Hydrogen Fuel-Cell Forklift Vehicle Releases in Enclosed Spaces

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ABSTRACT

Sandia National Laboratories has been working with stakeholders and original equipment manufacturers (OEMs) to develop scientific data for use in creating risk-informed hydrogen codes and standards for the safe operation of indoor hydrogen fuel-cell forklifts. An important issue is the possibility of an accident inside a warehouse or other enclosed space, where a release of hydrogen from the high-pressure gaseous storage tank could occur. For such scenarios, computational fluid dynamics (CFD) simulations have been used to model the release and dispersion of gaseous hydrogen from the vehicle and to study the behavior of the ignitable hydrogen cloud inside the warehouse or enclosure. The overpressure arising as a result of ignition and subsequent deflagration of the hydrogen cloud within the warehouse has been studied for different ignition delay times and ignition locations. Both ventilated and unventilated warehouses have been considered in the analysis. Experiments have been performed in a scaled warehouse test facility and compared with simulations to validate the results of the computational analysis.

1.0 INTRODUCTION

Hydrogen powered fuel-cells are replacing lead-acid batteries as the power source on forklifts used for moving materials within commercial warehouses. The onboard storage of compressed hydrogen gas along with indoor refueling in the closed warehouse environment introduces new operational requirements that must be considered in the development of safety guidelines. In order to provide a scientific basis for these safety guidelines, validated engineering models of unintended hydrogen releases are needed for scenario and risk analysis.

Sandia has been working with original equipment manufacturers (OEMs) to develop an understanding of unintended releases from hydrogen powered forklift vehicles in enclosed spaces. Our initial efforts have focused on the gaseous hydrogen indoor dispensing code in NFPA 52 (extracted and also appearing in NFPA 2) [1, 2] as it applies to hydrogen forklift vehicles in warehouses. Based on Table 9.4.3.2.1 in NFPA 52 a maximum of 0.8 kg of hydrogen may be dispensed and used in a forklift vehicle indoors without warehouse ventilation if the warehouse volume is at least 1000 m^3 and has a ceiling height of at least 7.62 m (25 ft). Larger fueling rates are allowed in unventilated warehouses if the warehouse volume is increased in accordance with Table 9.4.3.2.1 specifications. Forklift vehicle fueling and operation outside the parameter range specified by Table 9.4.3.2.1 is allowed if the warehouse is ventilated at a rate of a least 0.3 $m^3/min/m^2$ (1 $ft^3/min/ft^2$) of room area, but no less that 0.03 $m^3/min/0.34m^3$ (1 $ft^3/min/12ft^3$) of room volume.

As a first approach a set of indoor hydrogen release experiments was designed based on OEM forklift specifications, guidance in NFPA 52, and a leak sized based on OEM recommendations from a failure modes and effects anaysis (FMEA). A release scenario was defined where the entire contents (0.8 kg) of a 35 MPa hydrogen tank onboard a fuel-cell forklift was released and ignited at different times inside a full-scale (1000 m^3) warehouse. The hydrogen was released through a 6.35 mm opening meant to simulate a medium sized leak (based on the OEM FMEA) or thermally activated pressure relief device (TPRD) onboard the enclosure containing the forklift fuel-cell storage tank. The hydrogen was then allowed to exit through a grill on the side of the forklift and enter the surrounding warehouse.

[1] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94-AL85000.

The warehouse sizing, ventilation, and amount of hydrogen onboard were based on the parameters outlined in section 9.3.3 of NFPA 52 as discussed above. Based on this full-scale release scenario, subscale experiments were designed and performed in a scaled warehouse test facility (Fig. 1) at the SRI International Corral Hollow Experiment Site (CHES) to provide model validation data for simulations of forklift vehicle releases.

