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RISK ASSESSMENT AND VENTILATION MODELING FOR HYDROGEN VEHICLE REPAIR GARAGES

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ABSTRACT

The availability of repair garage infrastructure for hydrogen fuel cell vehicles is becoming increasingly important for future industry growth. Ventilation requirements for hydrogen fuel cell vehicles can affect both retrofitted and purpose-built repair garages and the costs associated with these requirements can be significant. A hazard and operability (HAZOP) study was performed to identify key risk-significant scenarios related to hydrogen vehicles in a repair garage. Detailed simulations and modeling were performed using appropriate computational tools to estimate the location, behavior, and severity of hydrogen release based on key HAZOP scenarios. This work compares current fire code requirements to an alternate ventilation strategy to further reduce potential hazardous conditions. It is shown that position, direction, and velocity of ventilation have a significant impact on the amount of flammable mass in the domain.

1.0 INTRODUCTION

Hydrogen fuel cell vehicle (FCV) usage has increased in recent years due to advancing technology and desires for a clean energy fuel in transportation systems. This has increased the need for additional maintenance facilities to be placed across the nation. Many corporations find that building new infrastructure can be difficult and many in industry transform existing maintenance facilities to accommodate the hydrogen vehicles by making them conform to the ventilation requirements. This can be an expensive and challenging process to upgrade the facilities, especially the large repair garages which can have over one hundred repair bays. The intention of the upgrades is to make the facilities safer in case of a FCV accident. The codes and standards developed for these facilities were based on expert knowledge field experience of other lighter than air fuels, but risk assessments and simulations of such hazards were not always taken into account. This study uses risk analysis to identify hazards and performed simulations of various hazards to inform future development of hydrogen codes and standards.

2.0 CONVENTIONAL FCV REPAIR FACILITY HAZOP

A hazard and operability (HAZOP) risk analysis identifies potential hazards in a system and potential operational disturbances that lead a system to deviate from expected behaviors [1, 2]. In this study, a HAZOP was used to identify what sort of leak scenarios might be significant in a hydrogen FCV repair garage, so that modeling efforts could focus on those specific scenarios. A HAZOP is a qualitative, inductive process which examines each system component and identifies scenarios, conditions, or failure modes that could lead to a release of hydrogen. In this study, failure was defined as an unexpected or uncontrolled release of gaseous hydrogen. Other hazards associated with vehicle maintenance activities (e.g., mechanical, electrical, ergonomic, and noise) were not considered as these hazards are not unique to hydrogen vehicle maintenance facilities. In addition, cascading failures or instances where multiple components failed were not analyzed. For this HAZOP, the hydrogen process parts and components of a generic hydrogen fuel cell vehicle identified, as shown in Table 1. Each component was analyzed in the context of the vehicle's operational state during service and maintenance activities typically conducted in maintenance garages. The operational states analyzed are shown in Table 1.

The HAZOP method used exhaustive enumeration, meaning every identified hazard, operational disturbance or deviation was examined individually for each hydrogen process part to identify potential causes of failure. The typical HAZOP method uses guide words to provide structure to the analysis; this led to analytical completeness. Each guide word was used in the context of the potential hazard or operational disturbance to determine if the affected process deviates from its intended design. For example, the process part "tank manual valve" during the operational state "service on non-fuel systems" could be combined with the "no or not" guide word to describe a spontaneous leak; the valve did not perform the intended function of containing hydrogen. The guide words used in this analysis are shown in Table 1. The process of analysing each process part, operational state and HAZOP guide word led to 490 unique scenarios. The scenarios were reviewed individually, and 18 scenarios were identified that could lead to an unintended release of hydrogen.

Table 1. Hydrogen process parts, service & maintenance activities and HAZOP guide words

Hydrogen process parts	Operational state	Guide words
Hydrogen tanks (2)	Defueling entire fuel system	No or not
Tank manual valves (2)	Defueling of system post-regulator	More
Tank pressure relief device (2)	Dead vehicle storage	Less
Defueling valves (2)	Engine operation/idling	As well as
Fuel system post-regulator	Service on non-fuel systems	Part of
Hydrogen supply regulator assembly	Service on fuel tanks	Reverse
Hydrogen venting tool	Service on fuel system components post-regulator	Other than
Fueling receptacle		
Automatic shutoff valve		
High-pressure defueling tool		

Inductive reasoning was then used to determine the effects of each hazard on the system. Each scenario was given a severity ranking, shown in Table 2. Severity was an assessment of the magnitude of consequence of failure. In assigning severity, the analysis team considered the worst possible consequence for a failure; the probability distribution of the severity of consequences was not considered in making the severity determination. The main differentiating factor was the amount of hydrogen released (full or half inventory).

