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RISK ASSESSMENT AND VENTILATION MODELING FOR HYDROGEN RELEASES IN 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 risk-significant scenarios related to light-duty 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. Modeling shows that position, direction, and velocity of ventilation have a significant impact on the amount of instantaneous flammable mass in the domain.

1.0 INTRODUCTION

Use of hydrogen and fuel cells in vehicles (light-, medium-, or heavy-duty) will create a need for vehicle maintenance facilities. Design of these maintenance facilities should ensure that they are safe in the event of an unintended hydrogen release, and so have additional ventilation requirements. While the codes and standards developed for conventional fuel maintenance facilities have been primarily based on expert knowledge and field experience, risk analysis and simulations of hazards specific to hydrogen have not always been taken into account. Additional ventilation requirements can be expensive both for retrofitting existing facilities and building new ones, and so it is important to examine the basis of the ventilation requirements to ensure they are increasing safety of the facility.

The possibility of hydrogen leaks is an important safety issue for maintenance facilities, since the hydrogen vehicle itself is being worked on and so there are a number of potential activities that could lead to a hazardous condition. López-Arquillos et al. performed an expert elicitation to identify relative risk levels of different hazards and maintenance activities for hybrid, battery electric, and hydrogen vehicles [1]. Hazards related to electricity, welding, and asbestos handling were identified has highest risk for all three vehicle types, although the installation/removal of hydrogen storage tanks was seen as relatively high risk. Related studies by Ekoto et al. [2] and Blaylock et al. [3] performed a hazard and operability study (HAZOP) for natural gas vehicles and identified intentional releases of residual pressure or the failure of a pressure relief device as high risk release scenarios. This study builds on those prior studies to identify hazardous release scenarios specific to hydrogen vehicle maintenance activities.

The accumulation of hydrogen in an indoor facility or enclosure is an important safety topic that has been studied experimentally and numerically. Past work has often focused on small equipment enclosures or garages and the accumulation of hydrogen within that enclosed space, such as Refs [4-6]. Pitts et al. analyzed an experimental release of helium into a scale model of a residential garage and found the biggest impact on concentration was due to changing vent locations relative to the release point [7]. Chen et al. also examined a helium release into a scale multi-car parking garage model and observed significant hydrogen concentration at the ceiling and high concentrations immediately next to the leak point underneath the vehicle [8]. That garage model only had a single opening for air to enter or leave the enclosure, a large door frame that did not extend all the way to the ceiling, giving plenty of space of hydrogen or helium to accumulate. Xie et al. used computational fluid dynamics (CFD) modeling to analyze a leak point underneath a vehicle in a small garage; the results showed significant flammable concentrations underneath and extending up the sides of the vehicle unless a fan located to one side of the vehicle was blowing fresh air ventilation, which decreased the flammable area significantly [9]. That same study also varied the shape and size of the vent inlet while maintaining the same volumetric flow rate and noted that the smallest vent inlet was the most efficient at reducing the hazardous area near the leak due to the increased velocity of the ventilation. Houf et al. looked at CFD model of a hydrogen leak from a forklift inside a warehouse and did not observe significant differences between an open warehouse and when ventilation was present [10]; however, this study used large doors or open walls for ventilation, rather than smaller inlets and outlets. Studies for natural gas vehicles in repair garages found that ventilation did not have much of an impact for small releases, and that obstacles such as roof rafters could actually promote mixing and dilution of the hazard with active ventilation [2, 3]. These studies considered fixed location ventilation inlets and outlets relative to the vehicle location.

This study uses risk analysis to identify hazards and performed simulations of various hazards to inform future development of hydrogen codes and standards. A HAZOP risk analysis is used to identify maintenance activities specific to hydrogen vehicles that could lead to hazardous releases. CFD modeling is then used with different ventilation flow rates and leak locations to quantify the effect that ventilation can have on mitigating a hydrogen release.

2.0 CONVENTIONAL FCV REPAIR FACILITY HAZOP

A HAZOP risk analysis identifies potential hazards in a system and potential operational disturbances that lead a system to deviate from expected behaviors [11, 12]. 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 hazardous condition, such as 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 were 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 components, operational states, and guide words used in this analysis are shown in Table 1; every item from each of these three lists were used in combination with every item from each of the other lists to exhaustively enumerate possible scenarios. The process of analyzing each process part, operational state and HAZOP guide word led to 490 unique scenarios. The scenarios were reviewed individually, and 109 scenarios were identified that could lead to an unintended release of hydrogen. Since these scenarios could occur during multiple operational states, the 109 different scenarios collapse into 23 scenario sets with possible operating states for each. More details about the HAZOP conducted and the results can be found in a separate report [13].

