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Codes and Standards Analysis

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Abstract

The following report contains work on three separate tasks. They are as follows:

Task A -- Safety Analysis of California Fuel Cell Partnership Building
Task B -- Development of Method to Determine Hydrogen Sensor Placement
Task C -- Safety Analysis of Home Refueling Systems

The work in Task A is an analysis of the existing system and procedures that deal with hydrogen leakage from hydrogen fuel vehicles. The work in Task B is the construction of a computer model of a 5000-square foot building. The model is to be used while developing a method for using helium-filled bubbles to determine hydrogen sensor placement. The work in Task C was divided into three additional areas:

Area 1 - Computer modeling of hydrogen leakage to assist in writing International Mechanical Code for ventilation and setbacks.
Area 2 - Determination of minimum hydrogen leakage rate that can support a flame.
Area 3 - Analysis of hydrogen flame impingement on gypsum board.

Introduction

The goals and objectives of this work effort were set by anticipating the needs of various projects and authors of codes and standards. The work effort had to be altered slightly in July 2000 and March 2001 to take into account information not known previously. Task A was changed from modeling of an underground garage to modeling of the California Fuel Cell Partnership building in Sacramento. Task B was postponed to allow for additional work in Task A and Task C.

Task A – CaFCP Building Safety Analysis

Task A addresses six questions concerning the CaFCP building in Sacramento CA. They are as follows:

1. Is the present ventilation adequate?
2. When should high ventilation flow rate be used?
3. Can a burnable mixture of hydrogen be drawn into the A/C system?
4. Should the garage door be opened in conjunction with high flow rate ventilation?
5. How will the present system handle PRD activation?
6. Is exhaust inlet placement optimized?

Six computer models have been run to analyze six accident scenarios. These six accident scenarios will be presented in the following seven figures. The conclusions reached about each of the six questions above will be addressed figure by figure.

The leakage rate was set at 80 SCFM hydrogen. This was chosen because it represents a reasonable maximum flow rate above which the excess flow valve would be activated. In addition, multiple safety systems would have to fail to produce an 80 SCFM hydrogen leak. At a leakage rate of 80 SCFM, the excess flow valve mounted in the tank would shut off hydrogen flow from the tank.

The air ventilation rates for the bay, without any forced ventilation, were measured as 371 SCFM. It would require a procedural error for a vehicle to be in the building under these conditions. If a vehicle is in the building, a ventilation rate of 2100 SCFM should be present. Figure A1 shows how large a combustible cloud would be produced for a leakage rate of 80 SCFM with a ventilation rate of 371 SCFM. The cloud surface mesh in red shows the boundaries of a 4.1% hydrogen concentration cloud, while the cloud surface mesh in blue shows the boundaries of a 0.82% hydrogen concentration cloud. 4.1% hydrogen is the leanest burnable mixture of hydrogen and air. The hydrogen leakage rate of 80 SCFM empties the fuel tank in 20 minutes. It can be seen that after five minutes of leakage a column of burnable mixture rises to the ceiling and begins to spread across the ceiling. After 20 minutes, a layer of burnable gas from 3.4 to 5.0 feet thick rests on the ceiling. It will take an additional 47 minutes for this cloud to completely disappear. The bay was receiving 0.265 air exchanges per hour; 0.208 air exchanges were required to remove all burnable gas mixtures.

The baseline ventilation rate of the bay is 2100 SCFM whenever a vehicle is present in the bay. This is depicted in Figure A2. If the system functions properly, this ventilation rate would increase to 6300 SCFM if a concentration of 0.82% hydrogen were detected 18 inches below the ceiling. If the system fails the ventilation rate would remain at 2100 SCFM as depicted in Figure A2. Once again the cloud surface mesh in red depicts 4.1% hydrogen concentration and the cloud surface mesh in blue depicts 0.82% hydrogen concentration. It can be seen the baseline ventilation rate of 2100 SCFM almost eliminates the accumulation of burnable hydrogen air mixtures at the ceiling. The bay would be emptied of burnable mixture two minutes after the fuel tank is empty (20 minutes). The bay was receiving 1.5 air exchanges per hour; 0.050 air exchanges were required to remove all burnable gas mixtures.

If the ventilation system functions properly the ventilation increases to 6300 SCFM when hydrogen is sensed. This is depicted in Figure A3. The red cloud surface mesh shows 4.1% hydrogen concentration. It can be seen that 6300 SCFM ventilation prevents the burnable column of hydrogen from reaching the ceiling. At 20 minutes, the column has not reached the ceiling and will disappear ten seconds after the vehicle runs out of hydrogen (at 20 minutes.) The bay was receiving 4.5 air exchanges per hour; 0.013 air exchanges were required to empty the bay of burnable mixture. To be adequate, the ventilation rate must prevent the accumulation of hydrogen concentrations greater than 4.1% on the ceiling of the building. 6300 SCFM is capable of this for leakage rates of 80 SCFM hydrogen. Therefore, a 6300 SCFM ventilation rate is needed.

Figure A4 shows the effects of moving the vehicle. Placing a vehicle as shown in Figure A4 creates the largest distances between the hydrogen leak and the exhaust vents. This does place the leak in close proximity to the air conditioning inlet. In this case, the ventilation rate began at 2100 SCFM and increased to 6300 SCFM after 38 seconds of leakage. This is the time when the first sensor detectss 0.82% hydrogen concentration. That sensor reached 0.41% hydrogen concentration after 27 seconds of leakage. If the sensor were raised 12 inches (to 6 inches below the ceiling) it would have reached 0.82% hydrogen concentration after 31 seconds. It can be seen that the ventilation system also prevents the burnable cloud of hydrogen from reaching the ceiling with a vehicle in this position. Once again the burnable cloud disappears within ten seconds of the vehicle running out of hydrogen (20 minutes). 6300 SCFM is capable of preventing hydrogen concentrations of 4.1% on the ceiling. A 6300-SCFM ventilation rate is needed.

The questions raised by the previous accident scenario are: does burnable hydrogen enter the air conditioning inlet in the upper corner of the bay, and what effect does opening the bay garage door have on the results? Figure A5 shows the bay with 4400 SCFM of air conditioning circulation included. The first sensor reaches 0.82% hydrogen after 60 seconds of leakage. This initiated the higher exhaust flow rate (6300 SCFM) and the opening of the garage door. It reaches 0.41% hydrogen after 37 seconds of leakage and would have reached 0.82% hydrogen after 42 seconds if located six inches from the ceiling instead of 18 inches. The garage door requires 23 seconds to open. Figure A5 shows the two accident scenarios (closed door, open door) after five minutes of leakage. It can be seen that opening the garage door has reduced the fresh air makeup flow through the air conditioning system, thereby increasing the hydrogen concentration in the air conditioning system to values above 0.82%.

Figure A6 shows the two accident scenarios after ten minutes of leakage. The hydrogen air mixtures exiting the air conditioning system, in the bay with the open garage door, were greater than 0.82% but less than 4.1%. The hydrogen-air mixture exiting the air conditioning system, in the bay with a closed garage door, was less than 0.82% hydrogen.

Figure A7 shows the two accident scenarios after 20 minutes of leakage. The ventilation systems in both bays have prevented the burnable column of hydrogen air mixture from reaching the ceiling. In both cases, the bays will contain no burnable hydrogen within ten seconds. The bay with the closed garage door will require 1721 seconds to empty below 0.82% hydrogen concentration. The bay with the open garage door will require 1706 seconds. The burnable hydrogen (4.1% by volume) does not enter the air conditioning system. Opening the garage door does not appreciably assist in removing hydrogen from building. However, raising the floor exhaust inlet vent to the ceiling would aid in the removal of hydrogen from the building.

Task B - Development of Method to Determine Hydrogen Sensor Placement

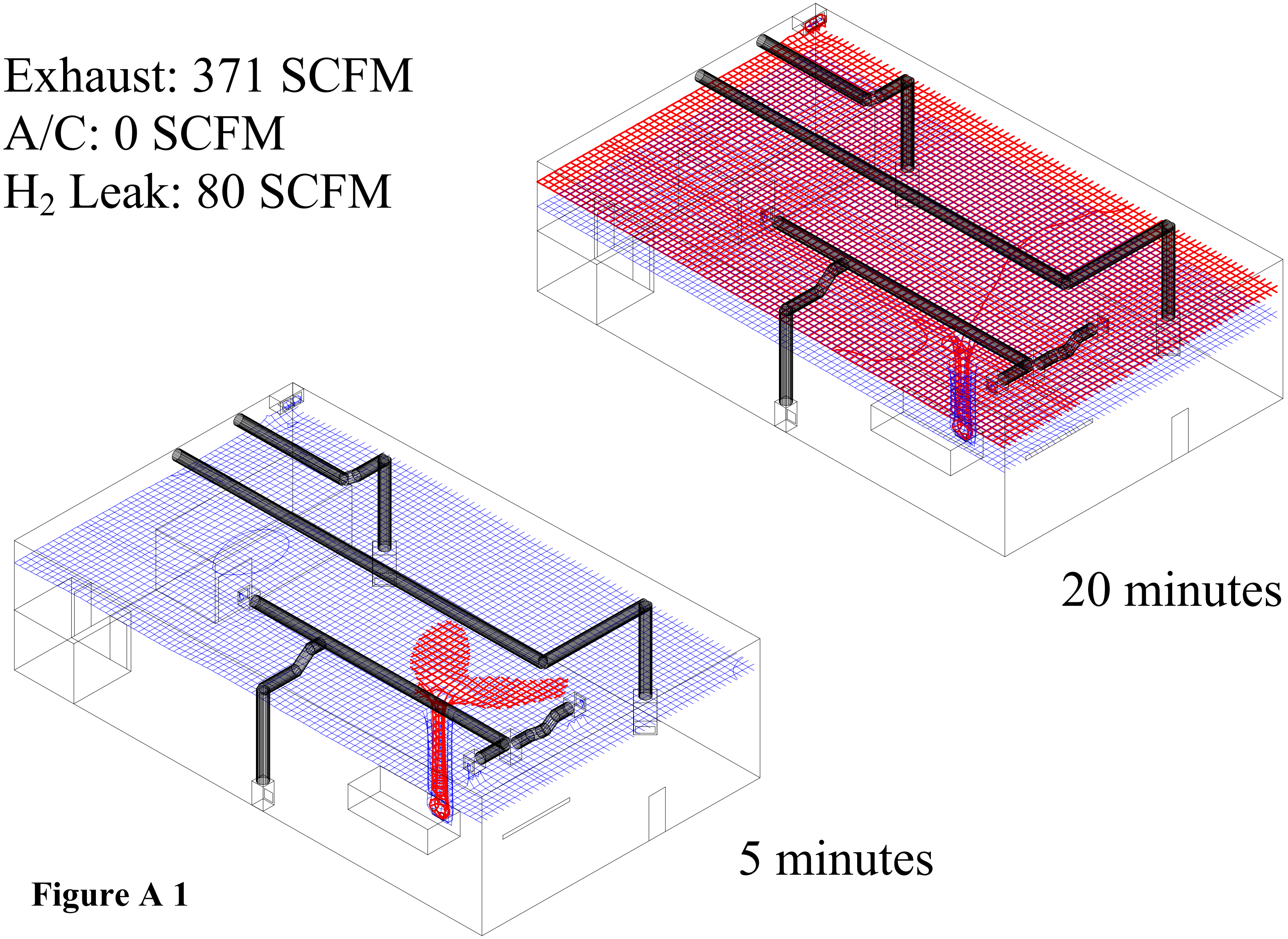
Task B, which was discontinued in March 2001, was the development of a method to determine hydrogen sensor placement. The procedure used to develop the method was to produce an experimentally-verified computer model of a 5000-square foot building with helium leakage. The model was then tested with hydrogen releases. The model will be used to test the accuracy of determining hydrogen sensor location with a method to be developed in the coming year. The development and testing of the computer model will be discussed herein.