Table 2. Severity values from operational deviations

Severity Value	Description
3	**Major:** Release of full inventory of hydrogen
2	**Moderate:** Release of 1 tank of hydrogen (half of full inventory)
1	**Minor:** Small release of hydrogen

Each scenario was also given a frequency value, estimating the likelihood of occurrence of an event. The criteria used to determine the frequency value was based on an order of magnitude scale and are presented in Table 3. These values were used in the HAZOP analysis to select the frequency value (1-5) that would apply to a given release scenario.

Table 3. Frequency values from operational deviations

Frequency Value	Description	Frequency
5	Intentional: Incident will occur on a set time frame	
4	Anticipated: Incident might occur several times during the lifetime of the facility	$f > 10^{-2}$/year
3	Unlikely: Events that are not anticipated to occur during the lifetime of the facility	10^{-4}/yr $< f < 10^{-2}$/yr
2	Extremely unlikely: Events that will probably not occur during the lifetime of the facility	10^{-6}/yr $< f < 10^{-4}$/yr
1	Beyond extremely unlikely: All other incidents	$f < 10^{-6}$/yr

A traditional, simplified tool used to communicate risk priority with a HAZOP is a qualitative risk ranking matrix, in this case a three-by-five matrix. The vertical axis represents the five frequency classes and the horizontal axis represents the three severity classes, as shown in Table 2 and Table 3. Figure 1 contains the risk matrix for this HAZOP analysis. High-risk scenarios were determined to have scores over 9, medium-risk scenarios had a score between 5-8, and low-risk scenarios had scores less than 5. Many different possible scenarios were considered by the authors, with input and discussion of vehicle manufacturers. Of those scenarios identified, 18 were considered to be of possible concern. Of the 18 scenarios identified, 14 were low-risk, 4 were medium-risk, and there were no high-risk scenarios.

	Consequence		
Frequency	**1**	**2**	**3**
1	1	2	3
2	2	4	6 (A)
3	3	6 (D)	9
4	4	8 (C)	12
5	5 (B)	10	15

Figure 1. Risk matrix for HAZOP analysis, showing four medium risk scenarios: A) external fire causes TPRD release, B) small release in low-pressure system, C) premature disconnect of venting tool, and D) premature disconnect of high-pressure defueling tool

The four medium-risk scenarios were analyzed further with the intent of determining which scenario would benefit from computational fluid dynamics (CFD) modeling.

(A) External fire causes TPRD release (risk metric 6): This scenario examined an external fire in close proximity to the vehicle. This scenario was not analyzed further because a large fire is an existing hazard and not unique to a FCV maintenance facility.

(B) Small release in low-pressure system (risk metric 5): This scenario examined a situation where there is a small release of hydrogen in the fuel system post-regulator. This is the most likely scenario since it will occur on a set time frame. This scenario is bounded by other scenarios, given that the premature disconnect of venting tool scenario would also release hydrogen at low pressure, but would release significantly more hydrogen; therefore, that scenario was examined instead of this one.

(C) Premature disconnect of venting tool (risk metric 8): This scenario examined when the venting tool used to vent hydrogen from the tank into the atmosphere outside the facility is disconnected before the venting is complete. This scenario was selected for further investigation because of its high-risk classification and because the only preventative measure is proper training for operators.

(D) Premature disconnect of high-pressure defueling tool (risk metric 6): This scenario examined the case in which the vehicle is being defueled using a high-pressure tool. This high-pressure defueling tool is rarely used because of the hazards associated with high pressure; it is only used when damage or other issue precludes the use of the lower pressure venting tool, and typically special procedures are in place to address the additional pressure hazard. Therefore, the lower pressure defueling scenario was analyzed instead of this one due to the higher likelihood of occurring.

3.0 SCENARIO ANALYSIS

The analyzed maintenance facility scenario examined when the tool used to vent hydrogen from the pressure vessels was disconnected prematurely and hydrogen was released into the maintenance facility. Four ventilation strategies were compared for a representative 12 bay repair facility. All scenarios used the same leak specifications coming from the vehicle. The first scenario examined the effects of no ventilation, considered to be a baseline case. The second scenario analyzed ventilation with the velocity specified by following the National Fire Protection Association (NFPA) 30A, Code for Motor Fuel Dispensing Facility and Repair Garages, Section 7.3.6.7 requirement of 1 cfm/ft^2 of floor area [3]; the leaking vehicle was placed away from these vents. The third scenario had the same ventilation rate, but the leaking vehicle was place directly in front of one of the vents. For the final scenario, a box fan producing a velocity of 300 cm/s (as compared to the 94.8 cm/s that results from the standard ventilation rate for the assumed vent size) was placed directly in front of the leaking vehicle. For all cases, the vehicle was placed 2 feet above the floor of the maintenance facility to simulate being raised on a lift.