Table 1. Lists of hydrogen process parts, service & maintenance activities and HAZOP guide words

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

Inductive reasoning was then used to determine the effects of each hazard on the system. Each scenario was given a consequence ranking, shown in Table 2. In assigning consequence, the analysis team considered the worst possible consequence for a failure; the probability distribution of the consequences was not considered in making the consequence determination. The main differentiating factor was the amount of hydrogen released (full or half inventory). The amount of hydrogen released was specific to light-duty vehicles that have an on-board storage capacity of 5 kg of hydrogen. Medium- or heavy-duty vehicles will have significantly more hydrogen on-board, and so the consequence levels would be different in that case; a partial release of a larger inventory could still be more hazardous than a full release of a smaller inventory.

Table 2. Consequence values from operational deviations

Consequence 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	Example 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 study, a three-by-five matrix. The vertical axis represents the five frequency classes and the horizontal axis represents the three consequence classes, as shown in Table 2 and Table 3. Figure 1 contains the risk matrix for this HAZOP analysis. The risk category was chosen as a combination of the frequency metric and the consequence metric. Low risk scenarios were thought to be those that were very unlikely to occur (frequency value of 1), a moderate release (consequence value of 2) that was extremely unlikely (frequency values of 1 or 2), or low-consequence releases (consequence value of 1), except when a release was intentional (frequency value of 5). High risk scenarios were thought to be high-consequence (value of 3) that were likely to occur in the facility (frequency values of 4 and 5) or an intentional moderate (consequence value of 2) release. These ranges are color-coded as green (low risk), yellow (medium risk), and red (high risk) in Figure 1. This risk matrix only describes possible categories for each scenario within a HAZOP. Of the 23 scenarios identified, 19 were low-risk, 4 were medium-risk, and there were no high-risk scenarios.

Risk Metric			
Frequency	Consequence		
	1	2	3
1	Low	Low	Low
2	Low	Low	Medium
3	Low	Medium	Medium
4	Low	Medium	High
5	Medium	High	High

Figure 1. Risk matrix categories for HAZOP analysis, showing qualitative frequency (1-5) and consequence (1-3) metrics combined into overall possible risk category

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

(A) External fire causes PRD release: 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 an FCV maintenance facility. This is not to say that an external fire could not affect the hydrogen within an FCV, nor that a hydrogen release during a fire is not worth examining. Rather, this scenario was not pursed further in this study because the ventilation code requirements of interest would not protect against an external fire or hydrogen jet fire; the ventilation is meant to protect against accumulation of a hazardous flammable mixture of hydrogen gas. Numerous other factors would need to be addressed in the event of an external fire large enough to cause a TPRD release, and there are several other code requirements (such as sprinklers) which would protect against this scenario. A different scenario considered the failure of the TPRD without a fire, which could lead to a moderate release. This was assumed to be lower frequency and so was not considered medium-risk; it would also lead to a release scenario similar to high-pressure defueling release (D), which was modeled in a separate report [13]. It should be noted, however, that the TPRD scenario could have a larger orifice diameter compared to the case studied in that report, which would lead to a shorter time to release the hydrogen inventory and possibly change the conclusions.

(B) Small release in low-pressure system: 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: 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 relatively high-risk classification and because the only preventative measure is proper training for operators.

(D) Premature disconnect of high-pressure defueling tool: 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. This scenario is examined in a separate report [13], but the lower pressure defueling scenario was analyzed here 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 [14]; 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 [15], 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 [15] 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 [16], 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 [17] with the default model parameters used: $C_{\epsilon 1} = 1.45, C_{\epsilon 2} = 1.92, \sigma_k = 1.0, \sigma_\epsilon = 1.3, C_\mu = 0.09$. The chemical transport and kinetic rate parameter specifications are handled by the Cantera code v1.7.0b for proper buoyancy effects [18]. The transport equations are 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 light-duty 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 located in the middle of the underside of a cuboid-shaped vehicle. The leak location was chosen because the fueling tanks and lines are located underneath the vehicle and because hydrogen might accumulate on this underside of the vehicle; if the leak were to the side of the vehicle, the hydrogen could disperse more easily. 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 [19] (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 a finite element solver like Fuego years to solve, even on a large number of processors. Assumptions were made to mitigate this issue. An alternative subsonic inlet (ASI) [20] 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 [21,22]. It was validated against experiments of hydrogen powered forklifts leaking into a room [21,23]. 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 [24]). 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 if placed 6 feet above the floor. A different case, which is beyond the scope of this paper but is contained in a separate report [13], 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. 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 ft	27 ft	16 ft
Vents in	4.5 ft	--	2 ft
Vents out	3 ft	3 ft	--
Car	6 ft	16 ft	5 ft
Aisle	26 ft	14 ft X 6 bays = 84 ft	16 ft