Figures B1 and B2 show the 5000-square foot warehouse with the flow field generated by the 8900 SCFM exhaust fans. Office space exists at either end of the warehouse accounting for the missing volumes on the first floor level at each end of the warehouse. It can be seen that the flow on the office wall at the near-end of the warehouse is complicated. A circulation is created with the flow moving to the left, high on the wall, and to the right near the floor. The gas motion created by the circulation is clearly visible in Figures B3 and B4. Hydrogen is leaking from the wall at 20 SCFM. The plot of 0.8% hydrogen at 10 and 30 seconds shows the top of the gas cloud moving to the left hand the bottom to the right. The gas leak was positioned on the office wall for verification of the model.

Figure B5 shows the boundaries of 0.8% hydrogen concentration after 60 seconds of leakage. The experimental verification was ended after 60 seconds. Figure B6 shows the boundaries of 0.8% helium concentration after 60 seconds of leakage. The clouds formed by helium were very similar to the clouds formed by hydrogen.

Instantaneous gas releases were performed in the center of the bay at the floor. The instantaneous gas releases were performed with no circulating airflow (exhaust fans were off.) Instantaneous releases were performed experimentally by constructing a breakaway clamshell plastic bag with measured nylon lines attached at multiple locations along the seam. The nylon lines allowed the bag to be snapped open. The bags were filled with a measured amount of helium or hydrogen.

