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RISKS INCURRED BY HYDROGEN ESCAPING FROM CONTAINERS AND CONDUITS

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Abstract

This paper is a discussion of a method for hydrogen leak classification. Leaks are classified as; gas escapes into enclosed spaces, gas escapes into partially enclosed spaces (vented), and gas escapes into unenclosed spaces. Each of the three enclosure classifications is further divided into two subclasses; total volume of hydrogen escaped and flow rate of escaping hydrogen. A method to aid in risk assessment determination in partially enclosed spaces is proposed and verified for several enclosure geometries. Examples are discussed for additional enclosure geometries.

Introduction

The escape of hydrogen (leak) from a container or conduit produces a risk of combustion. The spatial and temporal distribution of hydrogen produced by the leak is needed to assess the risk of combustion. Depending on the geometry into which the hydrogen is leaking, the flow rate of hydrogen from the leak, the total volume of hydrogen leaked, and any preexisting gas motion, the escaping hydrogen may produce a negligibly small cloud of combustible gases, a large cloud of combustible gases or a cloud of combustible gases in conjunction with a cloud of detonable gases.

Risk Assessment

This paper is a discussion of the clouds formed by escaping hydrogen. Estimates made for worst case accident scenarios often assume hydrogen-air clouds, which could not physically exist. As an example, the following is an accident scenario of hydrogen escaping under a hydrogen powered bus at a flow rate of 50 SCFM (1400 l/min). A "worst case" accident scenario would be to assume a stoichiometric, or somewhat richer, mixture of hydrogen and air evenly distributed under the bus. This produces a large volume of potentially detonable gases. If a detonation is assumed, as a further extension of the "worst case" scenario, a force large enough to raise the bus off the ground is created. In fact, applying these assumptions to any fuel would produce similar results.

In reality, hydrogen's very low density prevents this worst case scenario from occurring. Figure 1 shows the results of a computer model of hydrogen escaping downward from the middle of the underside of an idealized bus. The underside of the idealized bus contained two 24 inch deep cavities, one at each end of the bus (Geometry A). The ground clearance under the bus was 10.5 inches (to the bottom of the bus and bottom of the skirt that formed the walls around the cavities). Figure 1 shows the surface of constant 8% hydrogen concentration at 30 minutes. The flow had essentially reached steady state after 5 minutes of hydrogen leakage. The surface of constant 8% hydrogen concentration shows the basic flow pattern of the escaping hydrogen. The hydrogen spread out evenly in all directions from the leak until it reached the edge of the bus. The hydrogen rose upon reaching the edge of the bus and entrained ambient air. The rising mixture of hydrogen

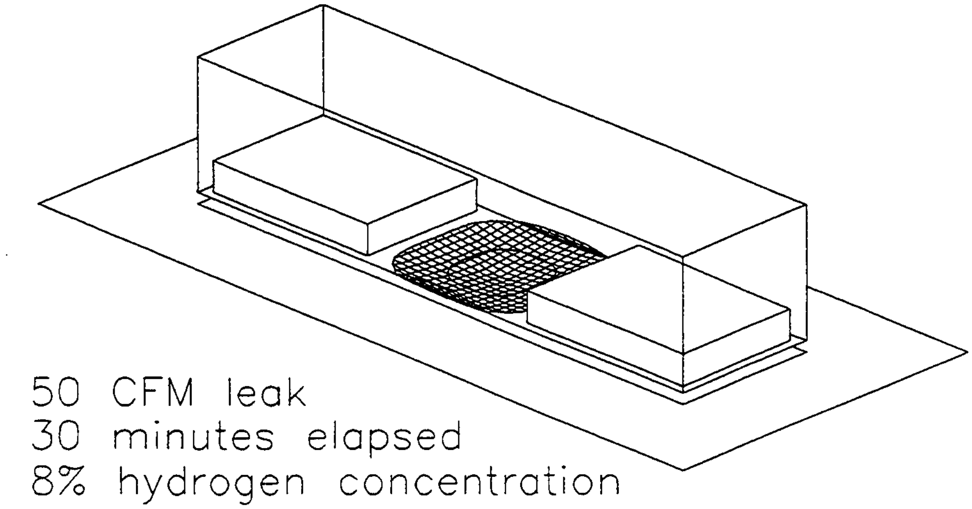

Figure 1 - Geometry A

and air at the sides of the bus drew the flow of hydrogen toward the sides of the bus, the shortest pathway out from under the bus. This flow pattern prevented the hydrogen concentration from exceeding 8% in the cavities.

Figure 2 shows the surface of constant 4.1% hydrogen concentration. 4.1% hydrogen concentration is the upward propagating lean limit of combustion (Coward 1961, Hansel 1993, Lewis 1961) and as such represents the leanest burnable mixture of hydrogen. It can be seen in Figure 2 that the cavities under the front and back of the bus were filled with hydrogen between 8% and 4.1% hydrogen. Hydrogen burns at very low speeds at those concentrations. Experiments with bus wheel wells (Photo 1) containing hydrogen-air mixtures averaging 10% hydrogen have shown flames speeds on the order of 10 to 12 ft/sec.

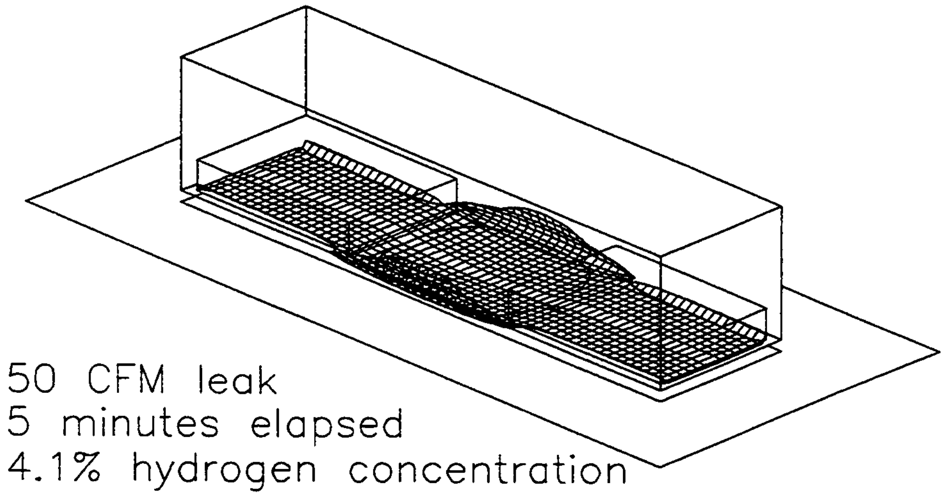

Figure 2 - Geometry A

Photo 1 - Bus wheel well test

Figure 3 shows the surface of constant 18% hydrogen concentration. 18% hydrogen concentration is the accepted value for the lean limit of detonation (Lewis 1961, Ordin 1997). The volume of gases was very small and the likelihood of detonation occurring was very remote.