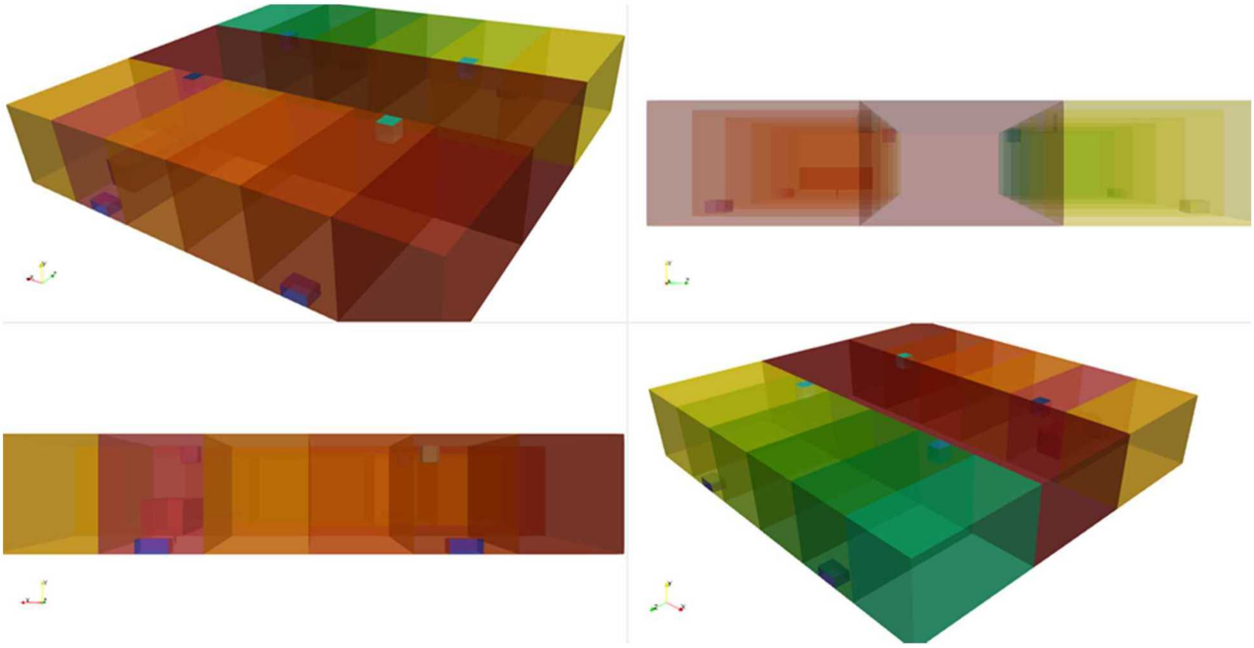

Figure 2. Layout of the mesh for a 12 bay maintenance facility. Inflow vents are near the floor and outflow vents are in the ceiling. Each of the colored blocks represents one bay with the aisle is shown in dark red, and the entire volume is open.

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 instantaneous flammable mass was 0.002 kg and occurred about 500 seconds into the simulation.