Computational fluid dynamics (CFD) simulations of hydrogen releases from the fuel-cell powered forklift inside the warehouse were performed using the Sandia developed FUEGO [3] CFD model. Concentrations taken from FUEGO simulations were then used in a FLACS (2010) [4] model of the warehouse to simulate the overpressure generated by ignition of the hydrogen cloud at different ignition delay times. The FUEGO/FLACS simulations were performed at both full scale (1000 m^3) and the scale of the experiments (1/2.8 scale). The scaled simulations were compared with data taken in the scaled warehouse experiments for the purposes of validating the modeling approach. The validated model was then used to perform additional full-scale release simulations to provide information for risk-informed hydrogen codes and standards development. The experiment and model validation simulations are described in the following sections.

2.0 SCALED WAREHOUSE EXPERIMENT

The model validation experiments were performed in a hardened sub-scale warehouse at the SRI International Corral Hollow Experiment Site (CHES) located near Livermore, CA. Figure 1a shows a photograph of the SRI test warehouse prior to construction of a rigid front wall that was added for the deflagration experiments. Appropriate scaling factors [5] were determined to create a set of scaled-warehouse tests that resembled as closely as possible the full-scale warehouse release scenario. This scaling approach has been successfully used for previous tests at the SRI facility involving releases from scaled hydrogen fuel-cell vehicles in tunnels [6]. The SRI test facility has a volume approximately $(1/2.8)^3$ and height approximately 1/2.8 that of the 1000m^3 full-scale warehouse with a 7.62 m (25 ft) ceiling. The scaled warehouse was 3.64 m wide by 4.59 m long by 2.72 m high with a total volume of 45.4 m^3. The layout of the experimental setup is shown in Fig. 1b.

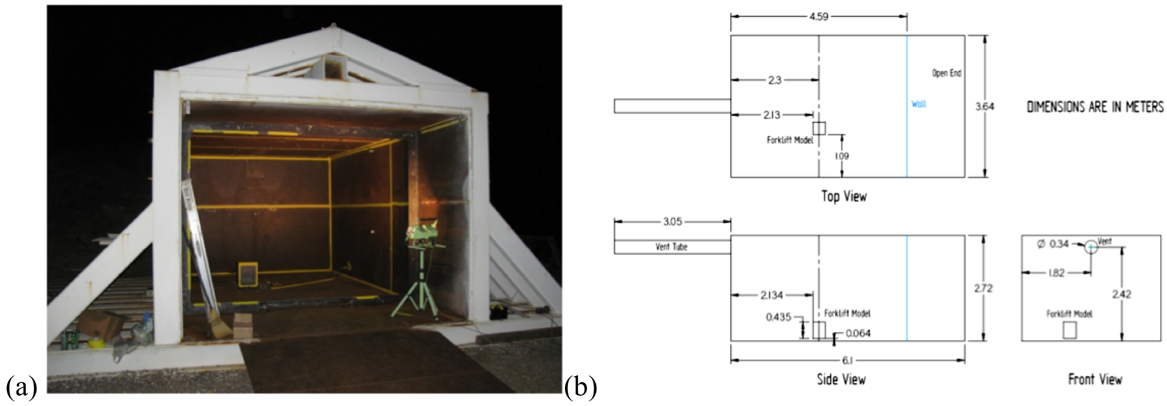


Figure 1. (a) Photograph and (b) layout of the scaled-warehouse test facility used for release experiments. Model forklift shown with release opening directed toward back wall.

The mass of hydrogen released in the scaled test was related to the mass of hydrogen released in the full-scale scenario by the volume ratio $(1/2.8)^3$. The time for the scaled mass release was related to the time for full-scale mass released by the Froude number and dimensionless time. The initial tank pressure for the experiments was 13.45 MPa (gage) and the tank volume was chosen so that it would hold the scaled mass of hydrogen. The release diameter (3.56 mm) was designed so that the tank blowdown curve in the scaled experiment agreed with the above scaling. Figure 2 shows a comparison of the measured mass release rate from the experiment with the calculated and scaled full-scale mass release rate.