The accident scenario of hydrogen escaping directly into the cavity under the bus is shown in Figure 4 (Geometry B). It is seen that the cavity fills with hydrogen richer than 18% concentration within 5 minutes. Venting of the cavity was necessary to prevent this dangerous accident scenario. Figure 5 shows the surface of 4.1% hydrogen concentration for a vented cavity (Geometry C). The volume of gases containing more than 4.1% hydrogen was less than the previous case because vents were employed at the top of the cavity. Figure 6 shows the surface of constant 18% hydrogen concentration. Once again, the volume of gases containing more than 18% hydrogen was very small.

All the previously described analyses were without any ambient wind. The presence of wind reduces the size of the hydrogen-air clouds produced.

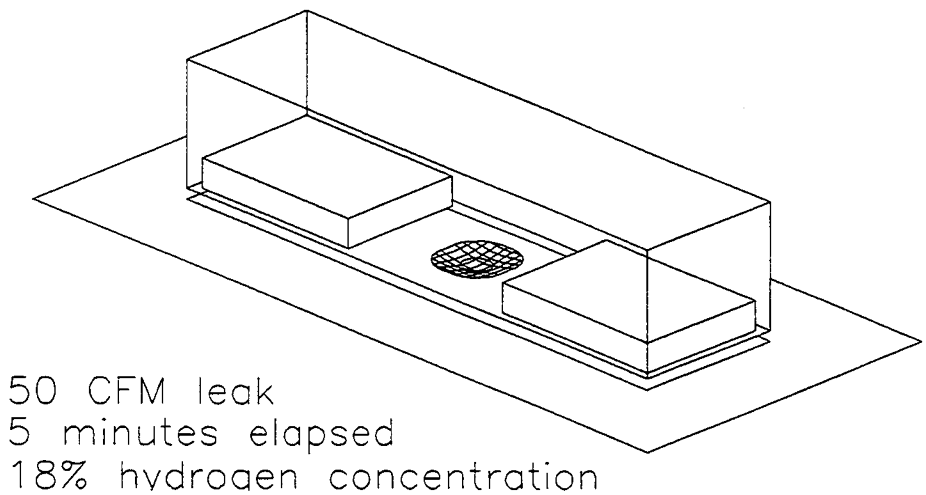

Figure 3 - Geometry A

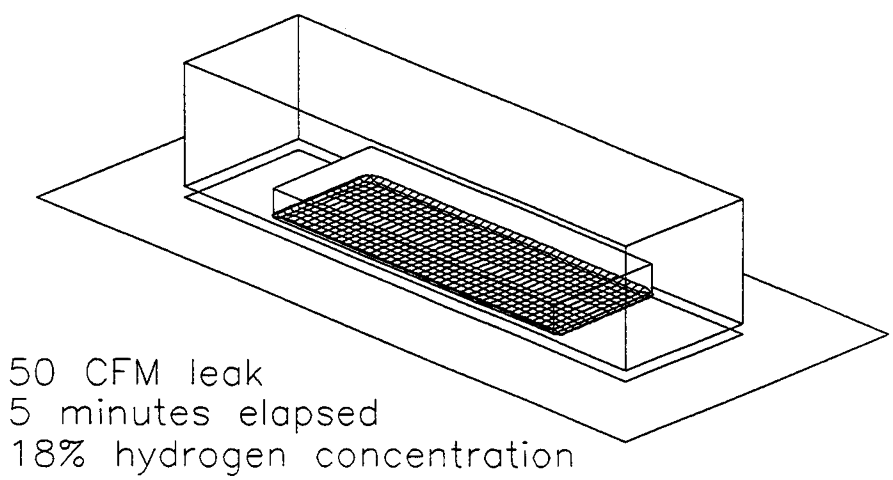

Figure 4 - Geometry B

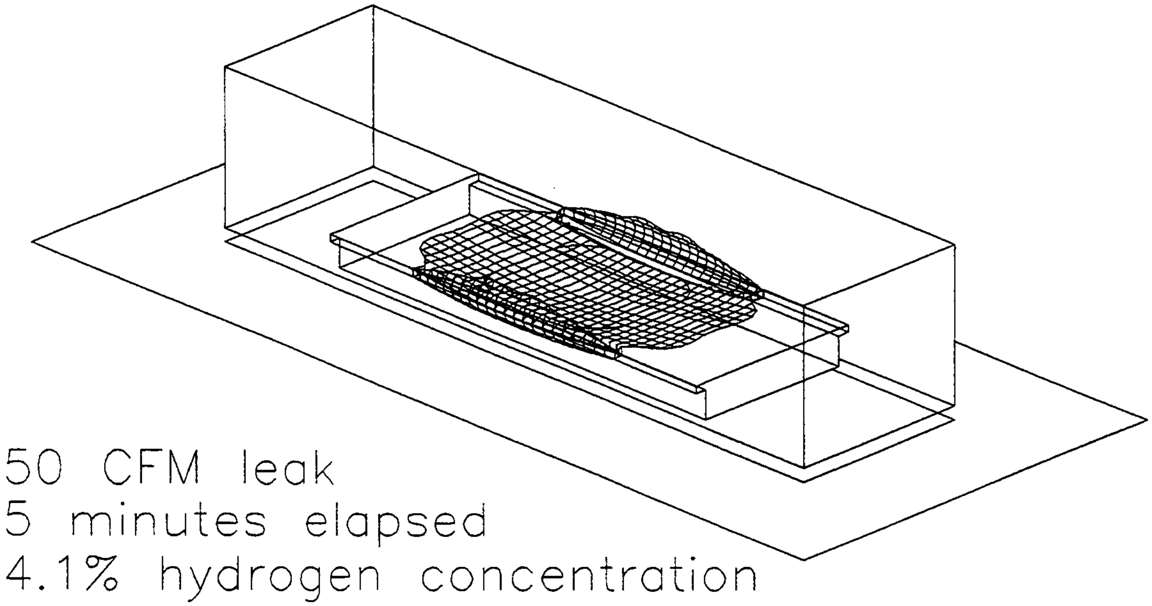

Figure 5 - Geometry C

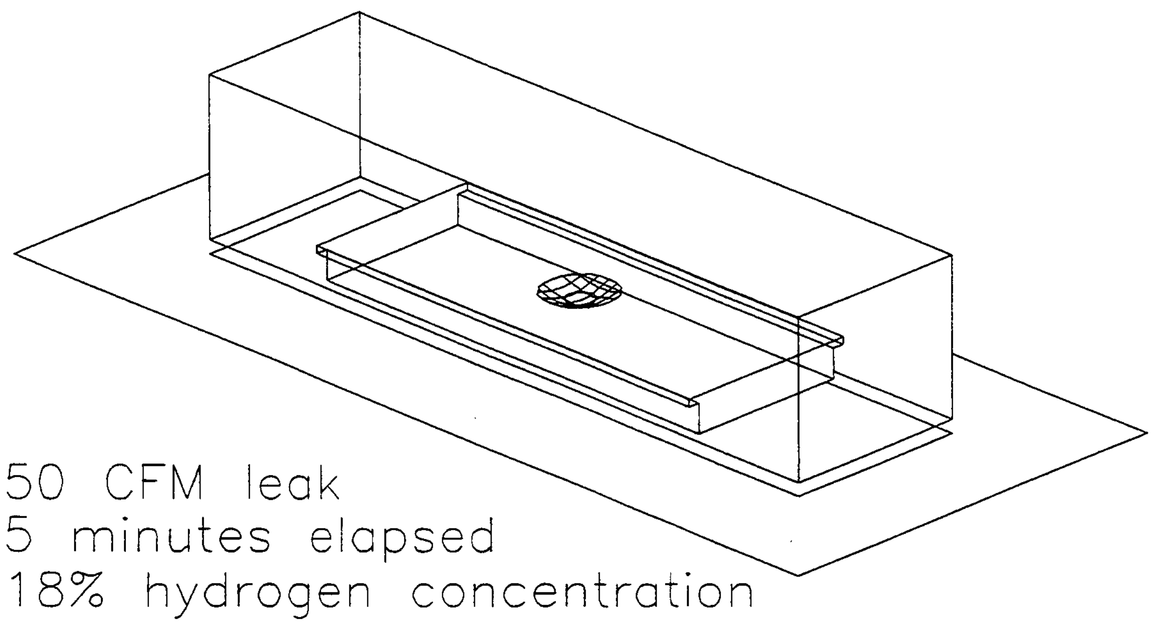

Figure 6 - Geometry C

Leak Classification

The use of "worst case" scenarios can considerably overestimate the risk incurred due to a hydrogen escape. To reduce this potential difficulty it is suggested that gaseous fuel escapes be classified by enclosure geometry and hydrogen flow quantity description. This could be 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.

Utilizing the above-listed classifications, general descriptions of the type of risks incurred can be made. 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 typically allow hydrogen to exit the enclosure 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 structures, which might potentially produce partial enclosures for escaping hydrogen, can be facilitated by simulating 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. 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.

Hydrogen Risk Assessment Method

The method of risk assessment utilizes three steps.

1. Simulation of the accident scenario with leaking helium.
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).

The following example is given, together with a comparison of the predicted hydrogen concentrations to experimentally determined values.

The geometry used for this example was a half-scale hallway. The dimensions were 114 inches (2.9 m) by 29 inches (0.74 m) by 48 inches (1.22 m). Figure 7 shows a schematic of the hallway. The hydrogen escaped from the floor at one end of the hallway (left hand side of figure). A roof vent and lower door vent existed at the other end of the hallway (right hand side of figure). Figure 7 shows an example of the velocity vectors predicted by the CFD model. Figure 7 also shows the points at which helium or hydrogen gas concentrations were measured. Figure 8 shows the results of the CFD model compared to the experimentally measured concentrations for helium escaping at 2 SCFM from the floor at the end of the hallway. Figure 9 shows the results of the CFD model compared to the experimentally measured concentrations for hydrogen escaping at 2 SCFM from the floor at the end of the hallway. It can be seen that the CFD model predicted the hydrogen behavior accurately.