Exhaust: 371 SCFM
A/C: 0 SCFM
H_2 Leak: 80 SCFM

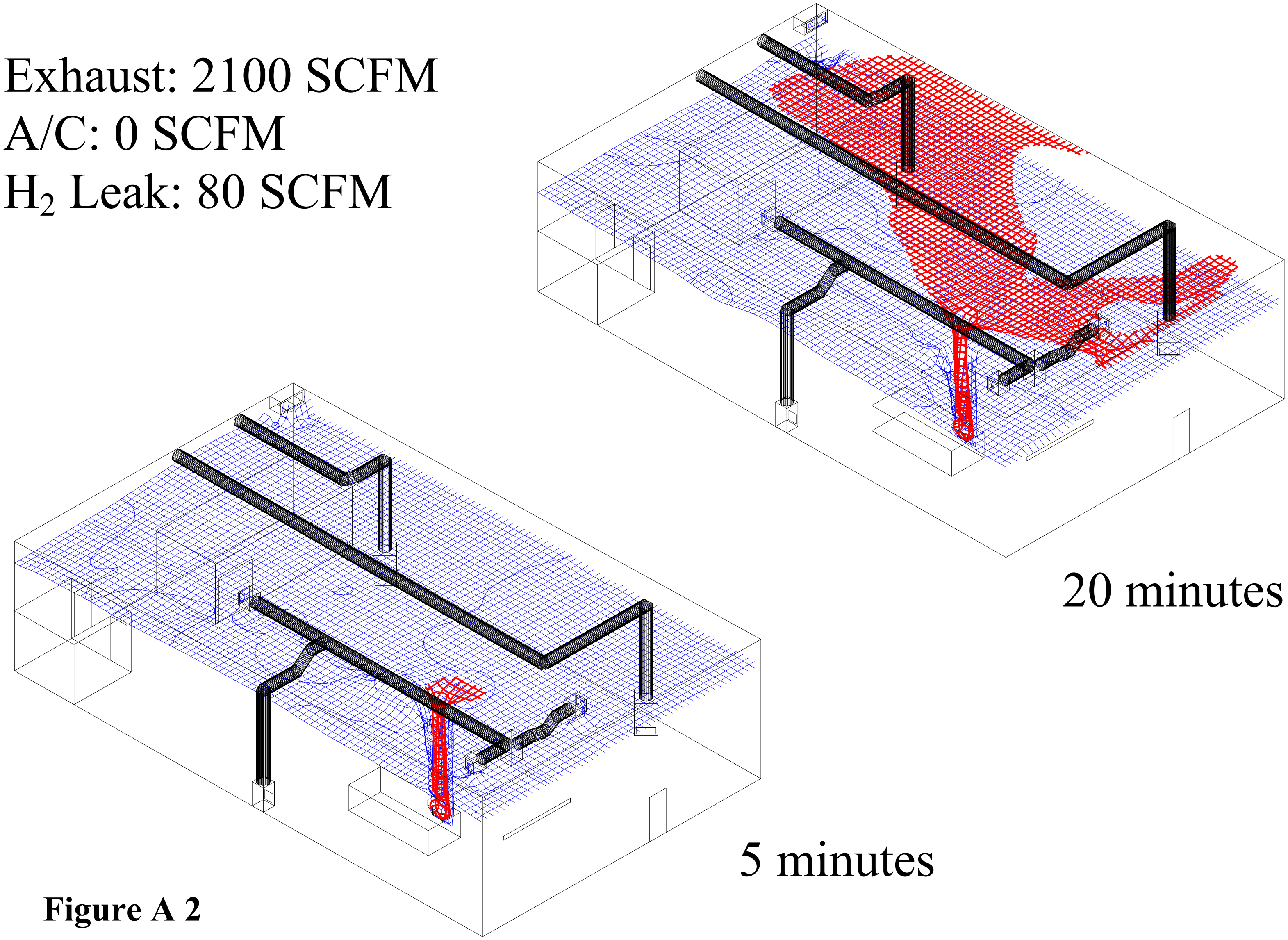


20 minutes

5 minutes

Figure A 1

Exhaust: 2100 SCFM
A/C: 0 SCFM
H_2 Leak: 80 SCFM

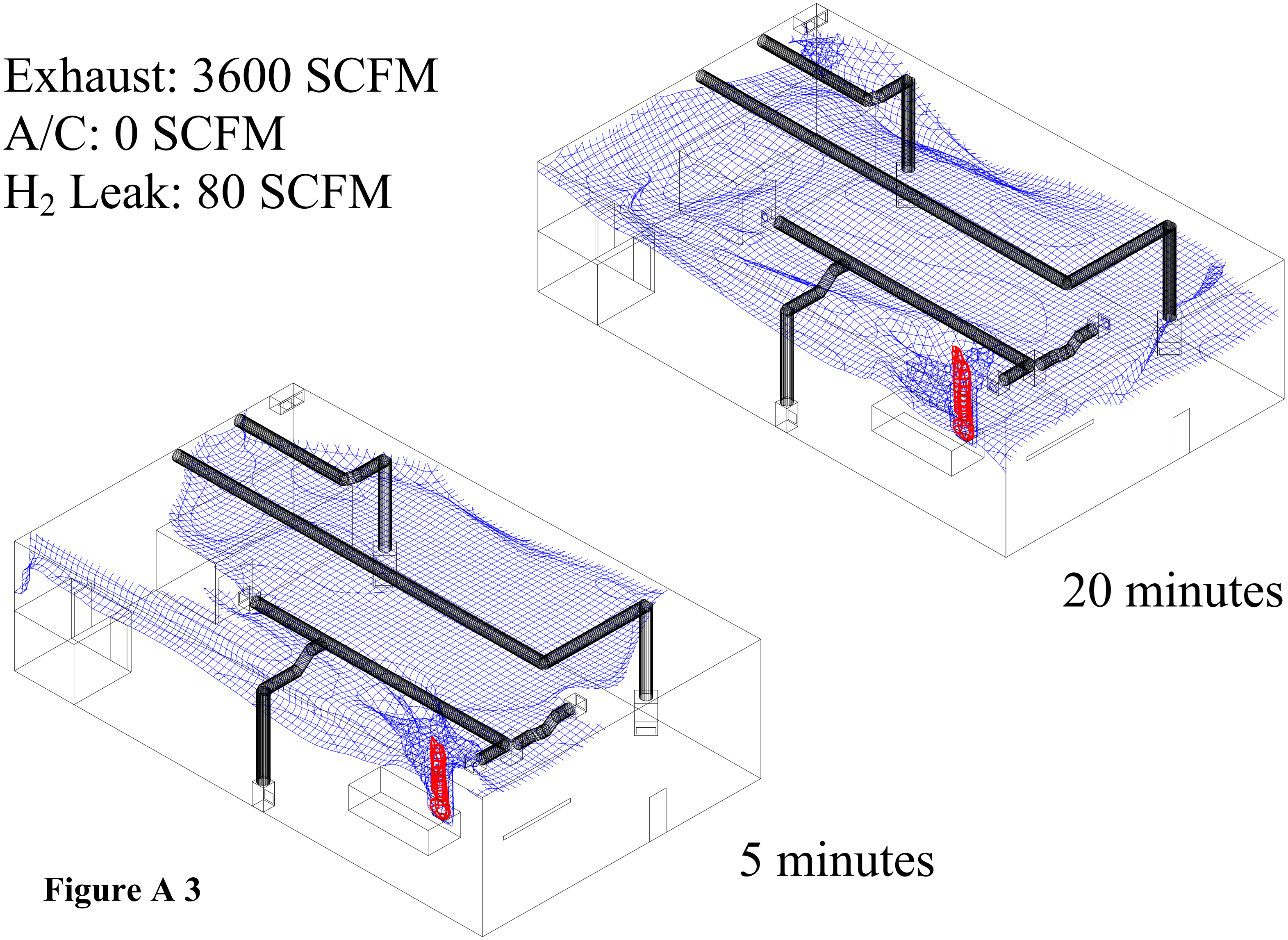


20 minutes

5 minutes

Figure A 2

Exhaust: 3600 SCFM
A/C: 0 SCFM
H_2 Leak: 80 SCFM



20 minutes

5 minutes

Figure A 3

Exhaust: 2100/6300 SCFM
A/C: 0 SCFM
H_2 Leak: 80 SCFM

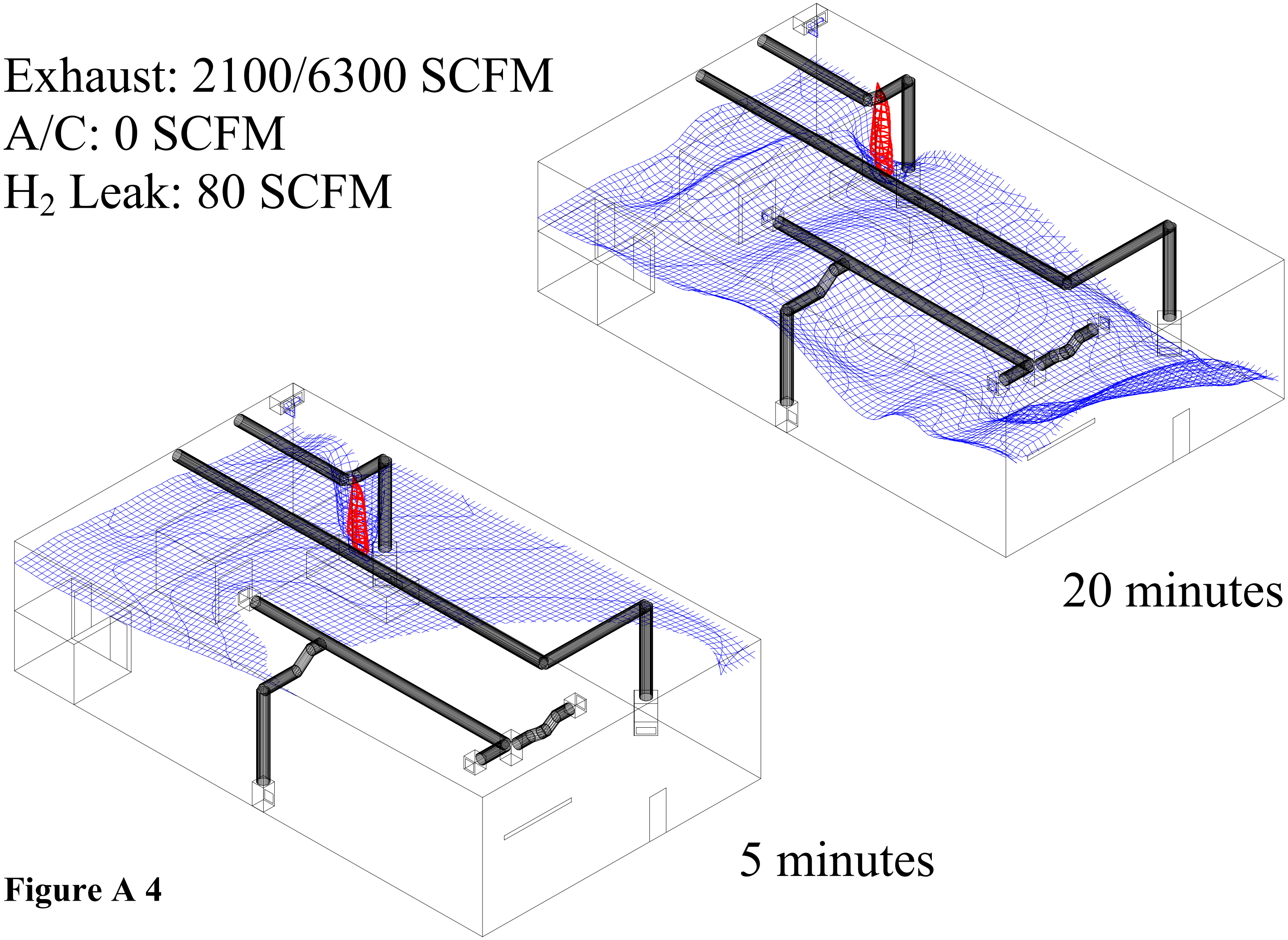
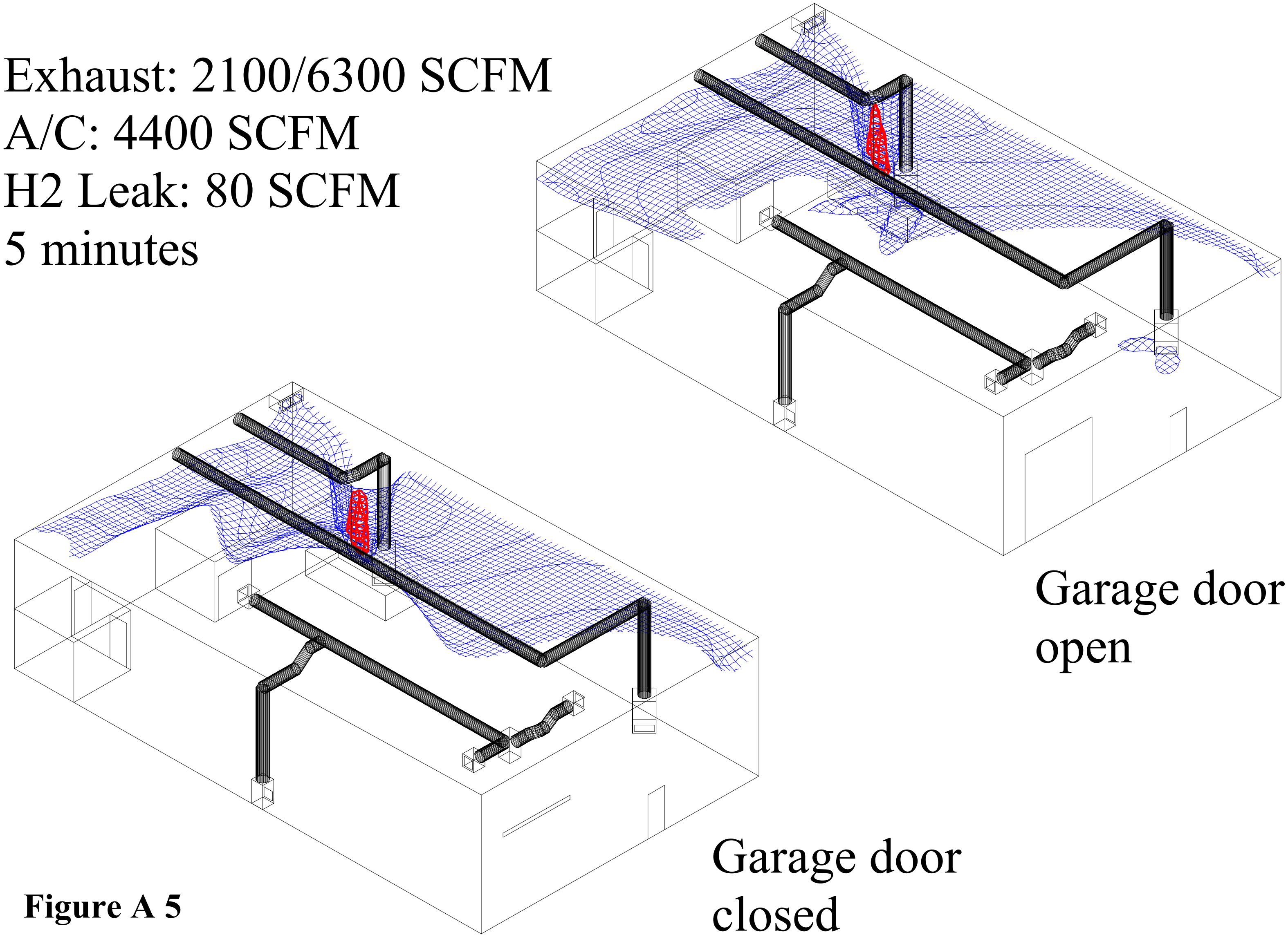


