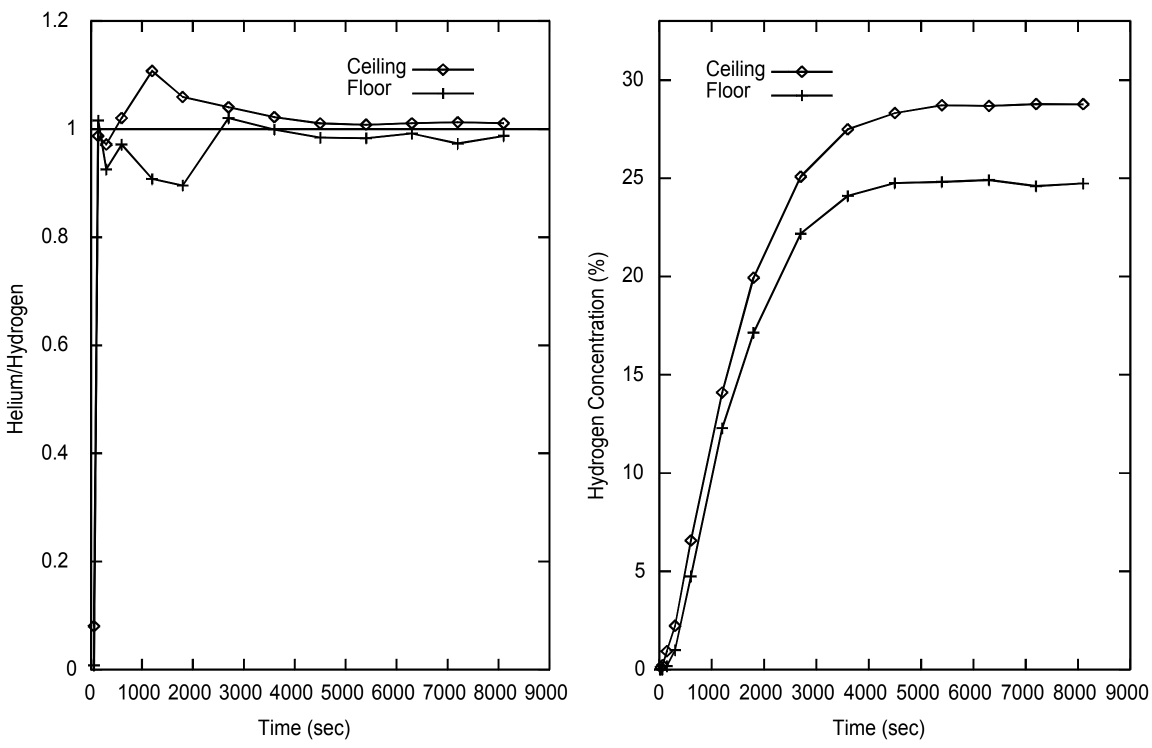


Figure 40 - Upstairs: Leakage at end of hallway (downstairs). Vent at opposite end of hallway (downstairs). Vent in ceiling (upstairs). Leakage rate: 27,184 l/hr

Hydrogen Safety Information Dissemination to Groups Outside the Hydrogen Community

This research effort has resulted in production of two BetaCAM videos and a personal interview video for the H2000 Project Safety video. Discussions began in the middle of June 1999 with Geoffrey Holland of Cognizant Media to establish the subject matter to be covered by the University of Miami. It had been previously decided to present animation of hydrogen leakage into a hallway to demonstrate hydrogen gas cloud motion. By mid-July, the subject matter of the first video to be provided to the H2000 project was established. It was decided that it was preferable to model a vehicle in a single car garage. This allowed a comparison of the leakage of hydrogen to the leakage of LPG or gasoline from that vehicle to be made.

The following accident scenario was modeled. A family size vehicle was parked in a single car residential garage. The accident scenario began when a fuel line leak released fuel after the vehicle was parked in the garage. The modeling was done assuming the vehicle was powered by gasoline, hydrogen, or LPG. In the cases of hydrogen and LPG the fuel pressure cutoff solenoids that would normally shut off with the ignition key were assumed to have also failed. The leak was assumed to be a circular hole producing a turbulent leak. This assumption was least favorable for hydrogen. If the leak was assumed laminar, as would be the case with a leak caused by corrosion, the hydrogen flow rate would have been 80% lower. The leakage rate for gasoline was experimentally determined for a circular hole in a standard gasoline fuel line. The leakage rates were 7200 liters/hr for hydrogen, 848 liters/hr for LPG, and 2.6 liters/hr for gasoline. The clouds of combustible gas produced by the leak were plotted using the lean limit of combustion for each fuel. The lean limits were 4.1% for hydrogen, 2.1% for LPG, and 1.3% for gasoline. The topic of fuel leakage into a garage has been addressed previously at the University of Miami. This work effort required additional modeling of the leakage of gasoline together with animation of the previous computational results. Figure 41 shows a draft frame of the animation of a combustible LPG cloud growing from a fuel line leak in an LPG fueled vehicle. Figure 41 shows the size of the combustible cloud produced by LPG leaking at a rate of 848 liters/hr. The cloud was defined by the lean limit of combustion for LPG (2.1%) and is shown after 30 minutes of leakage.