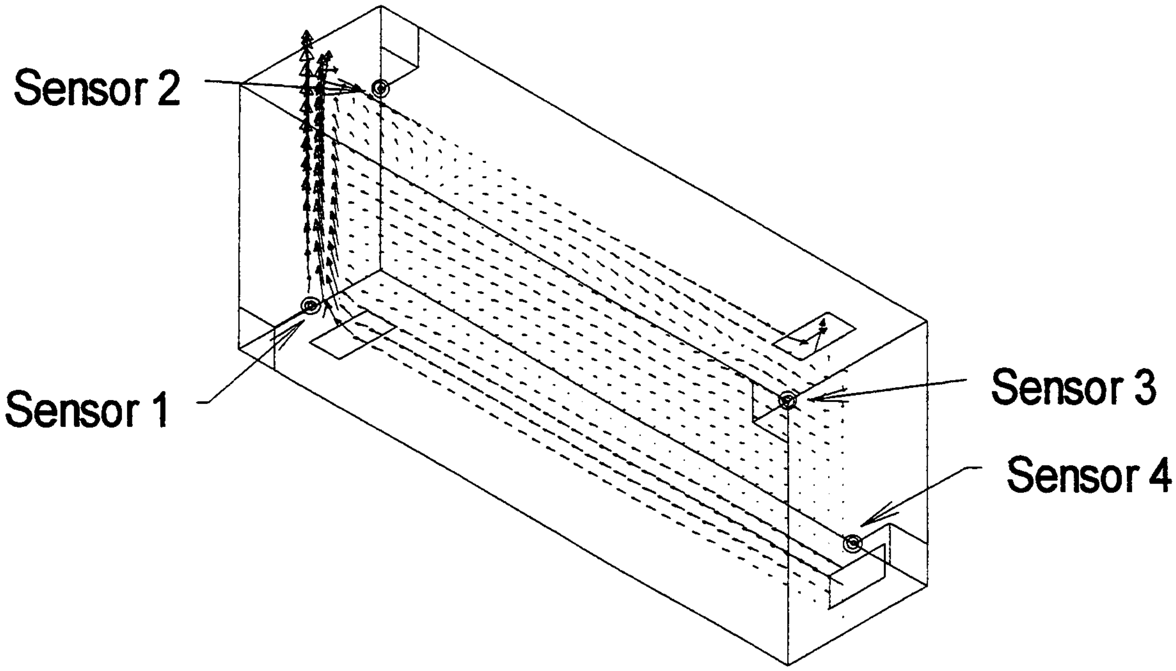

Figure 7 - Hallway with velocity vectors

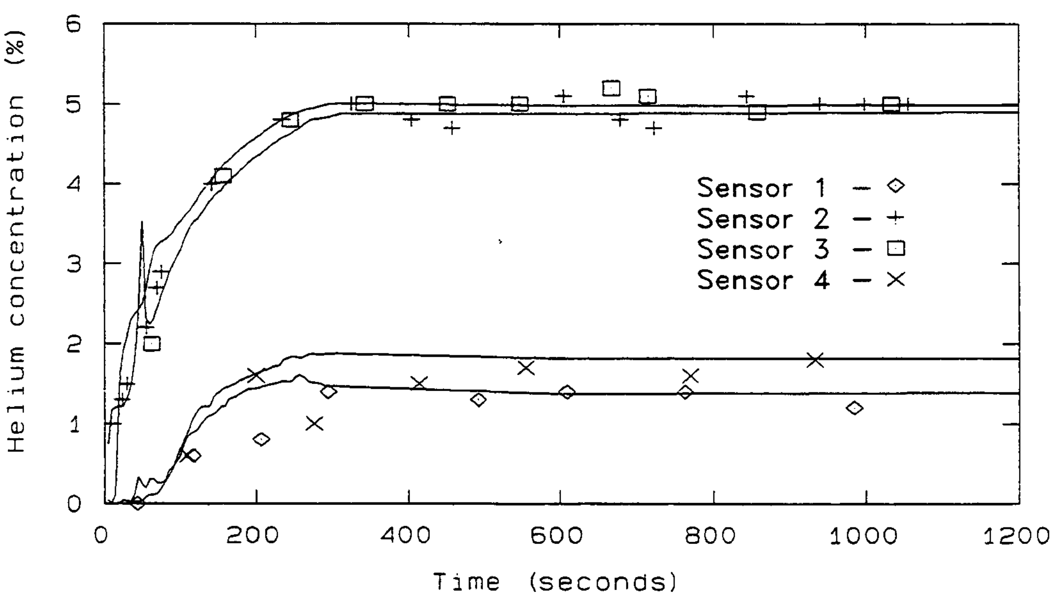

Figure 8 - 2 CFM leak at end of hallway

Figure 10 shows a comparison of the surfaces of constant 3% concentration for both helium and hydrogen. It can be seen that both gases rise from the floor, travel across the ceiling, and leave through the roof vent. The gas leaving the roof vent causes a drop in pressure, which draws air in the lower door vent. The general circulation in the hallway can be seen in Figure 7. All of the gases

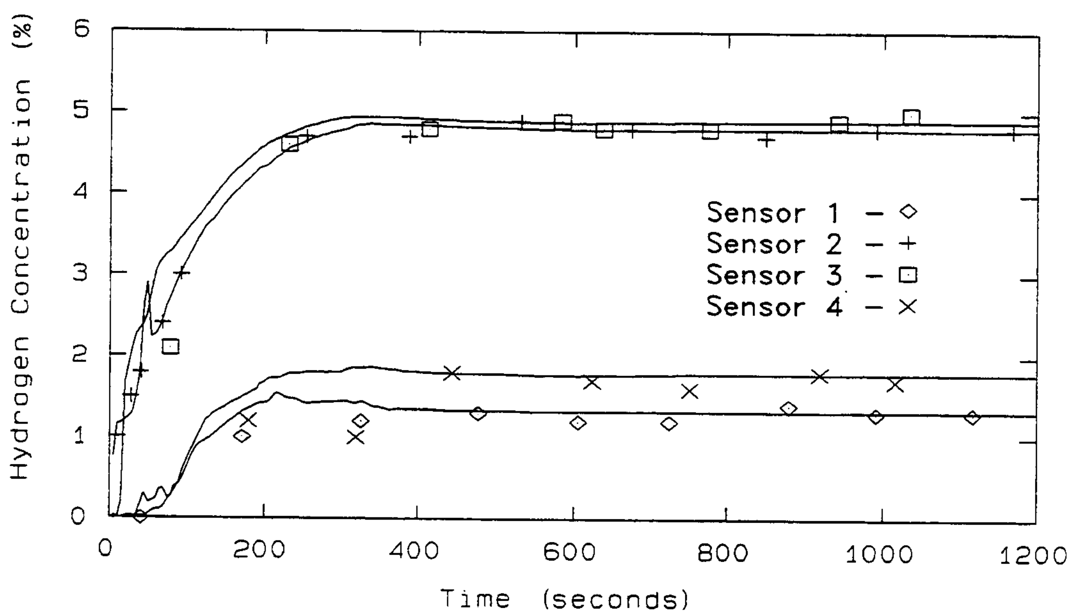

Figure 10 - 2 CFM Hydrogen leak at end of hallway

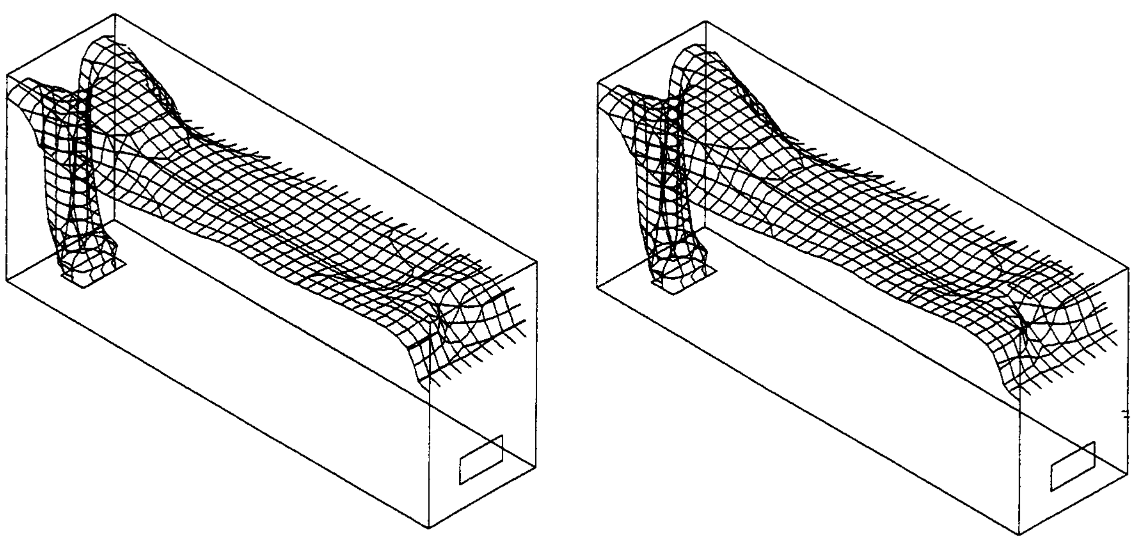

Figure 9 - Helium hydrogen comparison, 2 CFM leak at end of hallway, 1 min elapsed, 3% concentration

inside and above the surface of constant 3% concentration contain more than 3% helium or hydrogen. Those below the surface contain less than 3% concentration.

Figure 11 shows the surfaces of constant 1% concentration for helium and hydrogen. Comparison with Figure 10 gives an indication of the vertical concentration gradient in the hallway.

Figure 12 shows the results of the CFD model compared to the experimentally measured concentrations for hydrogen escaping at 2 SCFM from the middle of the floor in the hallway. Figure 13 shows the results of the CFD model compared to the experimentally measured concentrations for hydrogen escaping at 2 SCFM from the middle of the floor in the hallway. It can be seen that the CFD model predicted the hydrogen behavior accurately.