Figure A 4

Exhaust: 2100/6300 SCFM
A/C: 4400 SCFM
H2 Leak: 80 SCFM
5 minutes

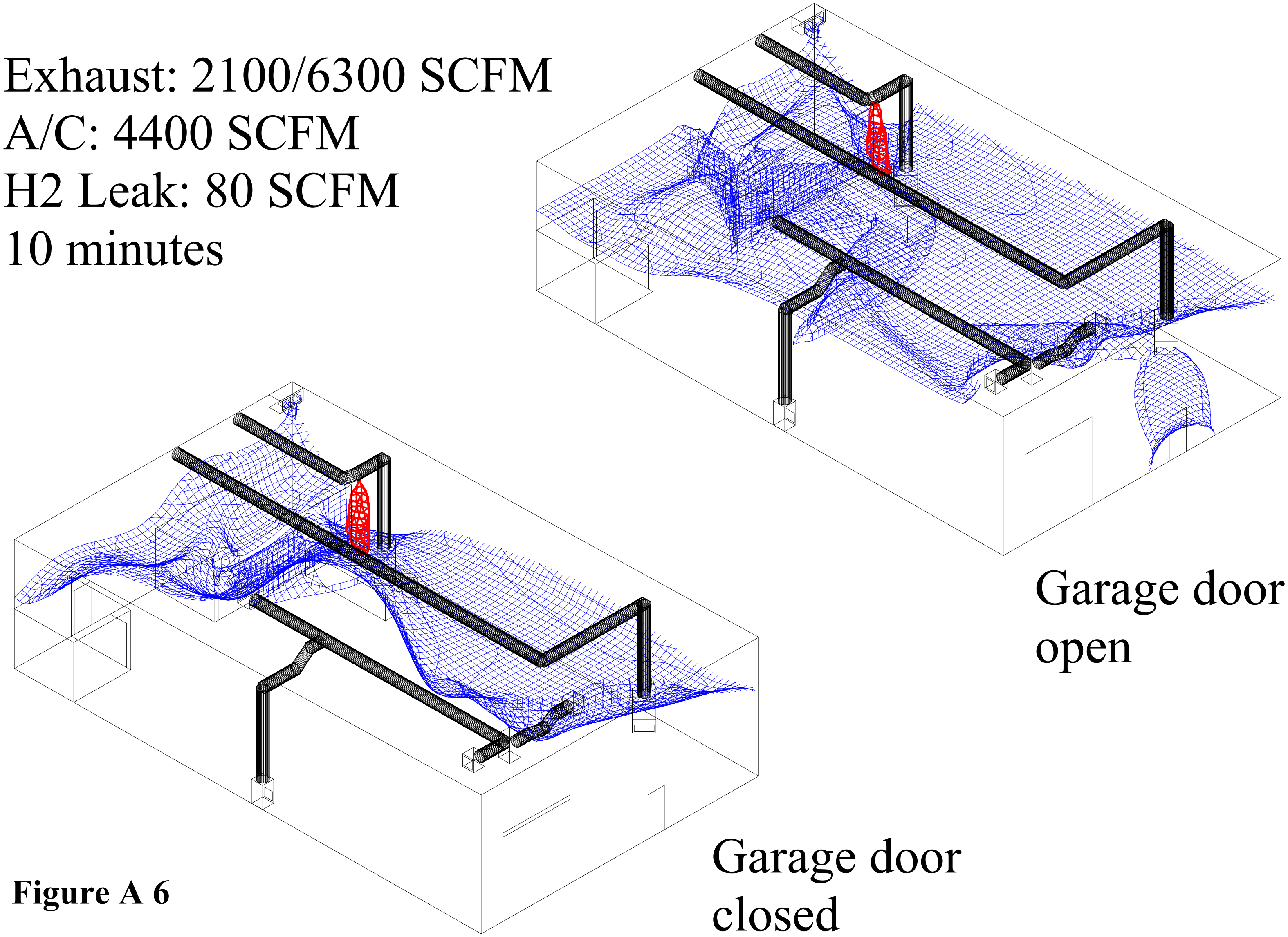


Garage door open

Garage door closed

Figure A 5

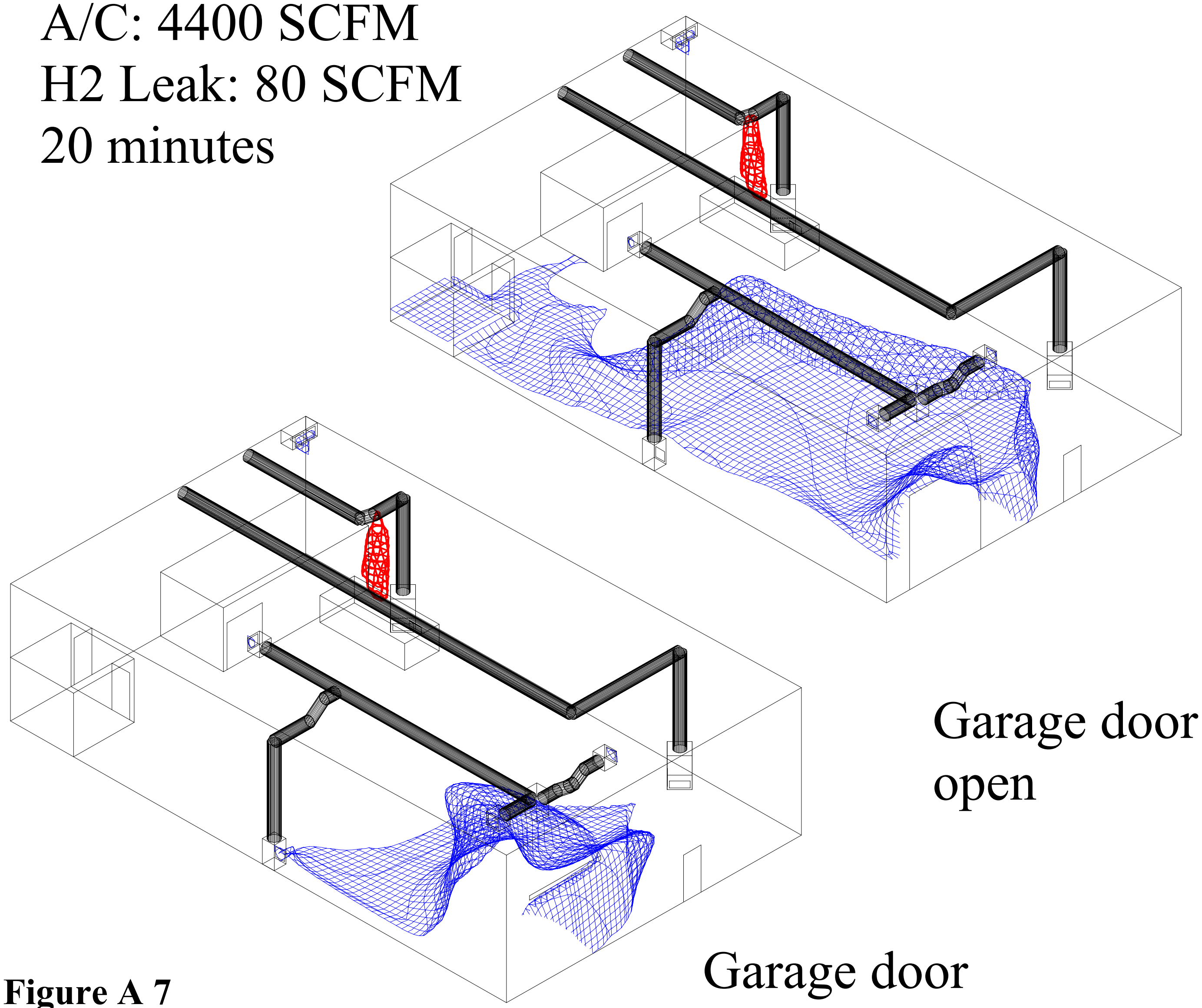
Exhaust: 2100/6300 SCFM
A/C: 4400 SCFM
H2 Leak: 80 SCFM
10 minutes



Garage door open

Garage door closed

Figure A 6



Exhaust: 2100/6300 SCFM
A/C: 4400 SCFM
H2 Leak: 80 SCFM
20 minutes

Figure A 7

Figure B7 and B8 show the position of hydrogen at 1.0% and 4.1% concentration one second after an instantaneous release of 8 cubic feet. The clouds are similar in size because there has been little diffusion in the first second.

Figures B9 and B10 show the same release at 2 seconds. Figures B11 and B12 show the same release at 3 seconds. The 4.1% hydrogen concentration cloud has risen off the floor, and is decreasing in size as it rises. Both the 1% concentration cloud (Figure B13) and the 4.1% concentration cloud (Figure B14) have reached the ceiling at four seconds. By ten seconds, the 1% concentration cloud (Figure B15) has spread over the ceiling. By seven seconds, the 4.1% concentration cloud (Figure B16) vanishes and there is no longer any burnable mixture of hydrogen and air in the enclosure.

The computer model of the 5000-square foot warehouse is finished and experimentally verified with helium and hydrogen. The next step is to determine if a method utilizing helium bubbles can be developed to show the proper locations for hydrogen sensors.