The forklift model measured 0.343 m long by 0.343 m wide by 0.435 m high and is shown in Fig. 3a. Hydrogen was released into a 131 mm wide by 131 mm high by 88 mm deep enclosed space on the forklift side facing the back wall of the garage; the enclosed space was packed with steel beads so that the flow was uniformly dispersed at the release opening. During a release, hydrogen from the nozzle passed through a porous frit and into the enclosure of steel beads that occupied appoximately 61% of the enclosure volume, before exiting the model forklift side into the warehouse through a perforated steel plate with a 51% open area (see Fig. 3b).

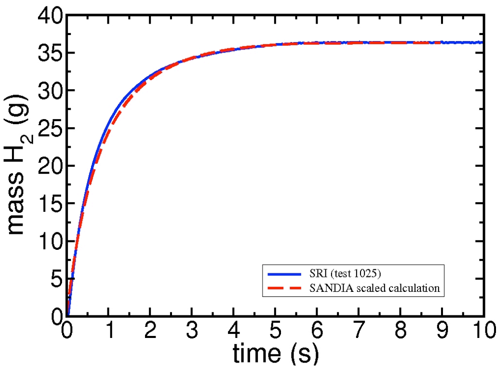


Figure 2. Scaled mass release rate for the scaled warehouse experiment (based on 0.8 kg of hydrogen forklift release in a 1000 m^3 full-scale warehouse).

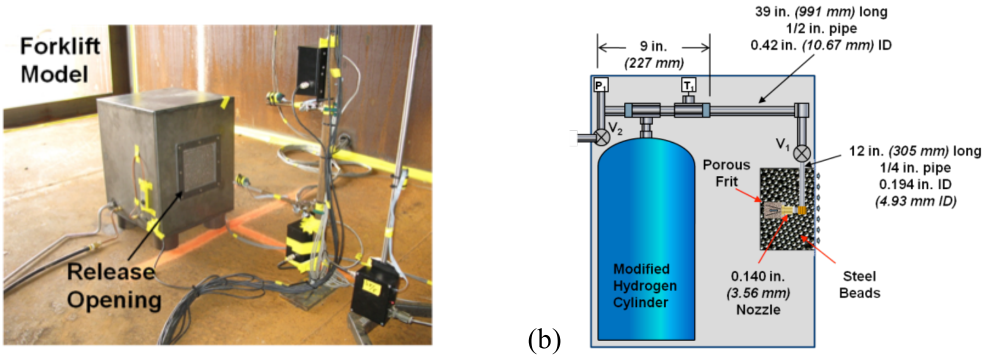
(a)  (b)

Figure 3. (a) Photograph showing the exterior and release opening for the model forklift used in the experiments. (b) Schematic showing interior of model forklift with hydrogen bottle, refilling line, porous frit, steel bead enclosure and perforated steel release opening.

Three different types of tests were performed in the scaled warehouse experiments. These included: (1) hydrogen dispersion tests to measure the time variation of the concentration in the unignited hydrogen cloud released from the model forklift; (2) ignition and flame front imaging tests to determine the shape of the flame front and its propagation speed; and (3) a set of deflagration tests where the overpressure produced from igniting the hydrogen cloud was determined for a given ignition delay time and ignition location. Here the ignition delay time is defined as the time between the beginning of the release and activation of the spark ignition source.

The front wall configuration of the warehouse was altered depending on the type of test performed. Figure 4 shows the various warehouse front wall configurations. For the flame propagation imaging and dispersion tests, the front end of the warehouse was either left open (Fig. 1a) or covered with a high-density polyethylene (HDPE) plastic sheet (see Fig. 4a). This allowed infrared and standard video images of the flame propagation to be visualized. Flame speed and overpressure measurements were also recorded as part of these tests. For the overpressure tests the warehouse open end was sealed with a steel wall containing a center access doorway, with a plywood blowout panel used to cover the doorway (Fig. 4b-d). The ignition source was a spark ignitor located either 3 cm above the top rear edge of the model forklift (on the side with the release opening grill) or 10 cm below the warehouse ceiling on the same vertical line (the midline of the grill on the side of the forklift).