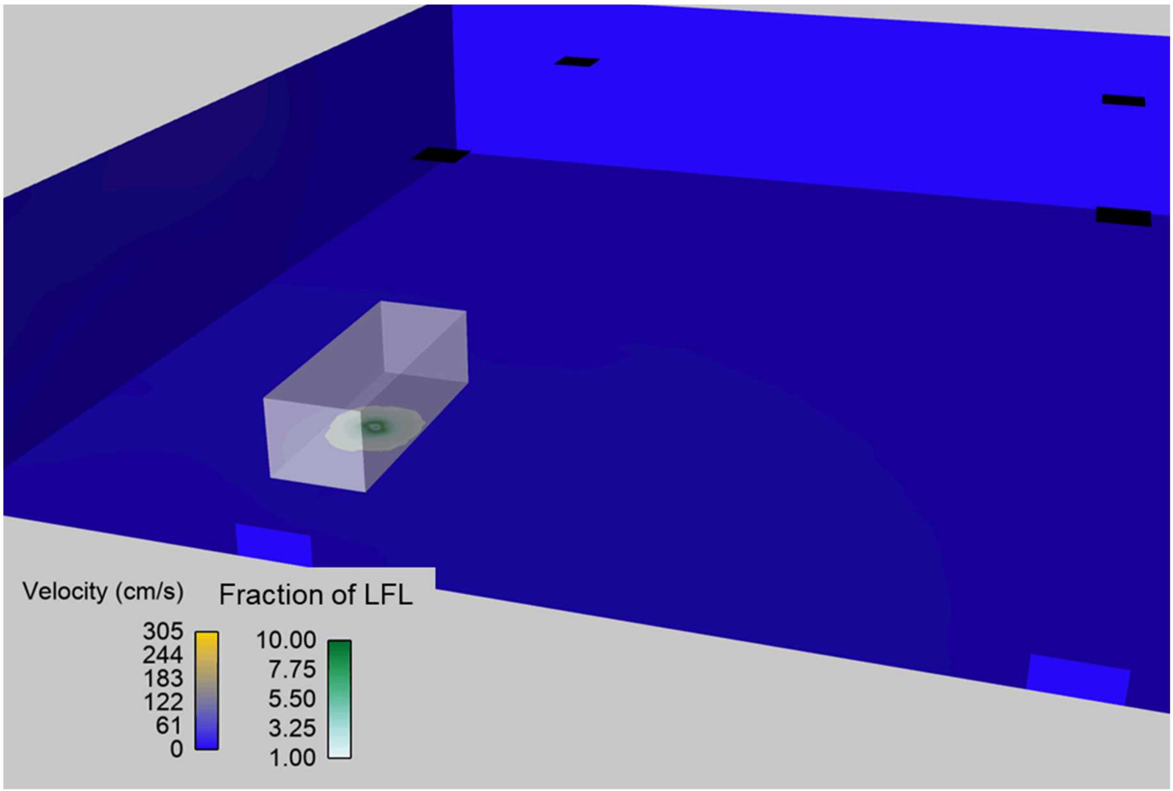

Figure 3. Time of maximum instantaneous flammable mass for this scenario is 500 sec into the release. The entire garage showing flammable mass as a cloud under the transparent vehicle, with walls and floor colored by velocity.

4.2 Standard Ventilation Away from Leak

For the second simulation, the 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 instantaneous flammable mass at 0.002 kg. The cloud of flammable mass in Figure 4 and Figure 3 are of comparable size.