The CFD solver, Fuego [4], was used to perform the hydrogen release simulations from a representative fuel cell vehicle inside the maintenance facility. Fuego is a Sandia National Laboratories developed code designed to simulate turbulent reacting flow and heat transfer [4] on massively parallel computers, with a primary focus on heat transfer to objects in pool fires. The code was adapted for compressible flow and combustion and is well suited for low Mach number flows. The discretization scheme used in Fuego is based on the control volume finite element method [5], where the partial differential equations of mass, momentum, and energy are integrated over unstructured control volumes. The turbulence model was a standard two equation (k-ε) turbulence model [6] with transport equations solved for the mass fractions of each chemical species, except for nitrogen which was modeled as the balance. For the calculations reported here, the first order upwind scheme was used for the convective terms.

3.1 Leak Description

A fuel cell vehicle tank holding 2.5 kg of compressed hydrogen was assumed to be leaking through a mid-pressure port starting at 1.5 MPa. The leak was modeled with a diameter of 0.86 mm; this diameter was chosen as representative of a possible leak size, rather than based on a specific fitting or tube. This is because a disconnection or leak could occur at the connection fitting of the defueling tool to the mid-pressure port, or due to damage or leak in any part of the tubing after the connection. These specifications were obtained through discussions with hydrogen FCV manufacturers. This information was put into MassTran [7] (a network flow modeler) to calculate the time for the tank to reach one atmosphere and the leak to stop. This slow leak would last approximately 3.75 hours for a full tank to completely empty. The position and orientation of this valve would most likely cause the jet of leaking hydrogen to be pointed downward, due to the possible leak points being under the vehicle, which is how it has been modeled for this study.

Trying to model both airflow in a large garage along with a high velocity leak through a small orifice sets up a problem that is computationally “stiff” and would take years to solve even on a large number of processors. Assumptions were made to mitigate this issue. An alternative subsonic inlet (ASI) [8] boundary condition was used which conserves the hydrogen mass flow as a function of time and taking the state of the gas to be that of the ambient pressure. This allowed the small diameter orifice (0.86 mm) to be transformed to a larger diameter orifice (chosen to be 10 cm based on previous experience) for the Fuego mesh and inflow. This leads to the velocity of the jet to be reduced. The temperature was determined to be the temperature at the orifice outlet from MassTran. This boundary condition has been used before and shown to be useful for these kinds of simulations [9,10]. It allows the speed of the incoming gas to be in the incompressible low-Mach region (which is required for this scenario to be modeled using Fuego [11]). An analytical model of the plume (see Section 4.6) shows that for the leak described in this paper the flammable concentration of hydrogen would not hit the floor. A different case, which is beyond the scope of this paper, examines a higher pressure leak in which the plume would impinge on the floor. To capture that behavior more closely, the height of the car on the jack is modeled at 2 feet instead of a more typical 6 feet, so that the plume from the high pressure jet can impinge or interact with the floor even at the lower ASI velocity. This does not affect the results presented in this paper, but the height of the car was kept consistent between the two cases. The other case will be presented in a forthcoming report. Additionally, a leak could occur due to damage or severing of tubing of the defueling tool; if the leak occurred in the tubing 4 feet below a car that was 6 feet high, the results would be very similar to a leak occurring at 2 feet.

3.2 Mesh and Problem Description

The mesh for this simulation used a non-structured grid and had 2 million elements. A grid resolution study was conducted on a similar mesh of a smaller garage which produced matching quantities of flammable mass. This indicated that the grid resolution for this simulation is also sufficient. The walls, floor, ceiling, and vehicle were all modeled with a wall boundary condition on those surfaces with a temperature of 294 K. Table 4 lists the dimensions for the 12 bays in the garage and Figure 2 illustrates the mesh layout and the 12 bays.

Fuego calculates the amount of hydrogen at each element in the grid. To calculate the amount of the flammable mass, the density of hydrogen was integrated over the volume where the concentration was between 4 and 75% by volume.

Table 4. 12 Bay Garage Dimensions

Item	Width	Length	Height
Bays	14’	27’	16’
Vents in	4.5’	--	2’
Vents out	3’	3’	--
Car	6’	16’	5’
Aisle	26’	27’ X 6 bays = 162’	16’