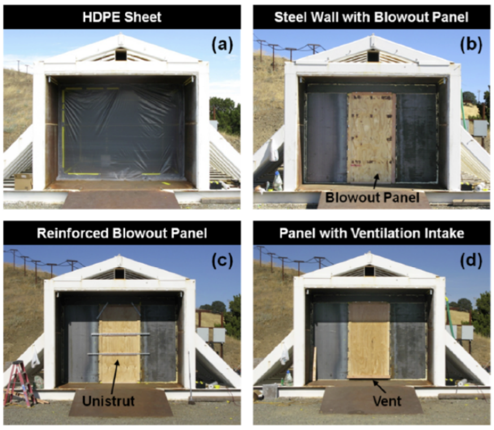


Figure 4. Photographs of scaled-warehouse test facility showing the different front wall configurations used for the various experiments.

For the dispersion tests, oxygen depletion measurements from fast-response Teledyne UFO 130-2 oxygen sensors were used to calculate hydrogen concentrations. Two dispersion tests were conducted with a well-sealed warehouse, while a third was conducted with active mechanical ventilation. The 6.3 m^3/min ventilation flowrate was selected based on application of the scaling factors to the NFPA 52 full-scale warehouse ventilation guidelines (1 ft^3/min/12 ft^3). Active ventilation was accomplished by placing two muffin fans in the 3.05 m long and 0.34 m diameter exhaust vent tube located on the backwall of the warehouse (see Fig. 1b). When the fans were running, air was pulled into the warehouse through an open vent (120.0 cm wide by 6.35 cm high) located near the bottom of the plywood pressure blowout panel on the steel front wall of the warehouse (see Fig. 4d). The flowrate through the exhaust tube was verified beforehand with an anemometer along seven radial locations 2.75 m downstream in the tube.

Figure 5 shows an infrared flame propagation image sequence from the scaled warehouse experiment when ignition occured 3 cm above the top rear edge of the forklift (3 sec ignition delay time). A flame can be observed traveling upward along the released plume before propagating into the hydrogen/air mixture that collected along the ceiling. When the release was ignited 10 cm below the warehouse ceiling (not shown) the flame propagated along the ceiling and was directed downward as it approached the warehouse side-walls. The flame did not propagate downward from the ceiling along the hydrogen plume toward the model forklift.

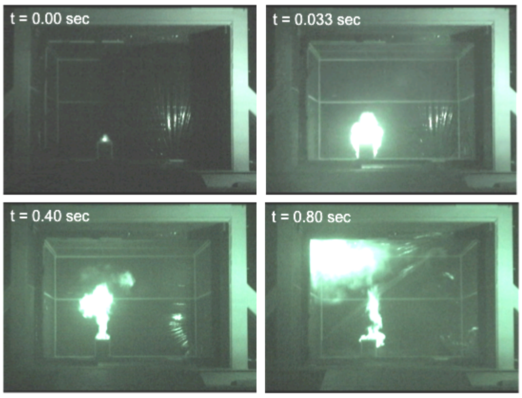


Figure 5. Infrared image sequence from scaled warehouse experiments showing flame propagation at approximately 0, 33, 400, and 800 msec after ignition. The ignition location was 3 cm above the top rear edge of the model forklift and occurred 3 sec after the beginning of the release. The hydrogen was released through the back side of the model forklift, directed toward the back wall of the warehouse.