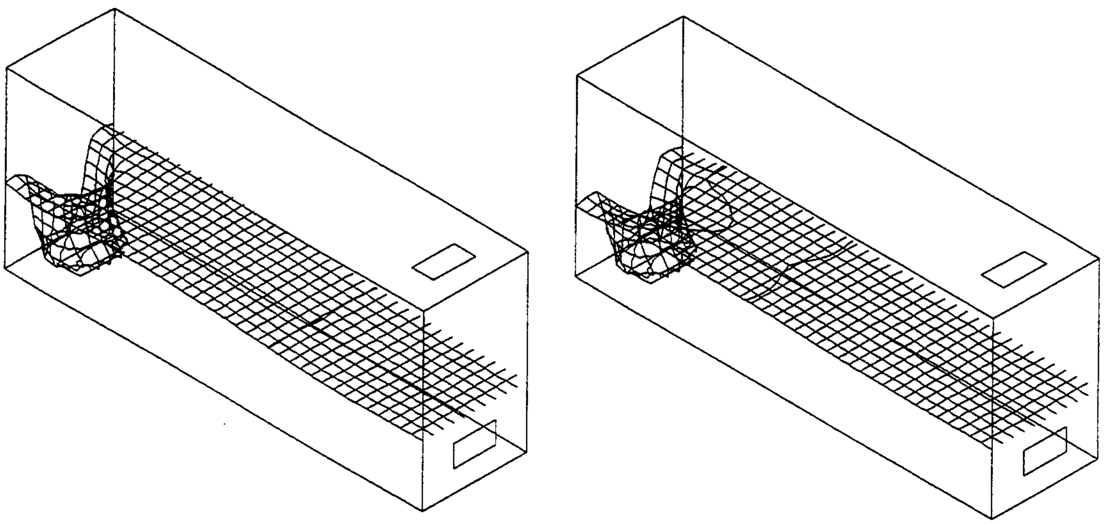

Figure 11 - Helium hydrogen comparison, 2 CFM leak at end of hallway, 1 min elapsed, 1% concentration

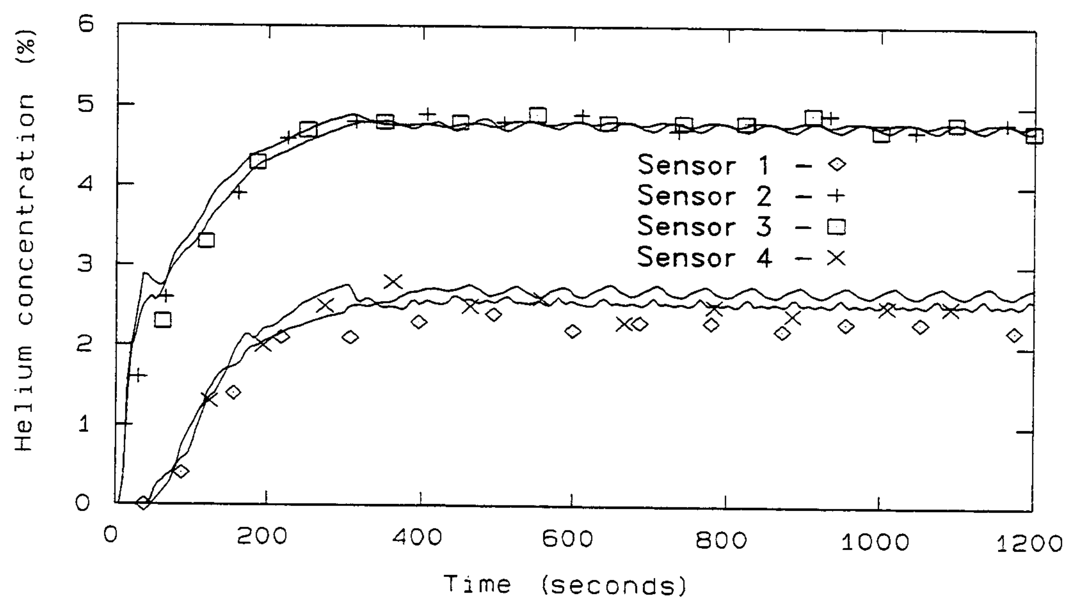

Figure 12 - 2 CFM Helium leak in middle of hallway

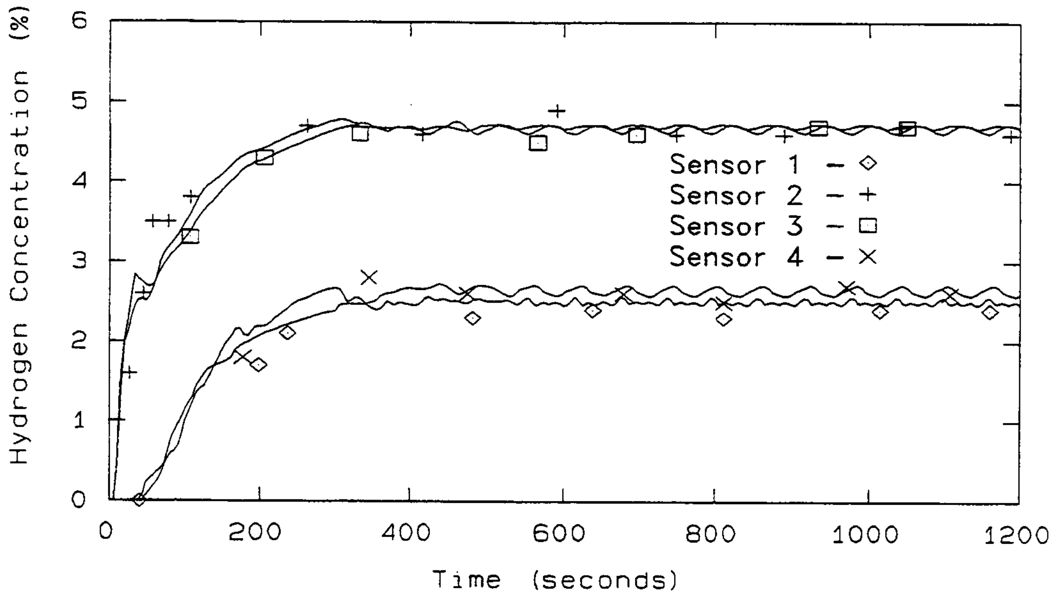

Figure 13 - 2 CFM Hydrogen leak in middle of hallway

The method was tested with an extended vertical vent (chimney). This was done to investigate a geometry that was potentially difficult to model. Figure 14 and 15 show the surfaces of constant 5% concentration versus time for both helium and hydrogen. In both cases the leakage rate was 2700 liters/hr into a 1 ft, by 1 ft, by 6 ft tall, vertical vent. The low density gas (helium or hydrogen) rises, entrains air, and forms a flow that attaches itself to various walls intermittently. The flow pattern fluctuates randomly. The concentration at a specific point was not predictable. It was therefore concluded that a vertical vent should be added to the hallway to test the ability of the CFD model to accurately predict hydrogen concentration.