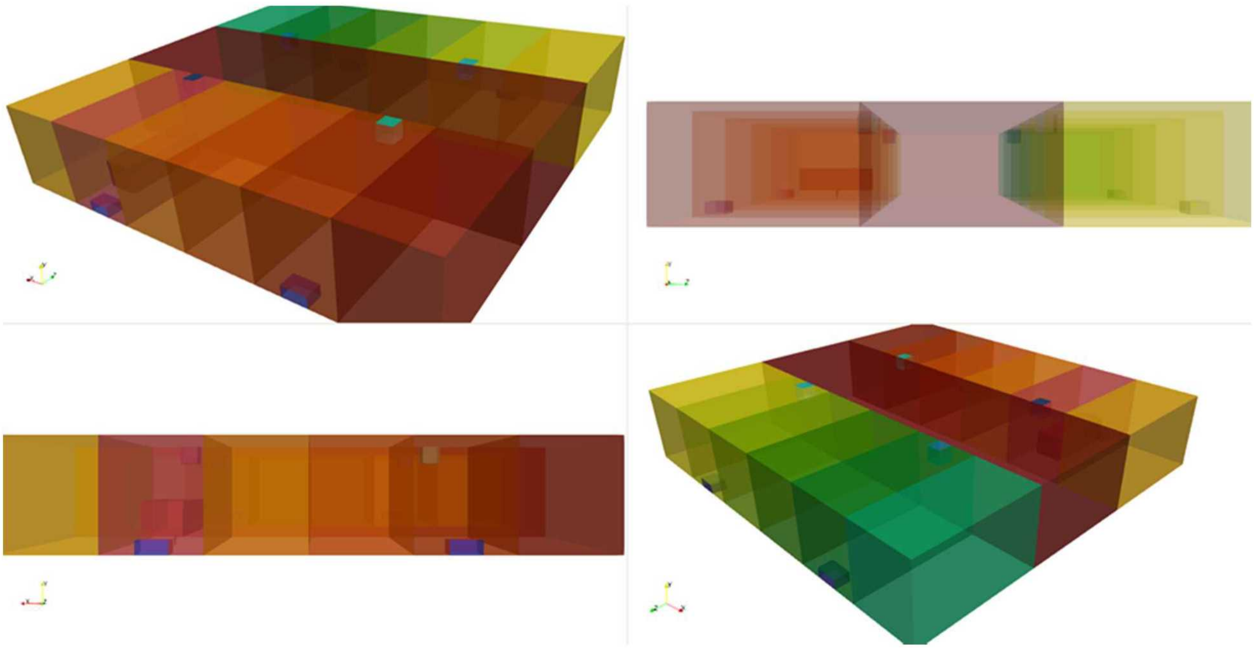

Figure 2. Layout of the mesh for a 12 bay maintenance facility. Inflow vents are near the floor and outflow vents are in the ceiling. Each of the colored blocks represents one bay with the aisle is shown in dark red, and the entire volume is open.

4.0 SIMULATION RESULTS

For all of the simulations, the same amount of hydrogen was released downward from a vehicle placed 2 feet above the ground surface, as if it were on a lift for maintenance. The different scenarios compared ventilation amounts and if the vehicle is placed directly in front of the inflow (Sections 4.3 and 4.4), or not directly in the airflow path (Section 4.2).

4.1 No Ventilation

For the case without ventilation, the hydrogen within the flammable concentrations (4-75% by volume) accumulated below the vehicle, as seen in Figure 3. Air and hydrogen flowed up around the vehicle but the hydrogen was diluted below the flammable range. The maximum amount of flammable mass was 0.002 kg and occurred about 500 seconds into the simulation.