For the confined deflagration overpressure tests, the open end of the warehouse was sealed with a steel wall and a plywood blowout panel was used to cover the center access doorway (Fig. 4b-d). Seven tests were performed with the release ignited either 3 cm above the forklift model or 10 cm from the ceiling of the warehouse. Several different blowout panel configurations were used to increase the pressure at which the panel breached. Two tests were also performed with active or natural ventilation using the vent tube on the back wall and the vent near the bottom of a plywood pressure blowout panel (Fig. 4d). Pressure transducers were used to measure the generated overpressure, while fast-response thermocouples were mounted along the facility ceiling and were used to measure flame speed. The maximum measured overpressure in the test series was 24.6 kPa, which occurred when the warehouse was well-sealed (including sealed ventilation ducts) and the ignition source was located 3 cm above the model forklift. When ignition occurred 10 cm below the top of the ceiling the maximum measured overpressure was 19.0 kPa.

During the tests it was observed that small increases in the warehouse leakage area led to a significant reduction in ignition overpressure. Hence, the leakage area of the scaled warehouse was measured for each test configuration by replacing the plywood blowout panel with a computerized fan system, Model 3 Minneapolis Blower Door, manufactured by The Energy Conservatory. For the well-sealed warehouse configuration the leakage area was measured to be approximately 36.7 cm^2 while for the ventilated warehouse the total leakage area was measured to be 971.6 cm^2. These leakage areas were incorporated in the warehouse deflagration models for the purposes of comparing the simulated ignition overpressures with the experimental data. It is important to note that the rise in overpressure may have resulted in deformation of the facility and led to an associated increase in the leakage area. Only a brief summary of the experiments has been given here and further details can found in Ekoto et al. and Merilo et al. [7, 8].

3.0 SCALED WAREHOUSE SIMULATIONS AND MODEL VALIDATION

Sandia's computational fluid mechanics code, FUEGO [3], was used to perform simulations of hydrogen fuel-cell forklift releases inside the scaled warehouse. For these simulations the high-pressure hydrogen gas was allowed to exhaust from the side of the forklift through a 131 mm by 131 mm opening with a uniform velocity that was directed toward the back wall of the warehouse. The transient nature of the hydrogen tank blowdown was modeled with the Sandia developed compressible network flow analysis code, NETFLOW [9, 10], the results of which were then used to develop a transient boundary condition for the exhaust opening in the FUEGO simulations. The NETFLOW model accounted for choking of the flow at the release orifice (3.56 mm), expansion into the enclosure, and exhaust of the hydrogen through the steel perforated plate (51% flow area) on the side of the model forklift. The FUEGO scaled warehouse model included the open area where the exhaust tube was located in the back wall of the warehouse and the vent located at the bottom of the plywood blowout panel in the forced ventilation simulations. For simulations of the tests involving forced mechanical ventilation the steady airflow through the warehouse was first calculated before initiating the release of the hydrogen from the side of the forklift. Figure 6 shows two frames from the transient simulation of the flammable hydrogen cloud release in the scaled warehouse at times of 1 and 3 seconds after the beginning of the release for a case without active ventilation. The simulation shows that the hydrogen plume rises from the side vent on the forklift and collects along the ceiling in the corner of the warehouse.

Ignition overpressure simulations for the forklift releases in the scaled warehouse were also performed. These simulations were based on three-dimensional flammable cloud volumes and concentrations maps extracted from the FUEGO dispersion simulations. A FLACS (2010) model was then used to perform a transient simulation of ignition of the cloud and the associated overpressure generated by the deflagration wave propagating rapidly across the cloud and the expansion of the hot gas inside the enclosure. The FLACS model included the ventilation openings in the back and front walls of the warehouse and additional models were built that allowed simulations to be performed with either an open warehouse front wall or the plywood blowout panel. The small warehouse leakage areas measured with the blower apparatus as part of the experiments were also incorporated into the model by adding a small slot of equivalent leakage area near the bottom center of the front wall.