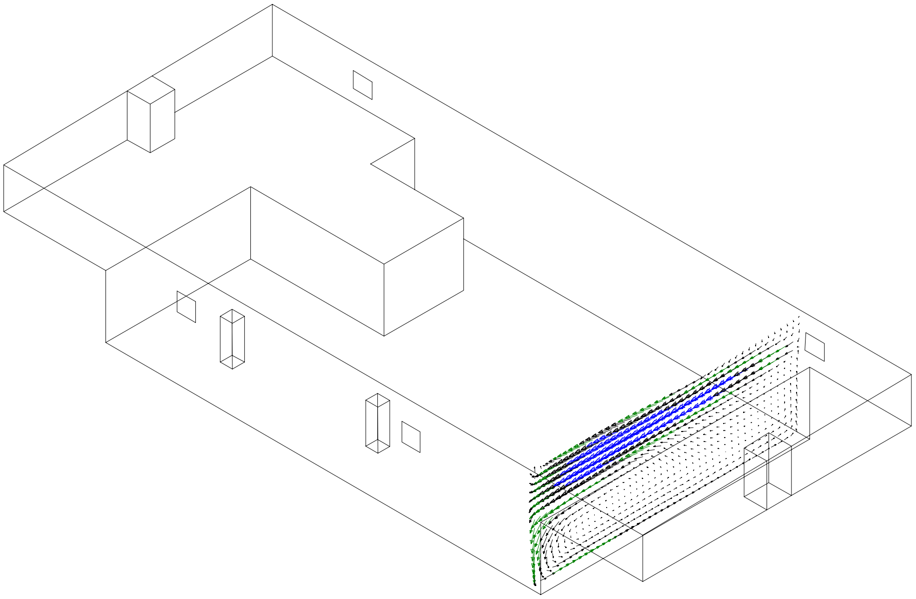


Figure B 1 - Flow field produced by 8900 SCFM exhaust fans

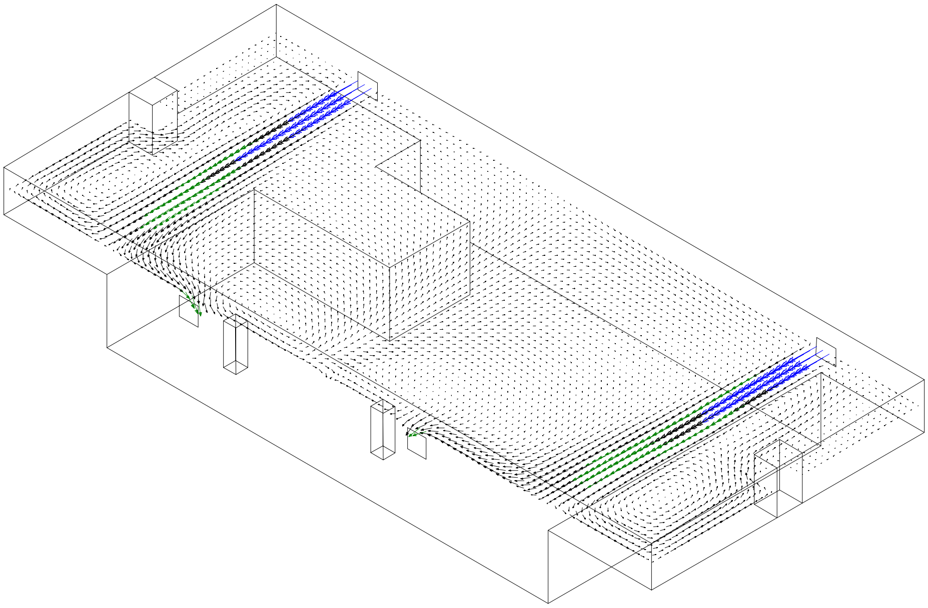


Figure B 2 - Flow field produced by 8900 SCFM exhaust fans

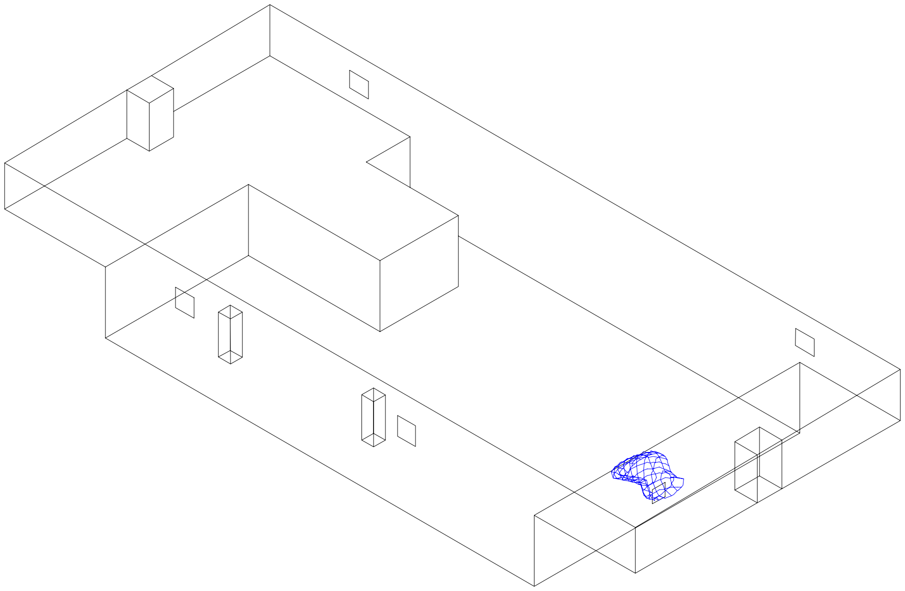


Figure B 3 - 20 SCFM hydrogen leakage after 10 seconds

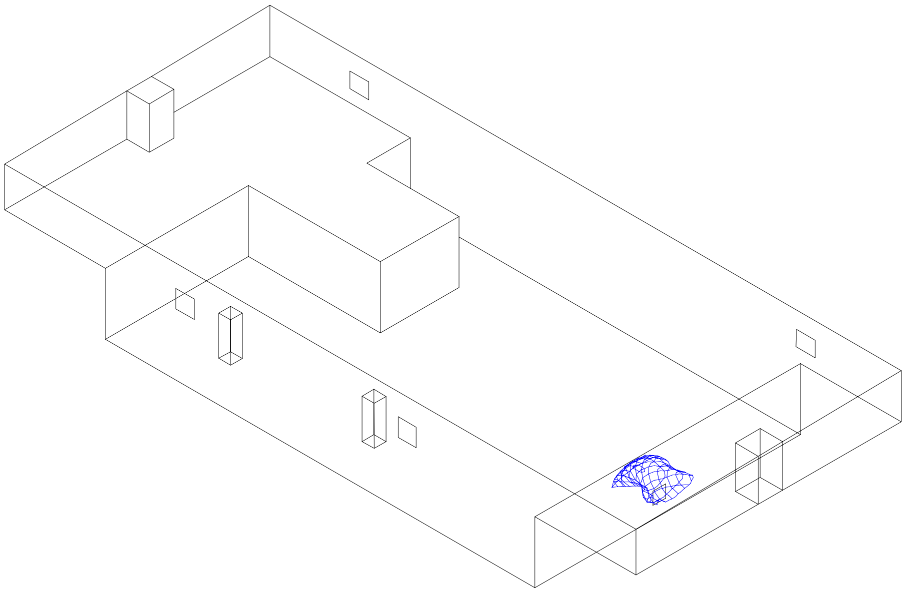


Figure B 4 - 20 SCFM hydrogen leakage after 30 seconds

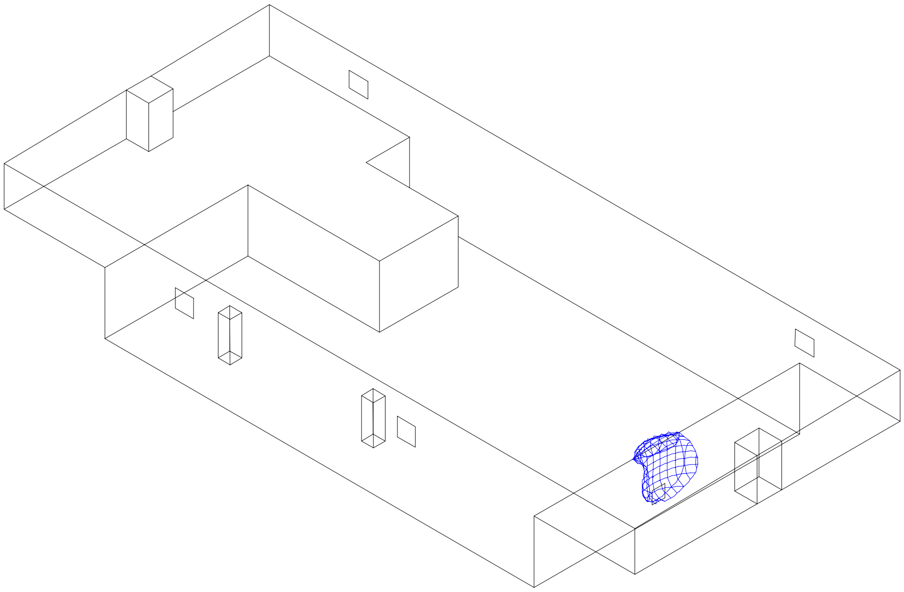


Figure B 5 - 20 SCFM hydrogen leak after 60 seconds

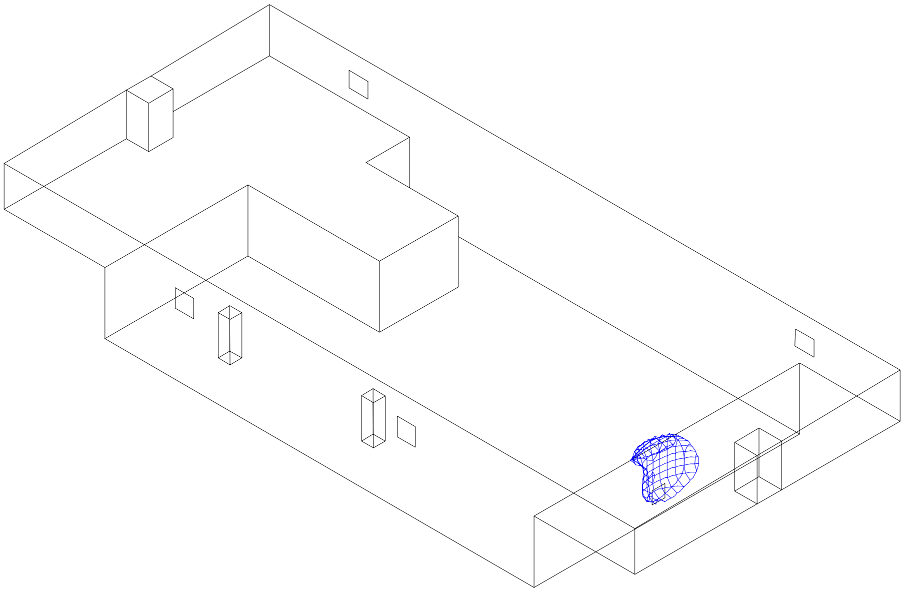


Figure B 6 - 20 SCFM helium leak after 60 seconds

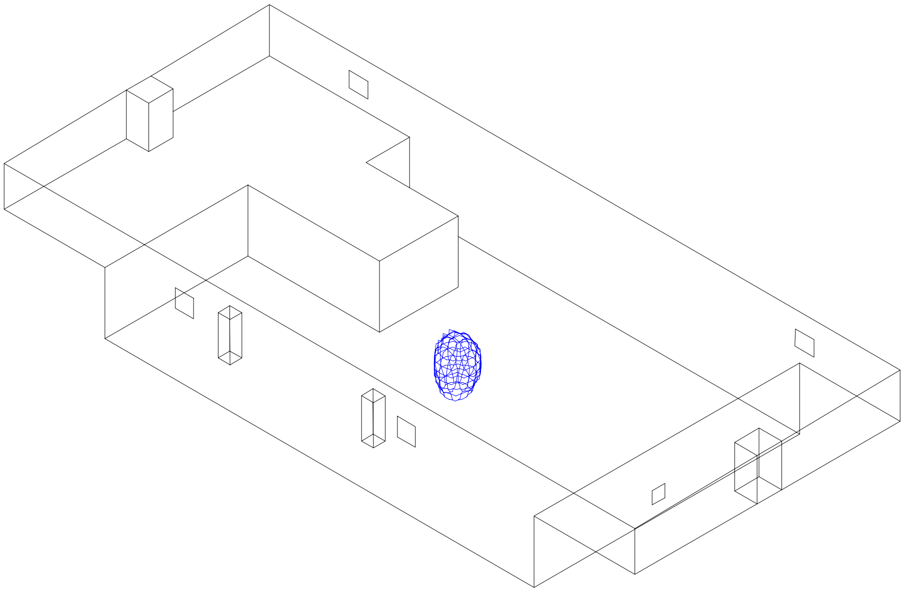


Figure B 7 - Instantaneous release, 8 cubic feet of hydrogen, 1% concentration after 1 second

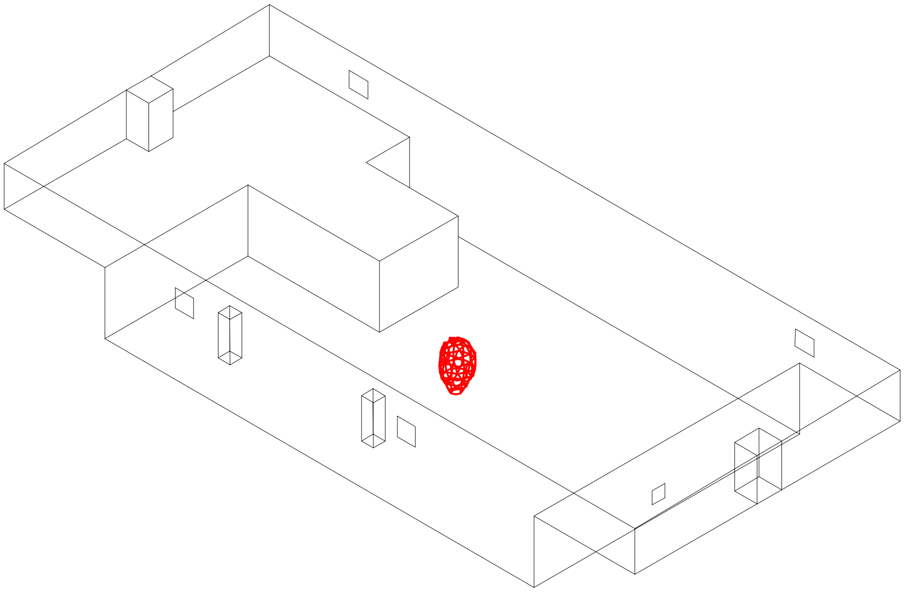


Figure B 8 - Instantaneous release, 8 cubic feet of hydrogen, 4.1% concentration after 1 second

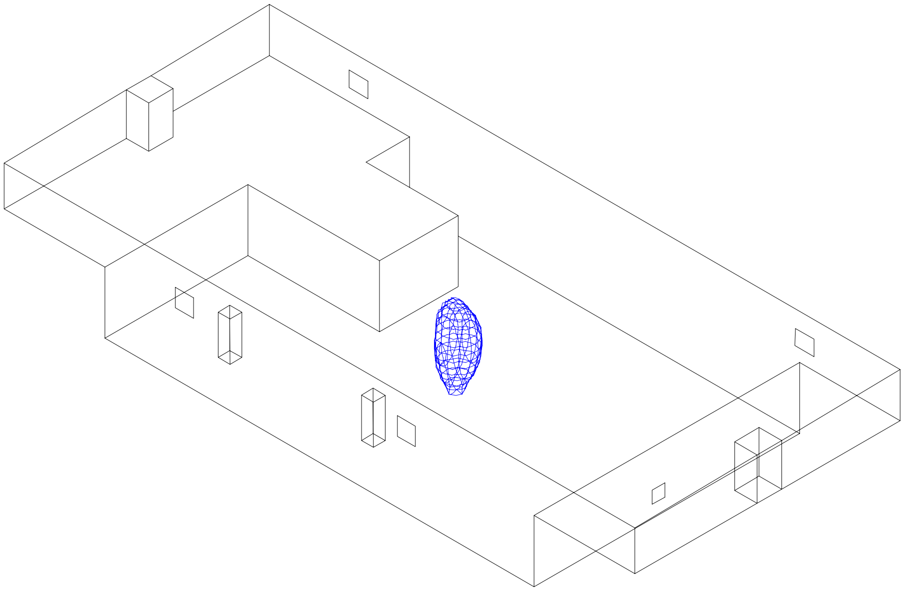


Figure B 9 - Instantaneous release, 8 cubic feet of hydrogen, 1% concentration after 2 seconds