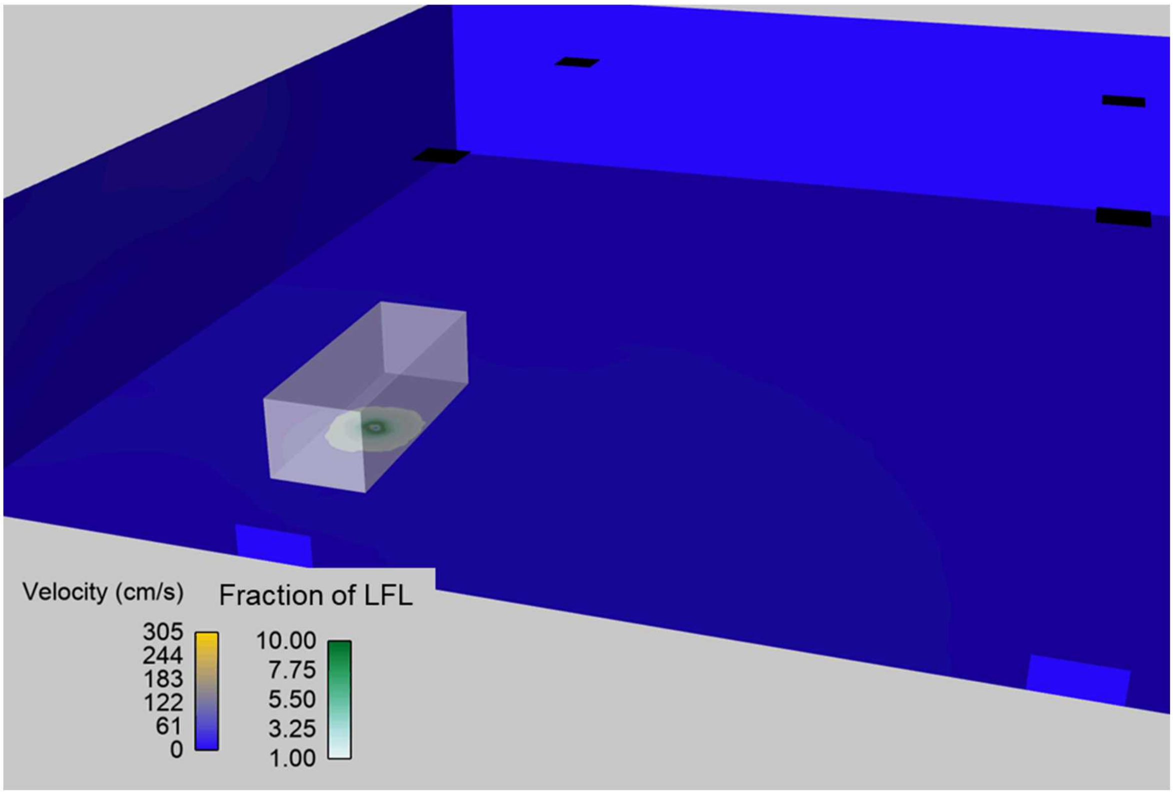

Figure 3. Time of maximum flammable mass for this scenario is 500 sec into the release. The entire garage showing flammable mass as a cloud under the transparent vehicle, with walls and floor colored by velocity.

4.2 Standard Ventilation Away from Leak

For the second simulation, NFPA 30A Section 7.3.6.7 prescribed a standard ventilation of 1 cfm/ft^2 was established. The vehicle was placed in between two inflow vents, so there is no direct flow under the vehicle. The simulated leak had similar characteristics to the first scenario without ventilation and also had a maximum amount of flammable mass at 0.002 kg. The cloud of flammable mass in Figure 4 and Figure 3 are of comparable size.

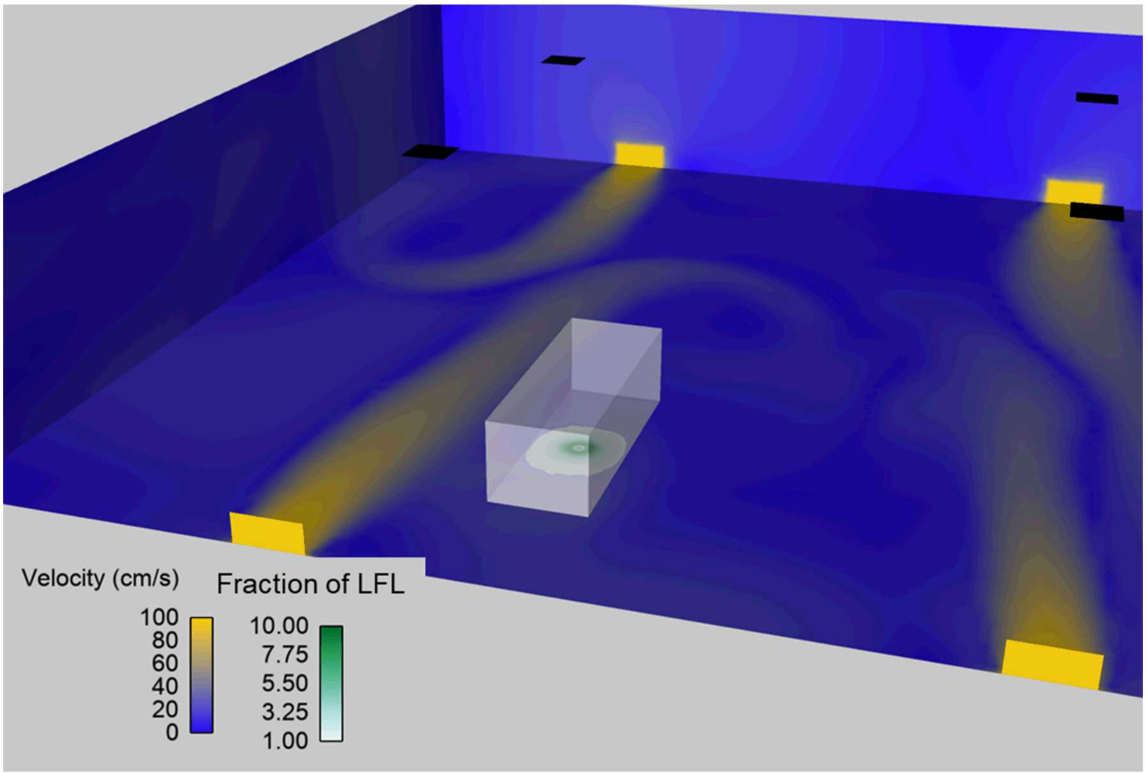

Figure 4. In this scenario, the vehicle is not near the incoming ventilation, and the maximum flammable mass occurred 640 sec into the leak. The entire garage showing flammable mass as a cloud under the transparent vehicle, with walls and floor colored by velocity. The ventilation can be seen in yellow on the floor of the garage.