Figure 16 shows the results of the CFD model compared to the experimentally measured concentrations for helium escaping at 2 SCFM from the floor at the end of the hallway and an extended vertical vent added to the roof vent. The concentration of helium was reduced compared to the hallway without the vertical vent because the vertical vent acted as a chimney, increasing the ventilation rate in the hallway. Figure 17 shows the results of the CFD model compared to the experimentally measured concentrations for hydrogen escaping at 2 SCFM from the floor at the end of the hallway and an extended vertical vent added to the roof vent. It can be seen that the CFD model predicted the hydrogen behavior accurately.

Comparison of Helium and Hydrogen Concentrations

The hydrogen concentration can be greater or less than the helium concentration depending on the enclosure geometry. Hydrogen is 8% more buoyant than helium and tends to rise more rapidly. The increased vertical velocity tends to increase both ventilation rate and gas mixing with air. If the exit vent is near the gas escape the increased gas mixing does not decrease the concentration of hydrogen in the hydrogen-air mixture leaving through the vent enough to overcome the increased ventilation rate, and hydrogen concentration tends to be lower than helium concentration. If the exit vent is far from the escape the increased gas mixing tends to reduce the concentration of hydrogen in the mixture leaving the enclosure enough to overcome the increased ventilation rate, and hydrogen concentration tends to be higher than helium concentration.