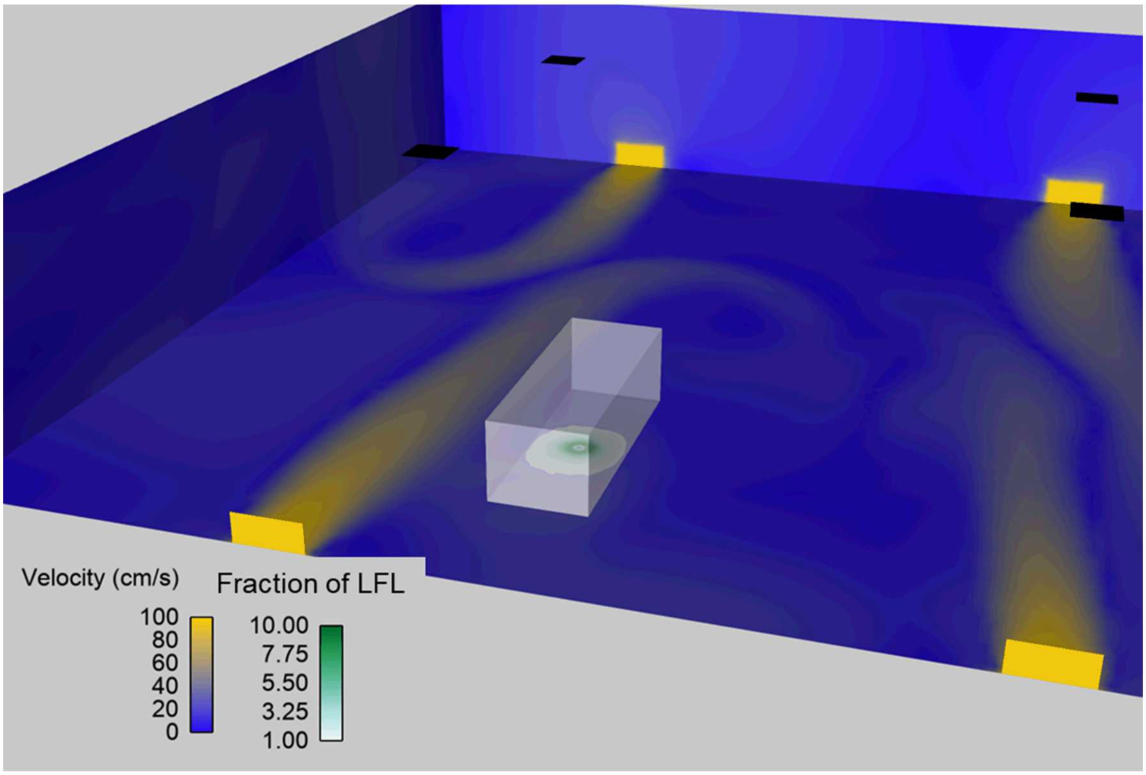

Figure 4. In this scenario, the vehicle is not near the incoming ventilation, and the maximum instantaneous flammable mass occurred 640 sec into the leak. The entire garage showing flammable mass as a cloud under the transparent vehicle, with walls and floor colored by velocity. The ventilation can be 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 instantaneous flammable mass of 0.00041 kg.

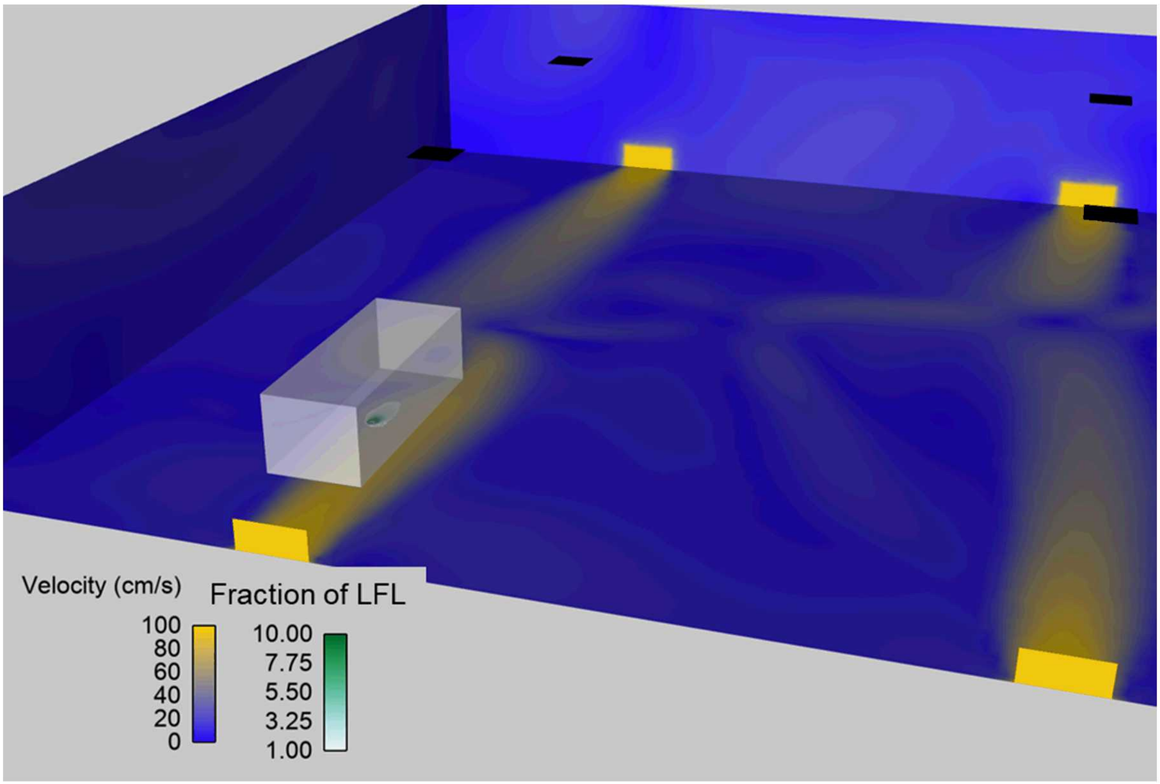

Figure 5. In this scenario, the vehicle is placed in front of the incoming ventilation, and a noticeable decrease in the amount of instantaneous flammable mass can be observed from the previous two scenarios. The maximum instantaneous flammable mass occurred 830 sec into the simulation. The entire garage 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 an instantaneous maximum of 0.000055 kg of flammable hydrogen.