4.3 Standard Ventilation Near Leak

The third simulation had the same ventilation flow as the second, but the vehicle was placed directly in front of one of the four inflow vents. Figure 5 shows a reduced cloud of flammable mass under the vehicle, which had a maximum mass of 0.00041 kg.

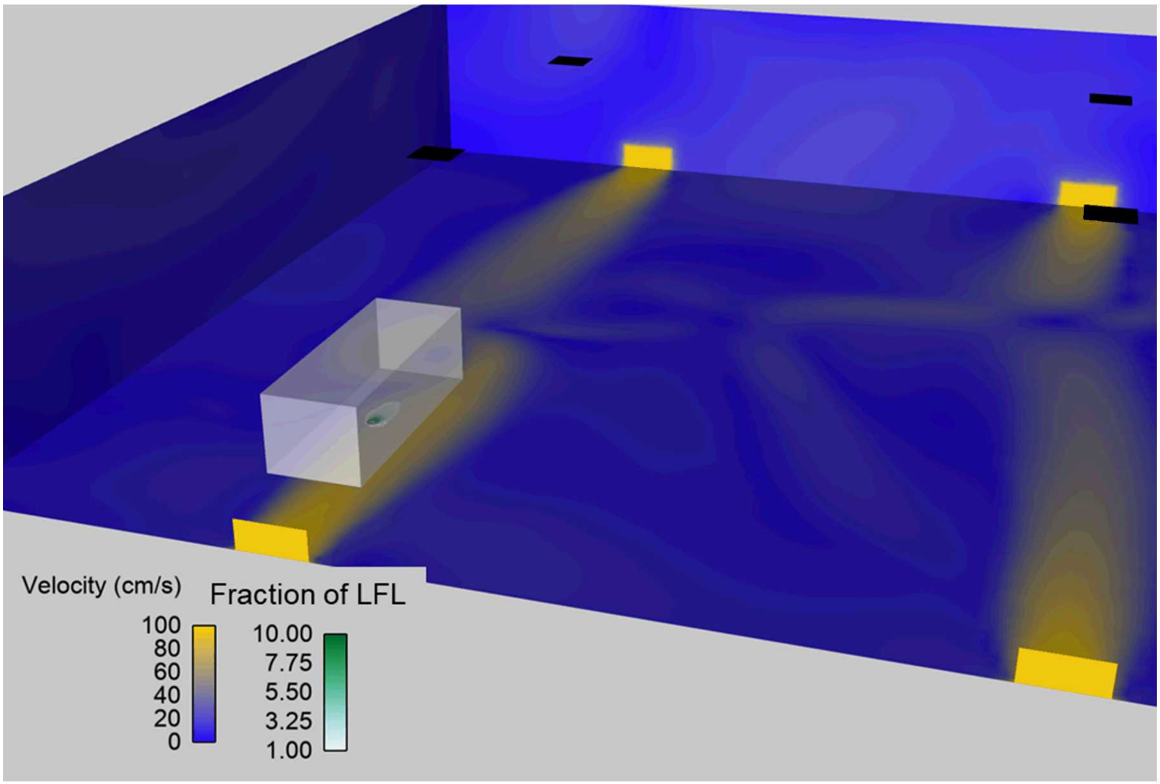

Figure 5. In this scenario, the vehicle is placed in front of the incoming ventilation, and a noticeable decrease in the amount of flammable mass can be observed from the previous two scenarios. The maximum flammable mass occurred 830 sec into the simulation. The entire garage showing flammable mass as a cloud under the transparent vehicle, with walls and floor colored by velocity. The ventilation can be seen in yellow on the floor of the garage.

4.4 Box Fan Ventilation Near Leak

For the final simulation, the velocity of the ventilation directly in front of the vehicle was increased to 3.0 m/s. This velocity can be achieved with a portable ventilation device, such as a box fan. Again, the amount of flammable mass was decreased by an order of magnitude, as seen in Figure 6, and contained a maximum of 0.000055 kg of flammable hydrogen.