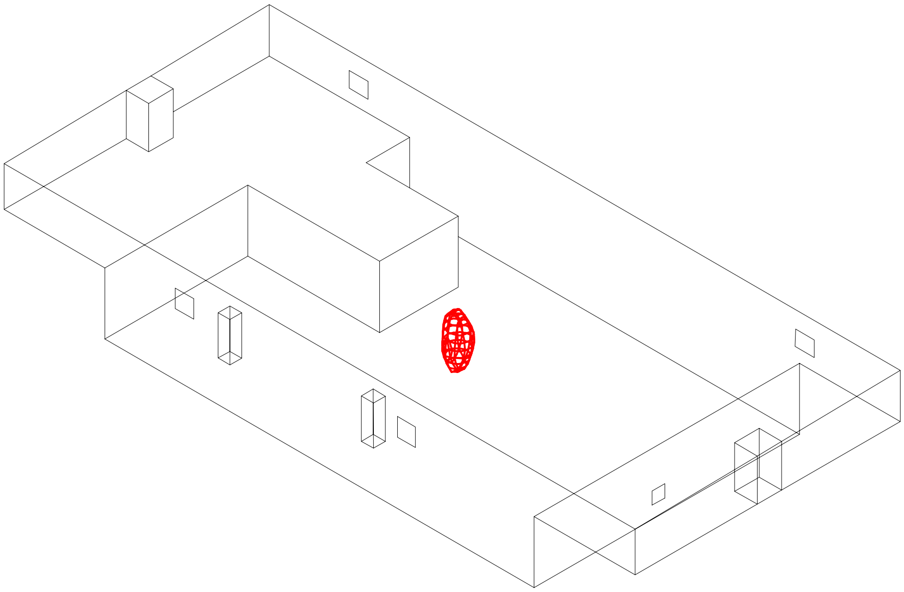


Figure B 10 - Instantaneous release, 8 cubic feet of hydrogen, 4.1% concentration after 2 seconds

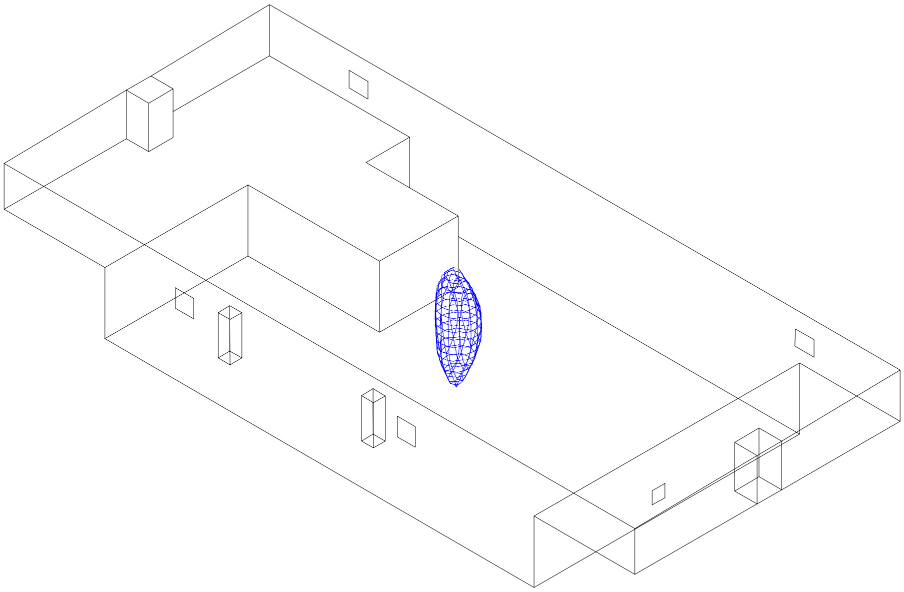


Figure B 11 - Instantaneous release, 8 cubic feet of hydrogen, 1% concentration after 3 seconds

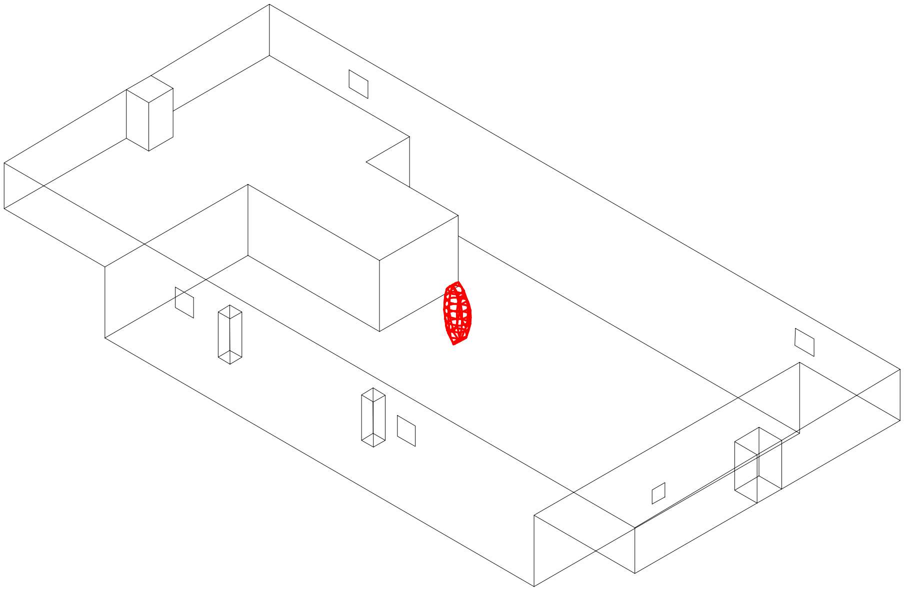


Figure B 12 - Instantaneous release, 8 cubic feet of hydrogen, 4.1% concentration after 3 seconds

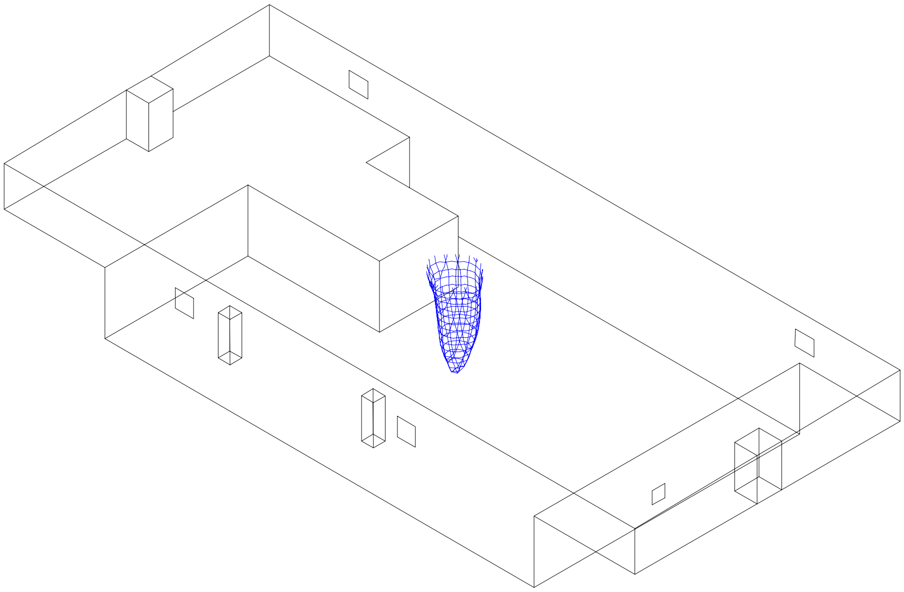


Figure B 13 - Instantaneous release, 8 cubic feet of hydrogen, 1% concentration after 4 seconds

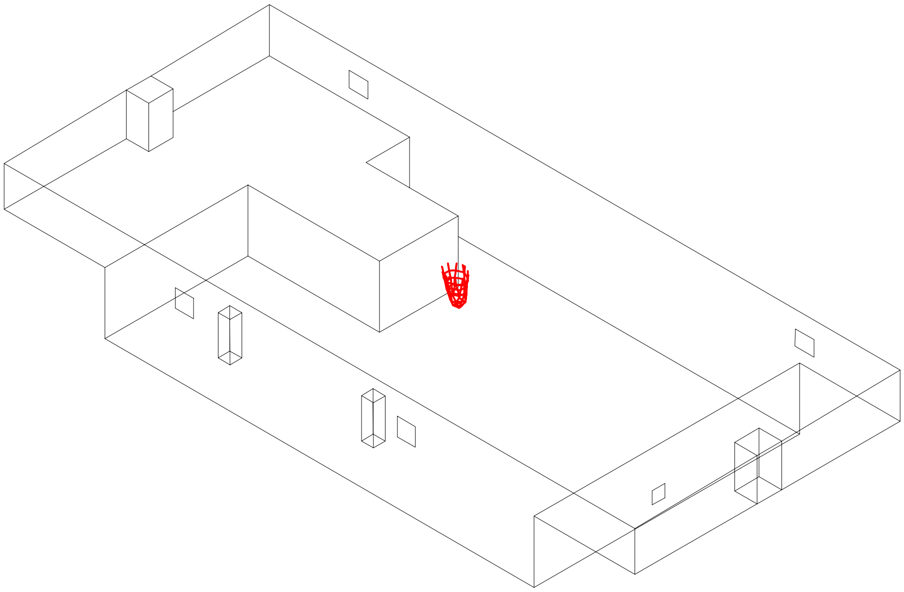


Figure B 14 - Instantaneous release, 8 cubic feet of hydrogen, 4.1% concentration after 4 seconds

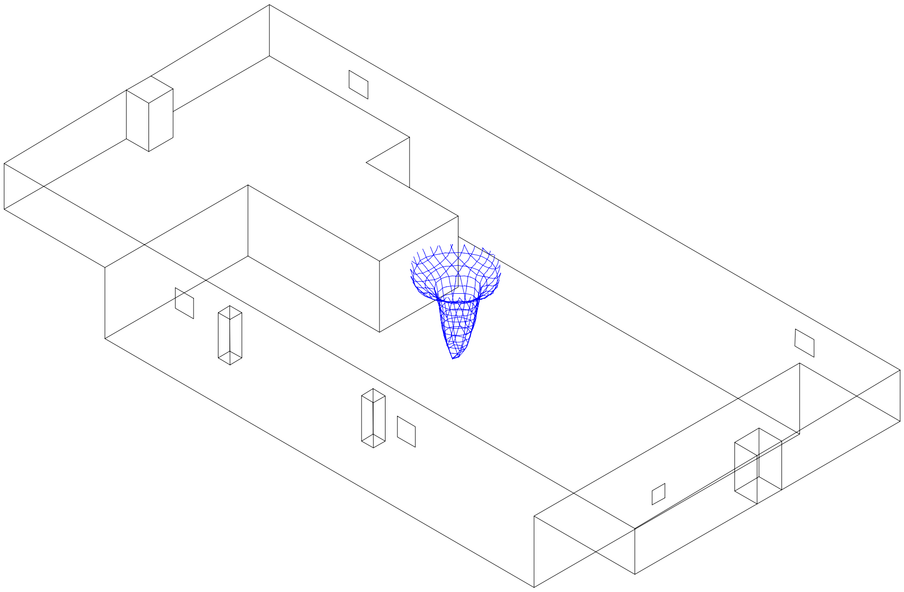


Figure B 15 - Instantaneous release, 8 cubic feet of hydrogen, 1% concentration after 5 seconds

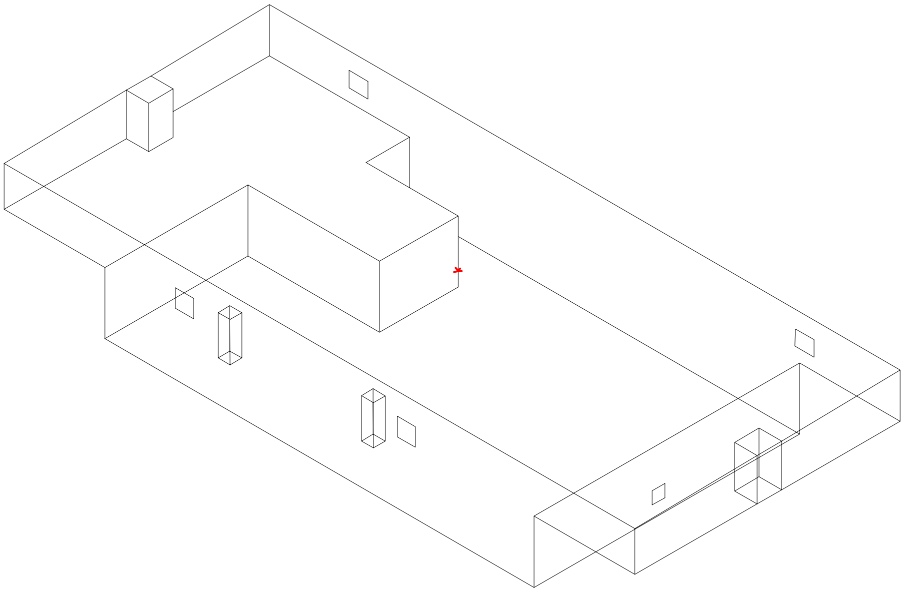


Figure B 16 - Instantaneous release, 8 cubic feet of hydrogen, 4.1% concentration after 5 seconds

Task C – Home Refueling System Safety Analysis

Task C addresses three questions concerning the writing of ICC building codes:

1. Are existing codes adequate for the use of home refueling systems in residential garages?
2. Is there a minimum safe hydrogen leakage rate?
3. What damage is done to gypsum board after hydrogen flame impingement?