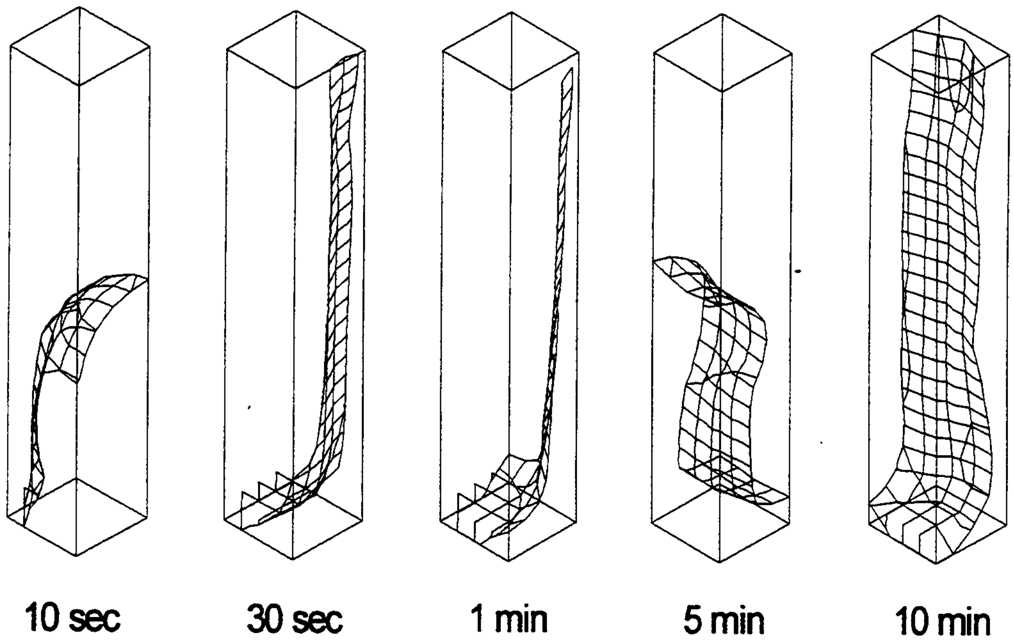

Figure 14 - CFD results for helium in vertical vent

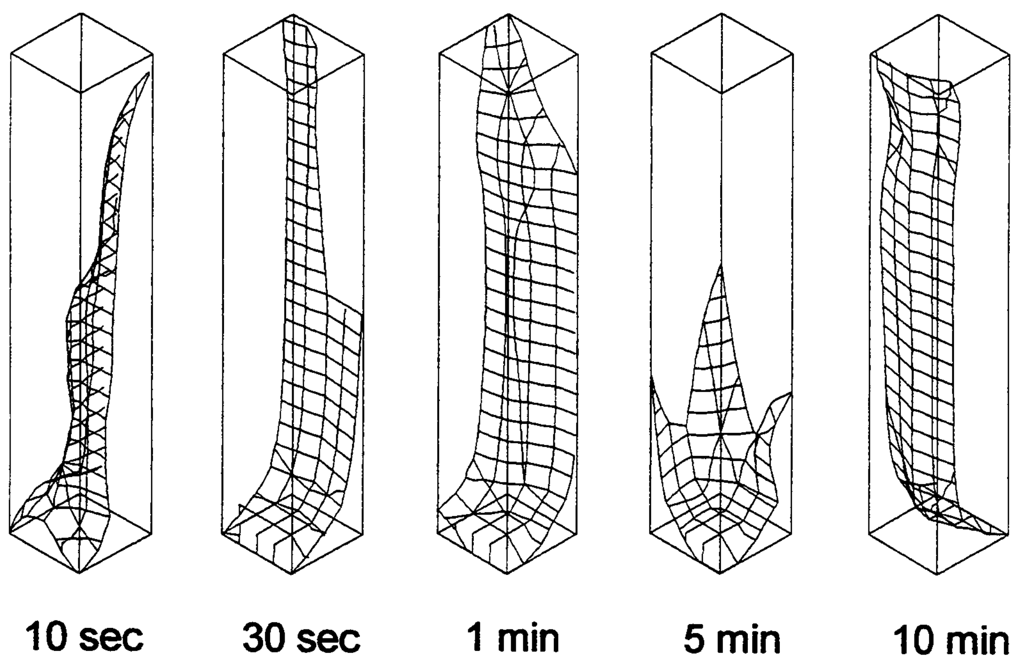

Figure 15 - CFD results for hydrogen in vertical vent

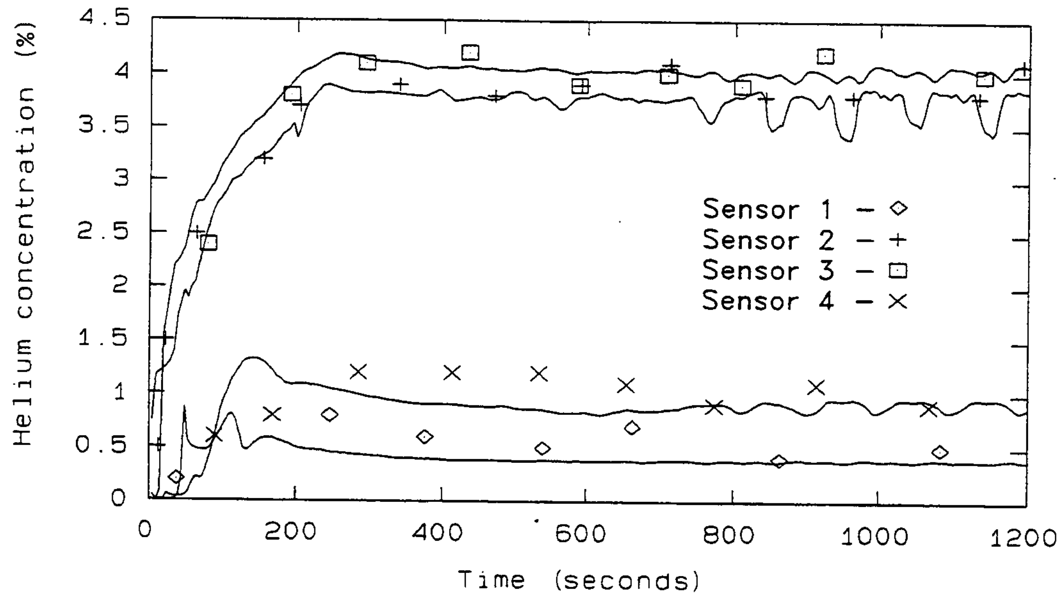

Figure 16 - 2 CFM Helium leak at end of hallway with extended vent

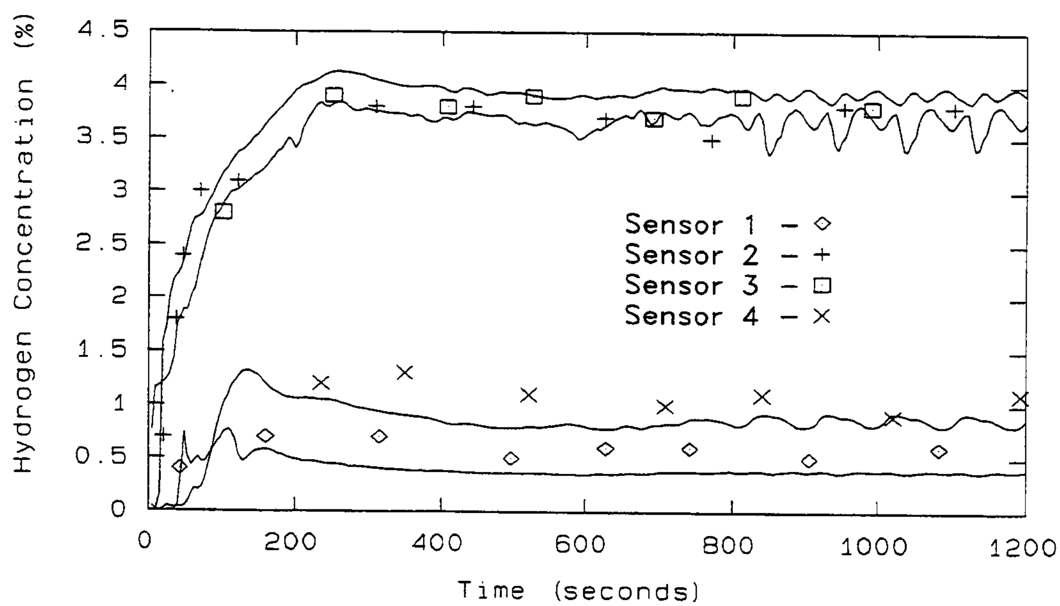

Figure 17 - 2 CFM Hydrogen leak at end of hallway with extended vent

Figure 18 and 19 depict a comparison of helium and hydrogen concentrations in a residential garage with a leaking home vehicle refill unit. Figure 18 is a schematic of the garage. There was a single vent in the garage door and a refill unit leaking 6800 liters/hr in the corner of the garage. The surface of constant 7.5% hydrogen concentration is shown after 20 minutes of leakage. Figure 19 shows a comparison of helium and hydrogen concentrations versus time. In this case, the hydrogen concentrations were higher than the helium concentrations. This was principally due to the use of a single vent from the enclosure. The single vent was very inefficient at removing hydrogen from the enclosure because it produced mixing of the vented gas with the incoming air. Efficiency could be greatly increased by installing both upper and lower vents. Hydrogen concentrations could be held below 2.5% for this accident scenario by utilizing upper and lower vents in the garage door.

Figures 20 and 21 depict a comparison of helium and hydrogen concentrations for a van parked in a garage with a single vent. The accident scenario was hydrogen escaping from under the front of the van. In this case, the presence of the van enhanced mixing to the point that helium and hydrogen concentrations were nearly identical. Again, the hydrogen concentrations could be held below 2.5% for this accident scenario by utilizing upper and lower vents in the garage door.

For the hydrogen escapes into enclosure geometries studied to date, the maximum deviation between helium and hydrogen concentrations was 15%.

Conclusions

1. "Worst Case" accident scenarios can considerably overestimate the risk incurred in hydrogen escapes.

2. A helium data verified CFD computer model can accurately predict the spatial and temporal distribution of hydrogen released in a hydrogen escape.

3. For the hydrogen escapes into enclosure geometries studied to date, the maximum deviation between helium and hydrogen concentrations was 15%.