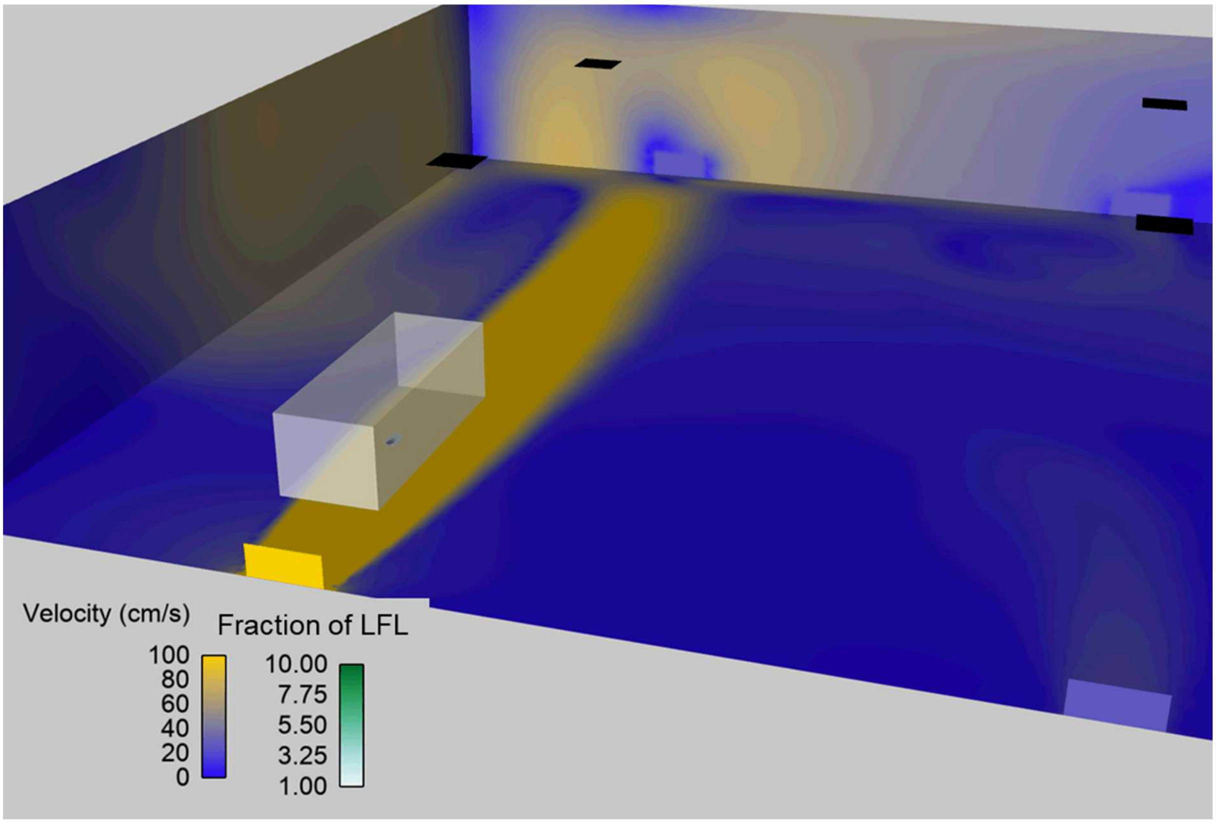

Figure 6. Providing a higher velocity fan near the vehicle decreases the amount of flammable mass even more than the standard ventilation. The entire garage showing flammable mass as a cloud under the transparent vehicle, with walls and floor colored by velocity. The ventilation can be seen in yellow on the floor of the garage.

4.5 Scenario Results Summary

A summary of the maximum flammable mass and associated times for the scenarios is given in Table 5. All of the maximum flammable mass values are small relative to the total amount of hydrogen released (2.5 kg). These results indicate that for the leak scenario considered, the standard ventilation away from the leak had little effect on the maximum flammable mass accumulated relative to the no ventilation case. The two cases with ventilation near the leak resulted in an order-of-magnitude reduction in the maximum flammable mass, with the high-velocity (box fan) ventilation case resulting in almost two orders-of-magnitude of reduction. This shows that directed ventilation is much more effective at reducing flammable concentrations than un-directed ventilation alone.

Table 5. Maximum flammable mass and associated time at which the maximum occurred

Scenario	$\max(m_{flam})$ $[kg]$	t $[s]$
No ventilation	2.0E-3	500
Standard ventilation away from leak	2.2E-3	640
Standard ventilation near leak	4.1E-4	830
Box fan near leak	5.5E-5	180

4.6 Plume Model

A drawback of the ASI boundary (as discussed in Section 3.1) that is needed for the CFD calculations is that the simulated leak velocity is lower than actual leak velocity. In order to determine whether the plume of released hydrogen would possibly hit the floor and spread out, the plume model from the

Hydrogen Risk Assessment Model (HyRAM) Toolkit was also used [12]. For a jet or plume of unignited hydrogen, HyRAM follows a reduced-order, one-dimensional model for a release of hydrogen through a circular orifice. This reduced-order model considered a fully developed flow at steady-state; therefore, the results of this model are not directly comparable to the results above, which consider the blowdown of a tank over time. This model was used for a release of hydrogen starting at 1.5 MPa, pointed straight downward from a height of 6 feet (1.83 m), and jets were calculated for a variety of pressures as the vehicle tank emptied over time. The height of 6 feet was used as a typical height that a vehicle would be at when raised off the ground in a repair garage; as discussed in Section 3.1, a leak could occur closer to the ground for a variety of reasons; if so, spreading of the plume may affect the results shown here. The results are shown in Figure 7, and show that the flammable region from an unignited plume from a vehicle on a lift 6 feet high would not reach the ground for the leak case discussed in this paper. This indicates that the accumulation shown in the simulation results above appears to be reasonable; since hydrogen mixtures in the flammable region (the region of interest) would not impact the floor and spread out at 6 feet, the hydrogen would instead remain under the vehicle.