The Use of Existing Codes for Home Refueling Systems

Task C was initiated with a survey of potential home refueling systems. Thirteen companies were identified as suppliers of hydrogen production equipment. They are as follows:

Electrolysis devices:

Bhabha Atomic Research Centre [BARC]
Trombay Bombay 400 085, India

Electrolyser Corporation, Ltd.
210-290 North Queen Street
Toronto, Canada, M9C 5L2

Hydrogen Systems NV
Brugstraat 45/1, B-2300 Turnhout
Belgium

Norsk Hydro ASA
N-0240 Oslo
Norway

Proton Energy Systems (PEM Electrolyzers)
50 Inwood Road
Rocky Hill, Connecticut 06067

Stuart Energy Systems
122 The West Mall
Toronto, Ontario
M9C 1B9 Canada

Teledyne Energy Systems
10707 Gilroy Road
Hunt Valley, MD 21031-1311

Fuel processors:

Dais-Analytic Corporation
11552 Prosperous Drive
Odessa, FL 33556

General Electric Company
3135 Easton Turnpike
Fairfield, CT 06431

Harvest Energy Technologies
9253 Glenoaks Boulevard
Sun Valley, California 91352

Hydrogen Burner Technology
1310 Logan Avenue, Suite E
Costa Mesa, California 92626

IdaTech, aka - Northwest Power Systems
924 S.E. Wilson Ave. Suite F
Bend, Oregon 97702

Wellman CJB Limited
Airport Service Road
Portsmouth, Hampshire, PO3 5PG
United Kingdom

Leakage rate for the hydrogen home refueling accident scenario was determined by the ICC. The hydrogen leakage rate was determined as 0.67 SCFM and was the result of a request by one of the above-mentioned suppliers. The proposal was made that the present codes would prevent hydrogen from accumulating above 0.8% hydrogen concentration.

The ICC International Mechanical Code requires either 100 CFM ventilation per car for a separate garage or 1.5 CFM/ft^2 floor area for multiple garages. The first accident scenario for a residential garage was a single wall fan that pulled in 100 CFM of fresh air through the middle of the wall (Figure C1). Gases go out at the bottom of the garage door near the home refueling unit. Figure C1 shows the gases of 0.8% hydrogen concentration after five minutes of leakage as they rise from the home refueling unit and reached the ceiling. Figure C2 shows that after 30 minutes the upper half of the garage contains a hydrogen concentration greater than 0.8%.

Figure C3 shows a garage in which 100 CFM of ventilation enters the single-car garage through an open door. After one hour of leakage, the upper 3/4 of the garage contains hydrogen concentrations greater than 0.8%.

Figure C4 shows a garage in which an exhaust fan produces 100 CFM of ventilation out of the wall opposite the home refueling system. Figure C4 shows the upper half of the garage contains hydrogen and a concentration greater than 0.8% after one hour of leakage.

Figure C5 shows the effects of removing 100 CFM of air from a slot 1/2 foot tall and 9 feet wide in the far end of the garage. Figure C5 shows the upper 2/3 of the garage is filled with hydrogen gases greater than 4.1% hydrogen after one hour and 45 minutes of leakage.

The present code allows garages using CBS construction to use partial blocks at the floor level to provide natural ventilation. Figure C6 shows the effects of the addition of a 100 CFM exhaust fan to one of those locations. It can be seen slightly more than the upper half of the garage is filled with a mixture greater than 4.1% hydrogen concentration after one hour and 45 minutes of leakage.

Figure C7 shows the effect of increasing the ventilation rate to 283.5 CFM (189 ft^2 floor area * 1.5 CFM/ft^2 = 283.5 CFM). It can be seen that the upper 2/3 of the garage is filled with gases that are more than 4.1% hydrogen.

It is concluded that the present code cannot assure the concentration of hydrogen remains below 0.8%, or even below 4.1% (burnable mixture of hydrogen and air.)