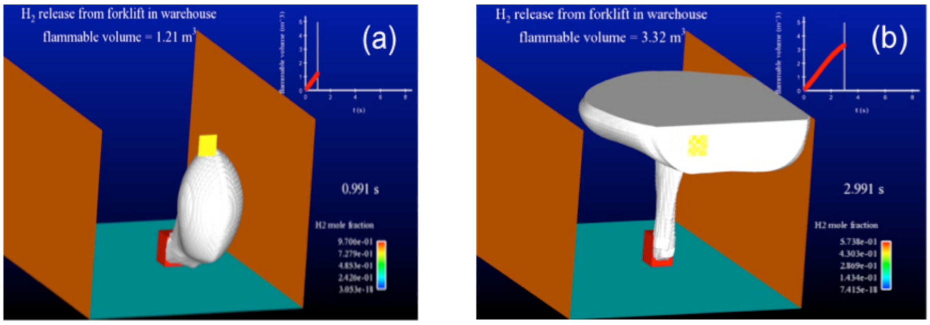
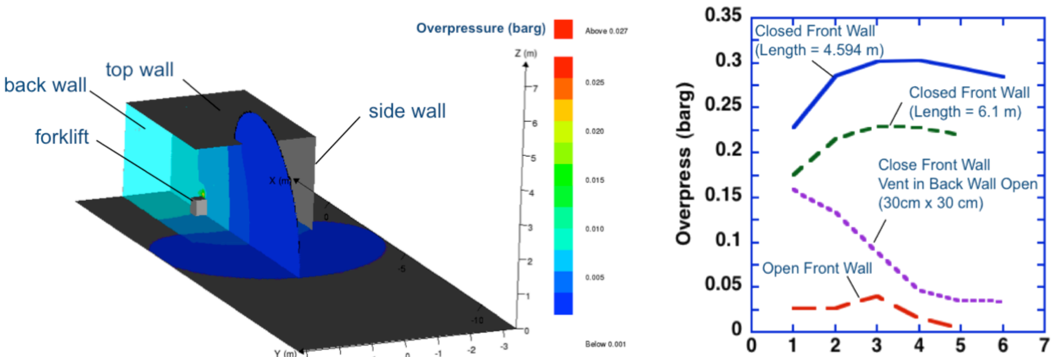


Figure 6. Simulation showing flammable volume of hydrogen (4% - 75% mole fraction) in the scaled warehouse experiment for (a) 1 sec and (b) 3 sec after the beginning of the hydrogen release. Results for case without ventilation.

FUEGO/FLACS simulations of the scaled warehouse were performed prior to the experiments to determine the appropriate placement of concentration sensors and to estimate the expected overpressure from ignition of the hydrogen releases. Pretest FLACS ignition deflagration simulations of the test geometry using three-dimensional concentration maps from FUEGO dispersion simulations indicated that the maximum ignition overpressure would be approximately 30 kPa (0.3 barg) if the warehouse was completely (100%) sealed and if the effects of wall heat transfer were neglected. Based on these simulations a wooden pressure relief panel was designed and placed in the doorway of the steel front wall of the scaled warehouse prior to beginning deflagration testing. Figure 7a shows a pretest simulation of the deflagration overpressure in the scaled warehouse for conditions when the front of the warehouse is open. Figure 7b shows a summary of pretest deflagration simulations for the scaled warehouse showing the effect of ignition delay time and warehouse configuration on peak overpressure.



(a) (b)

Figure 7. (a) Simulation showing maximum deflagration overpressure (barg) contours along the center plane, back wall, and floor of the scaled warehouse for case with an open front wall. Results are for ignition 3 cm above the forklift with an ignition delay time of 2 sec. (b) Pretest FLACS simulation results showing maximum deflagration overpressure as a function of ignition delay time for different scaled warehouse test configurations. Results neglect heat transfer to the warehouse walls.