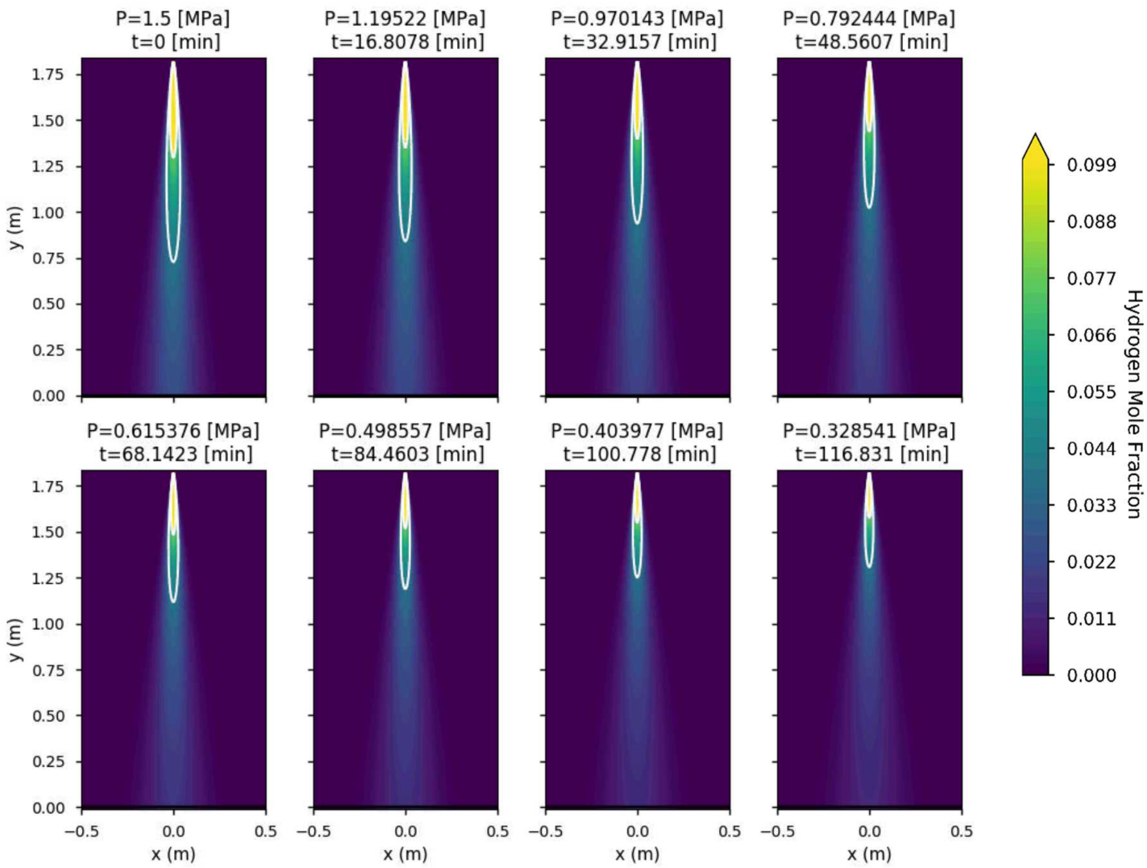

Figure 7. HyRAM flammable plumes as a function of time for a 1.5 MPa release. White contours show the χ_{H_2} = 4% and 8% flammable mass region. The maximum plume length is 3.61' and 1.74' for χ_{H_2} = 4% and 8% respectively.

5.0 CONCLUSIONS

This study examined a leak from a mid-pressure port on a hydrogen fuel cell vehicle in a maintenance garage. The results indicate that for certain cases where the leak occurs away from direct ventilation, it is possible to not reduce the amount of flammable gas present relative to a case with no ventilation, even when complying with ventilation regulations. However, when the leak was in the flow path of ventilation, the amount of flammable mass was reduced by an order of magnitude. It was also shown that with the type of ventilation that can be produced from a typical box fan (which would generate local ventilation velocities higher than typical ventilation), the amount of flammable mass is dramatically reduced to the point where it exists only directly near the leaking valve. This might provide a way to increase safety without structural changes to the garage or ventilation system.

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