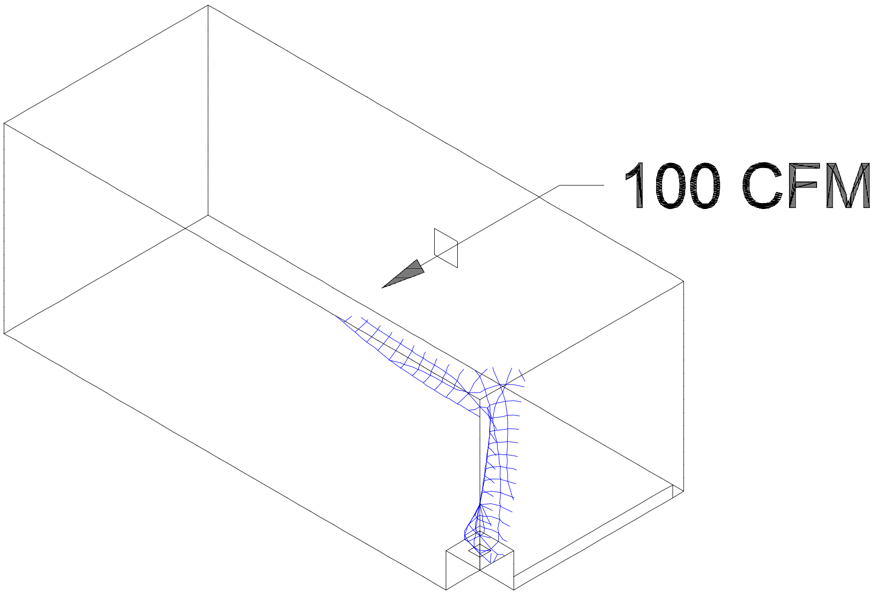


Figure C 1 - Residential garage 0.8% hydrogen at 5 minutes

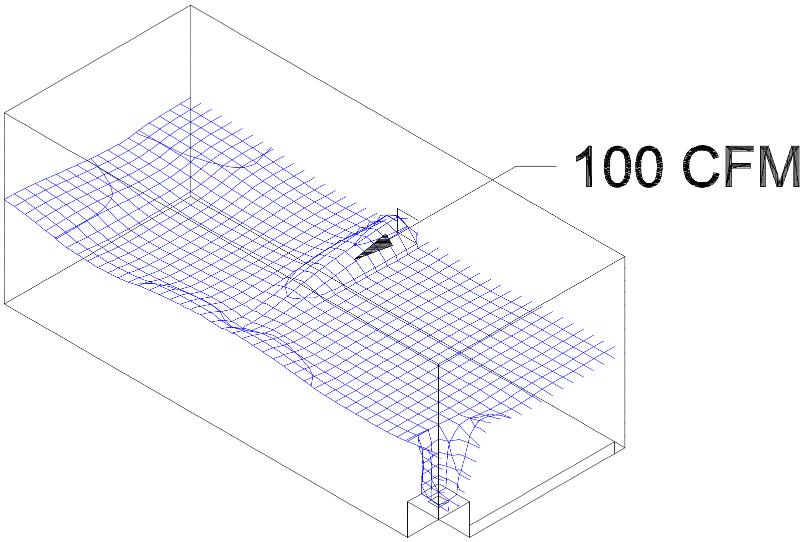


Figure C 2 - Residential garage 0.8% hydrogen at 30 minutes

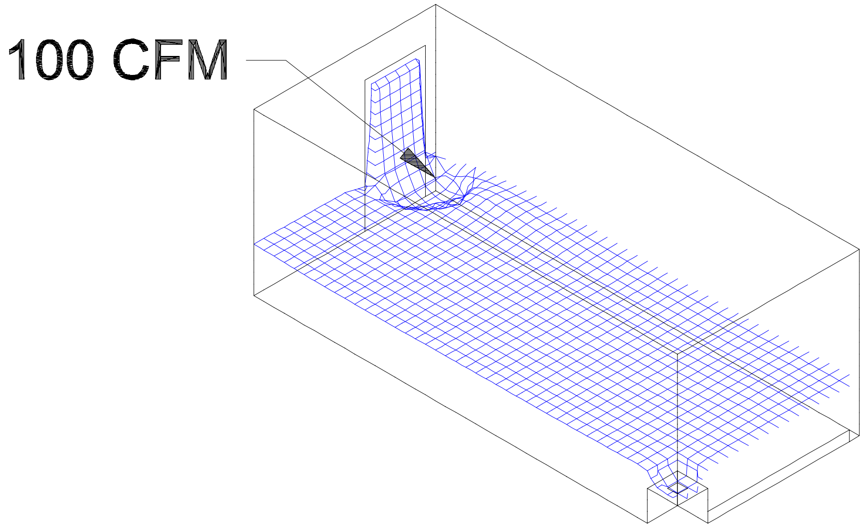


Figure C 3 - Residential garage 0.8% hydrogen 60 minutes

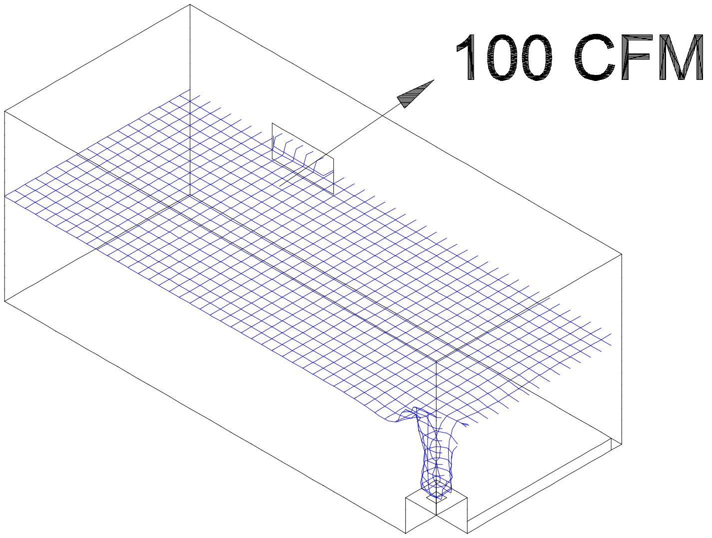


Figure C 4 - Residential garage 0.8% hydrogen 60 minutes

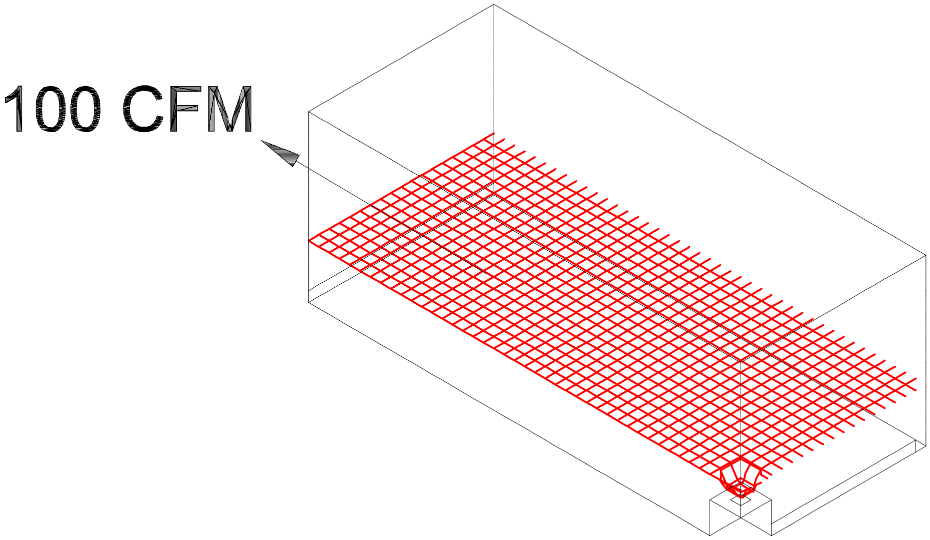


Figure C 5 - Residential garage 4.1% hydrogen 105 minutes

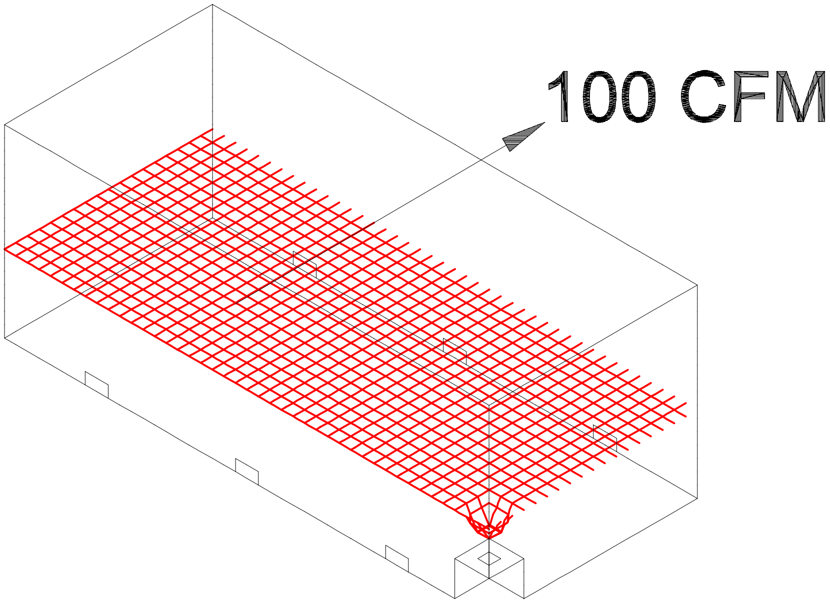


Figure C 6 - Residential garage 4.1% hydrogen 105 minutes

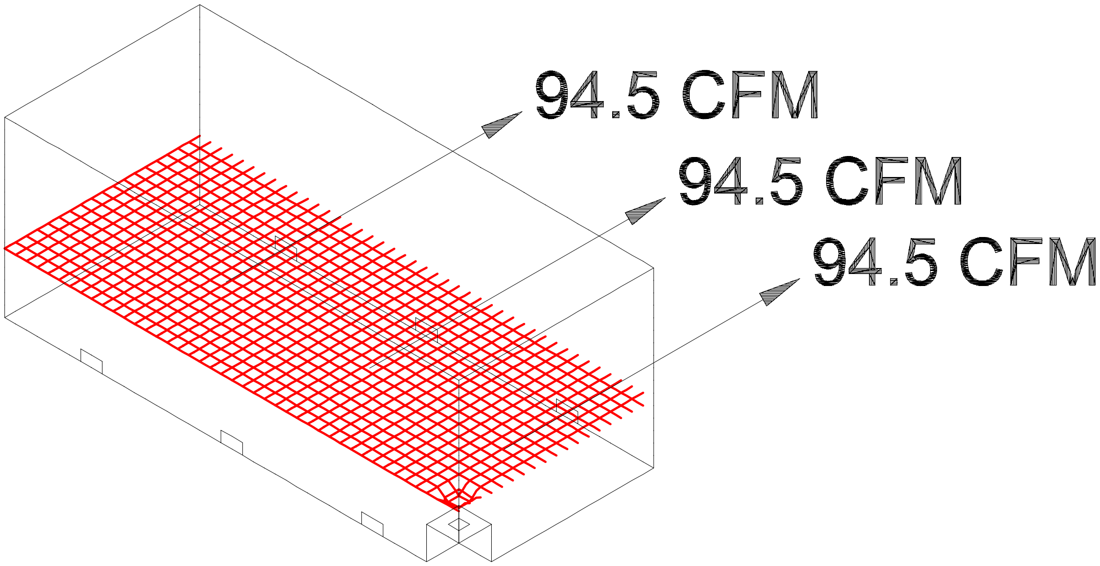


Figure C 7 - Residential garage 4.1% hydrogen at 165 minutes

Minimum Hydrogen Leakage Rate for Standing Flames

The risk incurred by the leakage of hydrogen into unconfined or large enclosures decreases as the flow rate decreases. At low leakage rates, the ability to sustain a flame, and therefore an ignition site, decreases and eventually becomes zero. Experiments were conducted to begin to determine what a minimum burnable flow rate of hydrogen would be. The experimental procedure was as follows:

1. A 3-inch long, 3-inch diameter cylindrical block of brass was machined to have exit holes of the following diameters (Note: the diameters are drill bit diameters):

Hole Number	Hole Diameter (cm)
1	0.061
2	0.089
3	0.127
4	0.175
5	0.203
6	0.262
7	0.323
8	0.419
9	0.513

2. Brass was chosen because of its high heat capacity (370 Joules/kg K).
3. Swagelock fittings were attached to the opposite side of the block in order to feed the hydrogen through the holes.
4. Hydrogen was allowed to flow through each hole, individually, and the flow rate was adjusted to 6 cc per minute. This flow rate was found to sustain a hydrogen flame at each hole.
5. The hydrogen flowing through each hole was ignited using a common match.
6. The flow rate was then reduced until a hydrogen flame was no longer present. The hydrogen flame was detected by measuring the temperature above the flame with a thermocouple. Since the brass block remained at constant temperature (26.1°C), temperatures recorded above 100°C at the flame location, were assumed to indicate the presence of a flame.
7. Steps 4, 5, and 6 were repeated for each hole.

No hole was able to support a hydrogen flame at less than 3.5 cc/min. The smaller holes were self-extinguishing, within five to ten seconds, due to water condensation.

Hydrogen Flame Impingement

The use of hydrogen fuel vehicles inside wood frame structures may result in hydrogen flame impingement on interior walls. The gypsum board that covers the wood frame can be installed in a variety of ways dependent on code requirements. Tests were run to determine the amount of damage done by hydrogen flame impingement on gypsum board mounted on two-by-four wood frames. The test utilized 1.7 pounds of hydrogen vented in 100 seconds beginning at a flow rate of 1000 SCFM. The jet was placed 2.5 feet away from the gypsum board as this distance was found to produce the maximum heat transfer in previous tests. Five tests were performed (See Table C1). Figure C8 – C10 show photos of the testing.

Table C1

Gypsum board thickness	Distance between two by fours	Maximum temperature rise at back of gypsum board
1/2 inch sheet	Twenty-four inches	144 degrees F.
1/2 inch sheet	Sixteen inches	142 degrees F.
5/8 inch sheet	Twenty-four inches	126 degrees F.
Two 5/8 inch sheets	Twenty-four inches	4 degrees F.
5/8 inch sheet with seam	Twenty-four inches	138 degrees F.

It can be seen that the use of two 5/8 inch sheets of Fire Code Type X gypsum board reduced heat transfer through the boards to nearly zero. This same test conducted with automobile door sheet metal produces a temperature rise on the order of 1400 degrees F.

Figure C 8 – Hydrogen flame impingement on gypsum wallboard seam

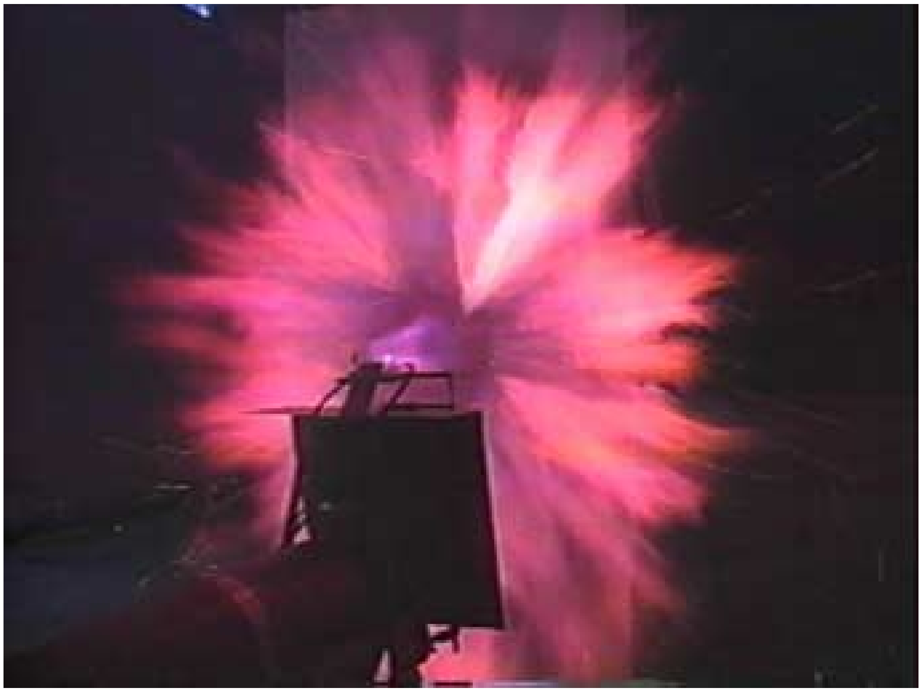


Figure C 9 - Hydrogen flame impingement, early in burn

Figure C 10 - Hydrogen flame impingement on gypsum wallboard (paper cover burning)