Figure 8 shows a frame from the transient simulation of the hydrogen release from the forklift in the scaled warehouse (closed front) 3 seconds into the release and comparison of the measured and predicted concentration from the experiments with and without forced ventilation at four sensor locations. Close agreement is exhibited between the simulations and experimental results. Both the simulations and experimental data show that buoyancy causes the released hydrogen to quickly rise and collect along the warehouse ceiling. Furthermore, the effect of the forced ventilation on the hydrogen concentration profiles is observed to be small in both the experimental data and the simulations.

Three-dimensional concentration maps 3 seconds into the release were taken from the FUEGO simulations and used in a FLACS simulation of the scaled warehouse to predict the transient nature of the deflagration ignition overpressure. Figure 9a shows a comparison of the predicted ignition overpressure from the simulations with data from a pressure sensor (P2) located in the center of the warehouse side wall nearest the forklift approximately 1.24 meters off the floor. Simulation results are shown for the case with and without heat transfer to the warehouse walls for a completely (100%) sealed warehouse. Results are also shown for simulations with and without heat transfer to the walls where the measured leakage area (36.7 cm^2) was incorporated into the model. The results with the measured air leakage rate and heat transfer to the walls are in good agreement with the experimental data. Both the experiment and the simulation show a peak pressure of approximately 25 kPa for this test. Results are also shown for the case where the front wall and backwall vents in the warehouse are open (natural ventilation) but the fan is not operated to create forced ventilation. These deflagration simulations were performed including the vent areas, measured air leakage area (36.7 cm^2), and wall heat transfer. Figure 9a shows that the simulated pressure peak occured earlier in time (~0.4 sec) than the measured data, but the peak and shape of the overpressure pulses are in good agreement with the data. The peak overpressure was approximately 5 kPa with vents open and no forced flow and was approximately a factor of 5 less than the overpressure observed when the warehouse was well-sealed without vents.

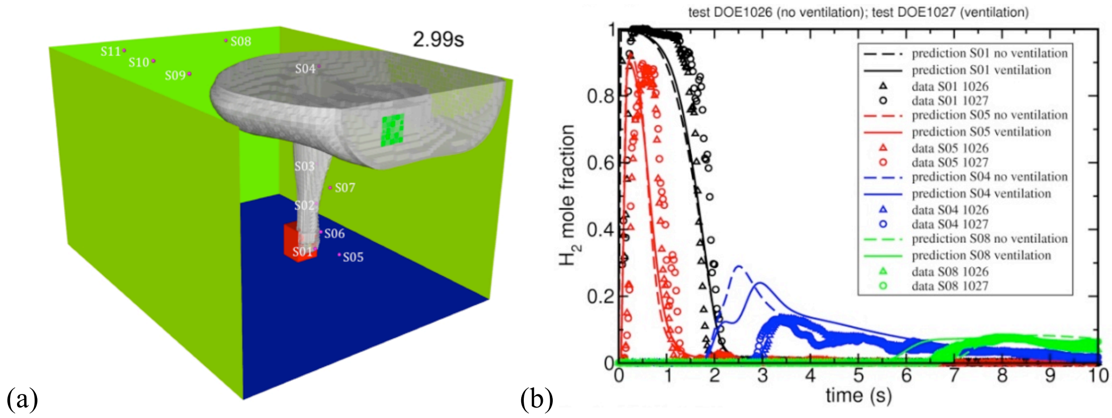


Figure 8. (a) Simulation showing flammable cloud in scaled warehouse 3 seconds into release and locations of concentration measurement sensors. (b) Comparison of measured and predicted concentrations with and without forced ventilation in the scaled warehouse at four different sensor locations (Test 1026 performed without active ventilation and Test 1027 performed with active ventilation).