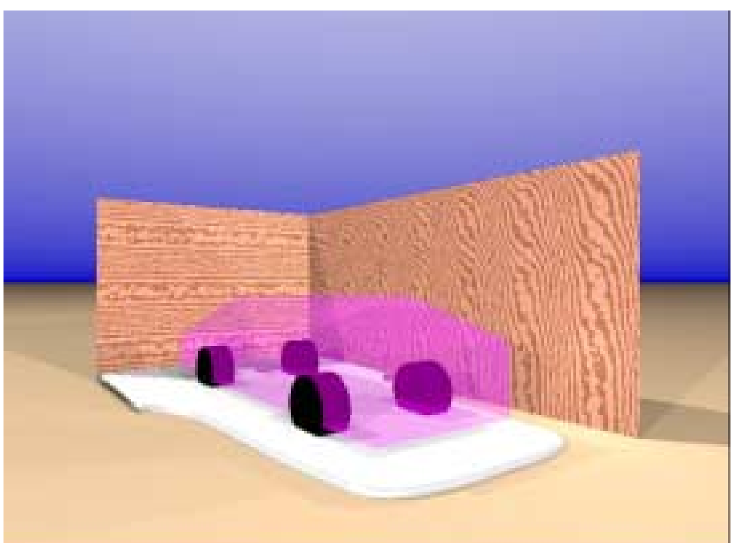


Figure 41 - Draft animation frame of combustible LPG cloud growing under vehicle

It was decided in late November that the format of the video needed additional detail, showing the relative position of the garage to the house and the vents in the garage door. The video of fuel leakage (H_2, LPG, and Gasoline) into a residential garage was updated to the format shown in Figures 42 through 46. Figure 42 shows the residential home that has a single car garage. The subject vehicle is shown moving up the driveway.

Figure 42 - Residential home with single car garage

Figure 43 shows the vehicle parked in the garage with the garage door almost completely closed. Note that there are a strip of 7-in. tall louvered and screened vents at the top and bottom of the garage door.

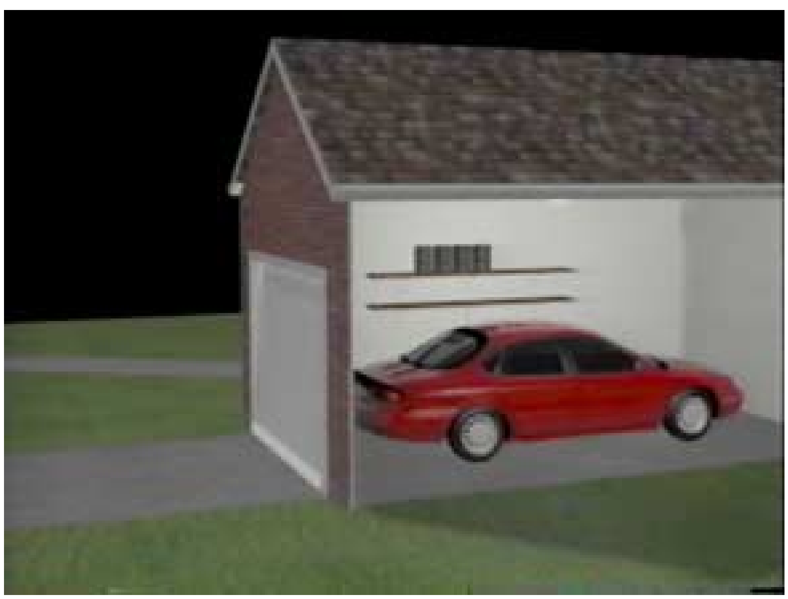


Figure 43 - Vehicle parked in garage (Note garage door vents)

Figure 44 shows the size of the combustible cloud formed by gasoline leaking at a rate of 2.6 liters/hr for 30 minutes.

Figure 44 - Combustible cloud produced by gasoline

Figure 45 shows the size of the combustible cloud formed by LPG leaking at a rate of 848 liters/hr for 30 minutes.

Figure 45 - Combustible cloud produced by LPG

Figure 46 shows the size of the combustible cloud formed by hydrogen leaking at a rate of 7200 liters/hr for 30 minutes.

Figure 46 - Combustible cloud produced by hydrogen

In February, Geoffrey Holland came to Miami to videotape interviews for H2000 and see the results of the animations. While he was in Miami it was decided to also provide a video of hydrogen leakage and ignition from a 1985 Mercury Cougar tested in previous DOE research.

The final BetaCAM form of the leakage into a single car garage was sent to Cognizant Media on March 22nd. The BetaCAM copy of hydrogen leakage and ignition from a 1985 Mercury Cougar was sent on April 12th. Figure 47 is a frame from that video that shows hydrogen leaking at 3000 cubic feet per minute.

Figure 47 - Hydrogen release and ignition

Acknowledgements

The authors would like to acknowledge the Department of Energy without whose support this work would not have been possible.