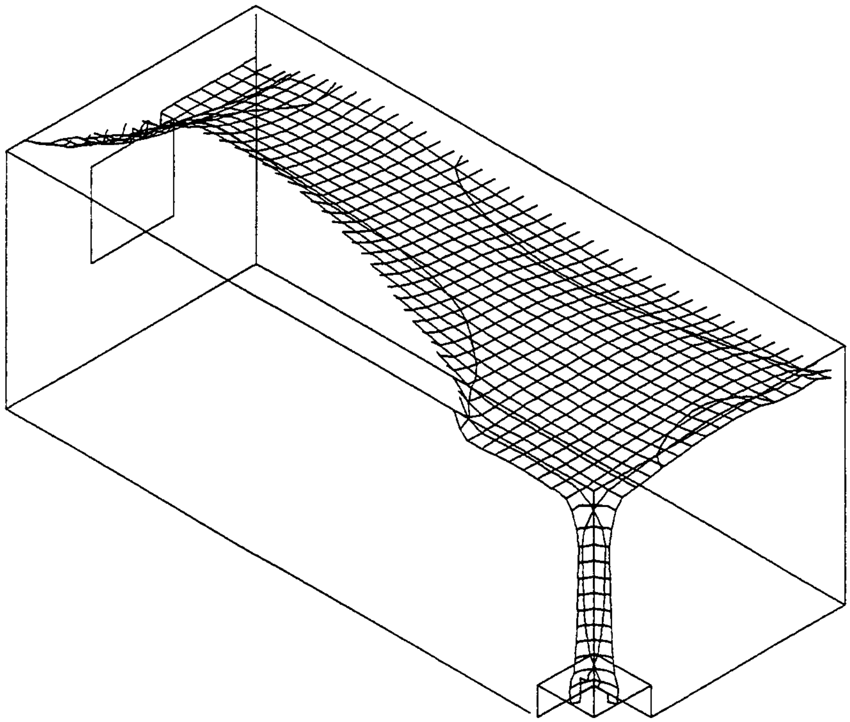

Figure 18 - 7.5% Hydrogen, 6800 l/hr after 20 minutes

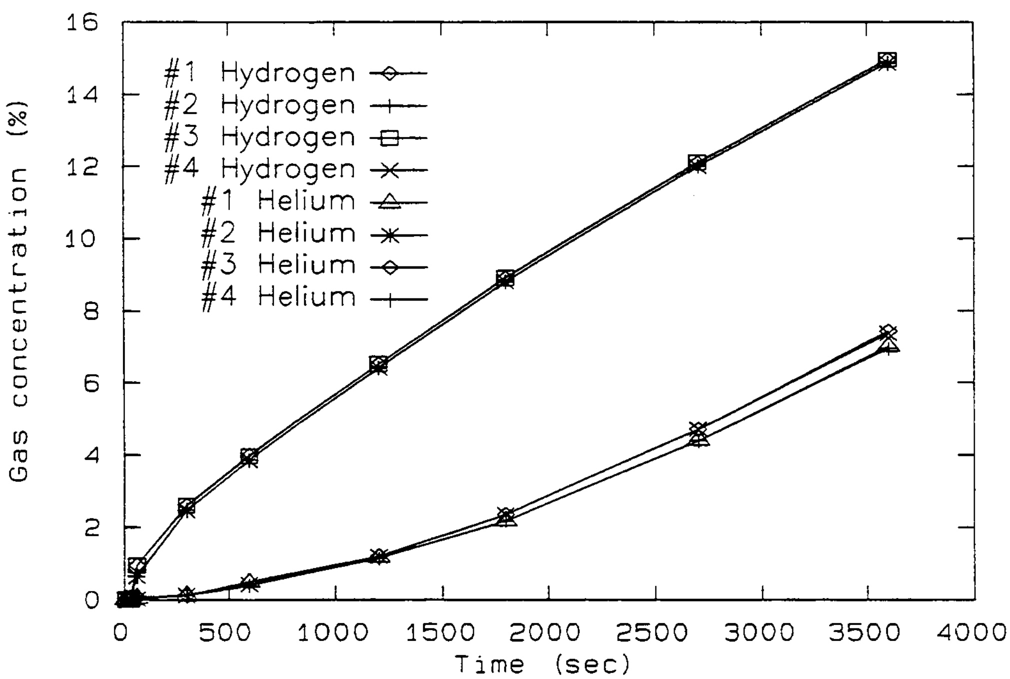

Figure 19 - Home refill scenario 6800 l/hr

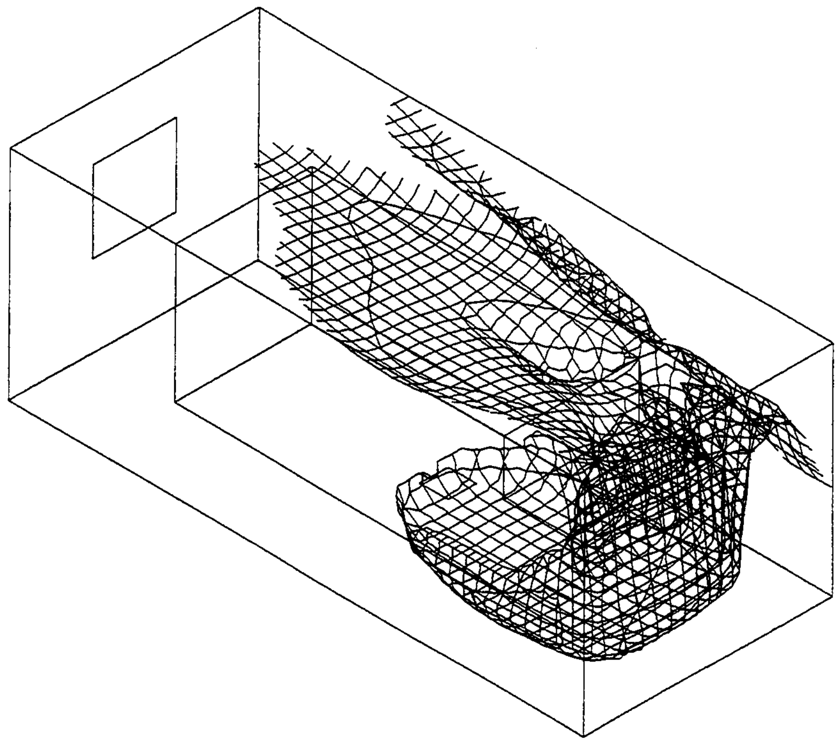

Figure 20- 6.5% Hydrogen, 6800 l/hr after 20 minutes

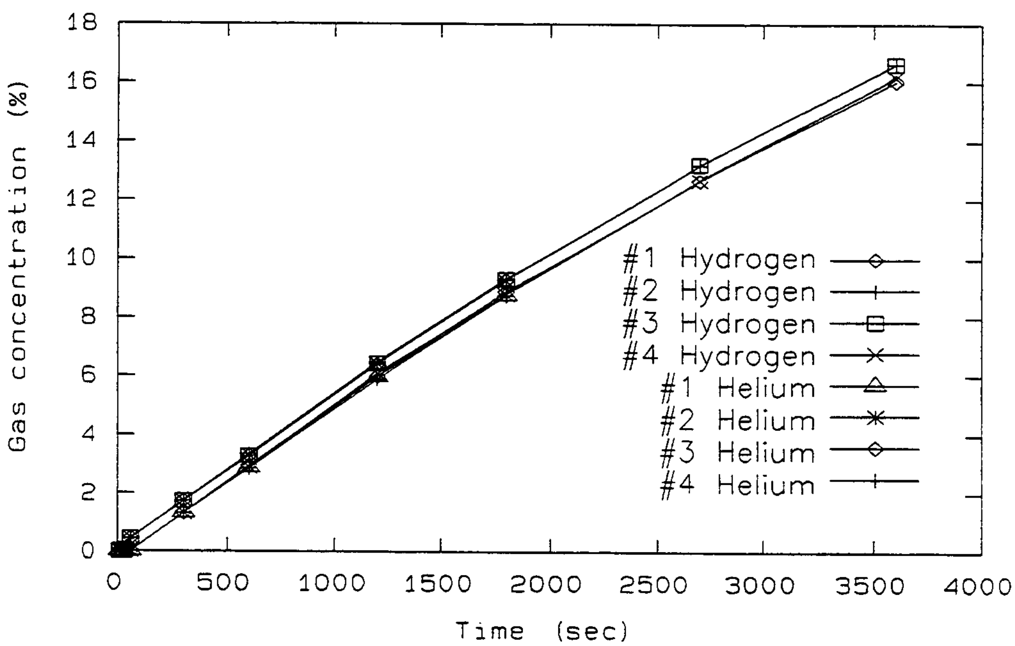

Figure 21- Leaking van scenario 6800 l/hr

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