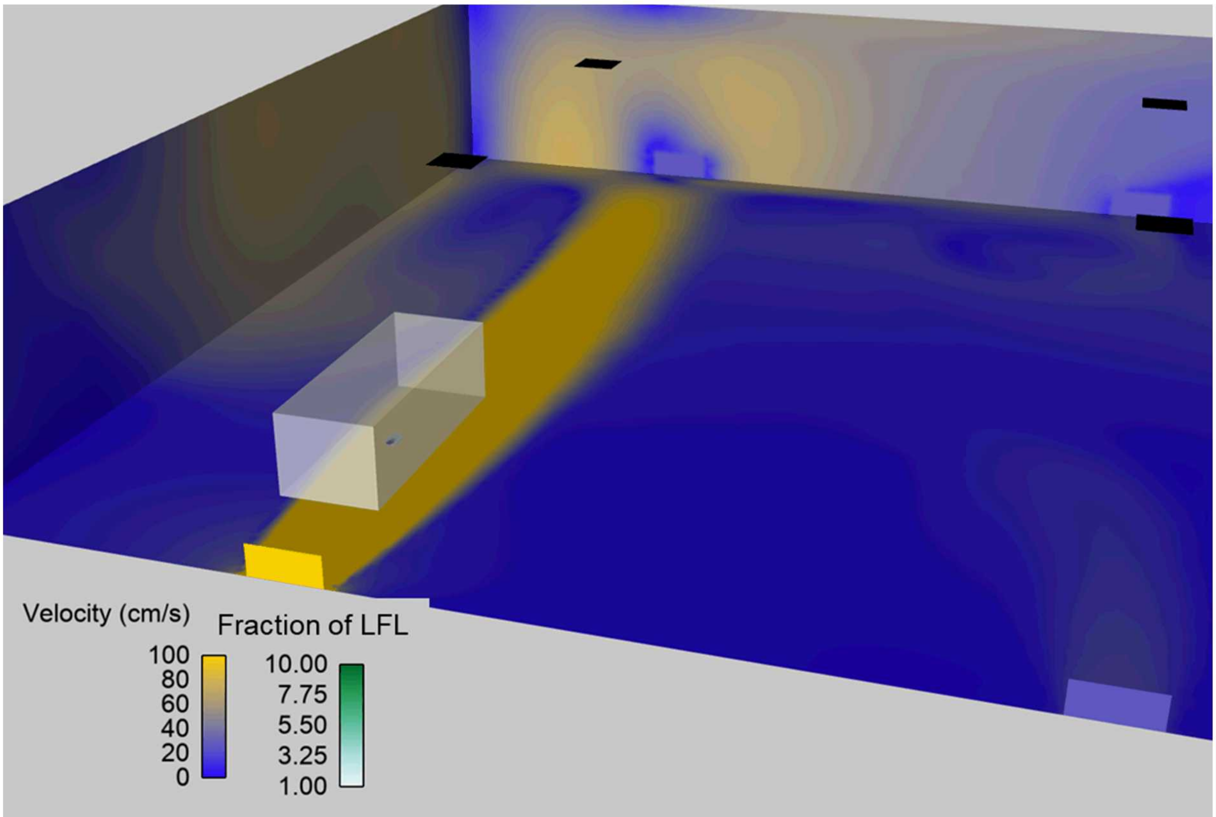

Figure 6. Providing a higher velocity fan near the vehicle decreases the amount of flammable mass even more than the standard ventilation. The entire garage showing flammable mass as a cloud under the transparent vehicle, with walls and floor colored by velocity. The ventilation can be seen in yellow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

4.5 Scenario Results Summary

A summary of the maximum instantaneous 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	Maximum Instantaneous Flammable Mass [kg]	Time at which Maximum Occurred [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 the 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 used [25]. 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.

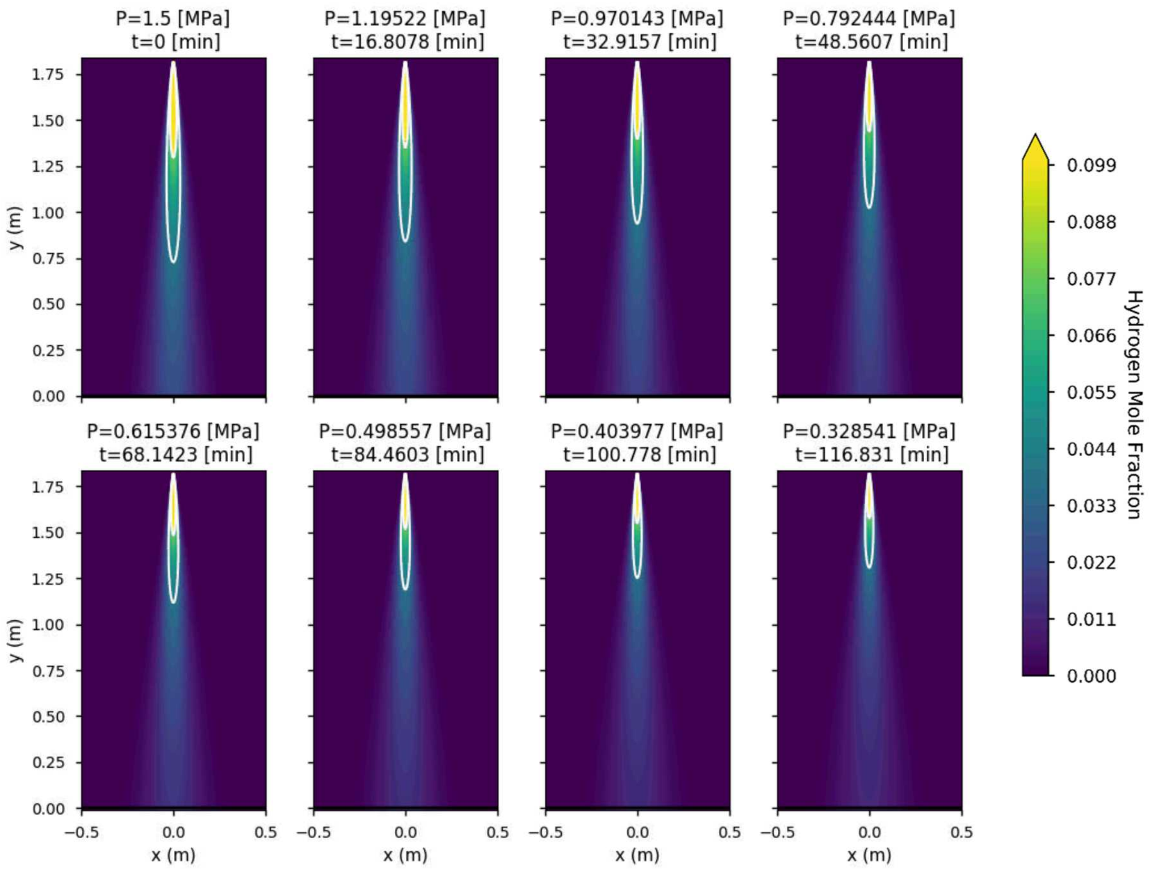

Figure 7. HyRAM flammable plumes as a function of time for a 1.5 MPa release. White contours show the χ_{H_2} = 4% and 8% flammable regions. The maximum plume length is 3.61 ft and 1.74 ft for χ_{H_2} = 4% and 8% respectively.

5.0 CONCLUSIONS

This study used a qualitative risk assessment tool to identify the most risk-significant hydrogen release from a light-duty vehicle in a repair garage. This was determined to be a leak from a mid-pressure port on a hydrogen fuel cell vehicle in a maintenance garage. CFD modeling 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. Based on these results, it is suggested that use of direct ventilation might provide a suitable way to increase safety without structural changes to the garage or ventilation system. Ventilation can vary widely between different facilities, and this study only looked at a few cases of different ventilation speeds for a particular facility; thus, these results may or may not be applicable to a particular facility. Further analysis of different leak locations and speeds, in combination with different ventilation configurations would be critical to more fully understanding what ventilation requirements would be most effective. Additionally, a more quantitative risk assessment could be performed if more complete data were available to better identify and understand risk-significant release scenarios.

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