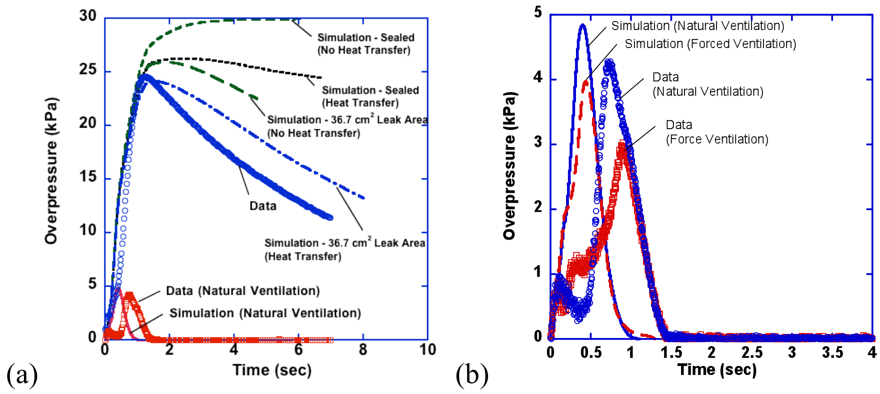


Figure 9. (a) Comparison of simulations and data for ignition deflagration overpressure for the scaled warehouse for the case with no ventilation and non-forced (natural) ventilation through the open vents (3 sec ignition delay time). Ignition location is 3 cm above the forklift and time is measured from the beginning of spark ignition. (b) Comparison of simulations with experimental data for ignition deflagration overpressure in the scaled warehouse for the case with either forced ventilation (ventilation fans on – 6.3 m^3/min) or natural ventilation (ventilation fans off) through the vents.

Figure 9b shows a comparison of simulation and experimental data for the transient variation of ignition deflagration overpressure (pressure sensor P2) with either forced (ventilation fans on) or natural ventilation (ventilation fans off) through the warehouse vents. From the experimental results overpressure for the case with forced ventilation was approximately 3 kPa while the case with natural (passive) ventilation was about 4.2 kPa. This difference in overpressure was probably within the experimental uncertainty of the tests. The simulation results show approximately the same trends as the experiments, with the overpressure for the natural ventilation case being approximately 1kPa greater than for the case with forced ventilation. These results showed that forced ventilation at the scaled NFPA 52 rate (6.3 m^3/min) had little effect on the peak deflagration overpressure. This was consistent with the experimental and simulation results of Fig. 8 which show that the same forced ventilation rate has little effect on the concentration distribution within the scaled warehouse. The overpressure reduction with open vents compared to the well-sealed warehouse (see Fig. 9a) seems to be a result of the vents providing a pathway for the expanding combustion gases to vent to the outside environment, thereby relieving the pressure.

In the ignition deflagration overpressure tests the pressure that develops inside the scaled warehouse was dependent on the rigidity of the enclosure and how well it was sealed. Several different strength blowout panels were used during the experiments in an effort to find a panel that would not breach and would remain well sealed during the duration of a test. Initial blowout panels used in the tests were built from a single sheet (1.27 cm thick) of plywood and bolted to the steel wall with a wooden frame (5.08 cm by 10.16 cm thick) to increase attachment strength to the facility (see Fig. 4b). This single plywood sheet panel breached during the unventilated warehouse tests. For the well-sealed warehouse results shown in Fig. 9a, three 1.27 cm (0.5 inch) thick plywood sheets were layered together to increase the strength of the panel in addition to using the external wooden (5.08 cm by 10.16 cm thick) frame to bolt the panel to the steel wall. Metal Unistrut was then mounted across the front surface of the plywood as shown in Fig. 4c to further increase the panel's strength and to reduce bending. This reinforced panel did not breach and remained relatively well sealed for the test duration.

Deflagration simulations of the experiments where the single sheet plywood panel breached were modeled by including a pressure relief panel in the FLACS model the same size and at the same location as the plywood blowout panel. In the model the pressure relief panel was set to open at the same overpressure where the experimental data indicated the breach occurred (approx. 13 kPa). Figure 10a shows a frame of a high-speed movie taken of the single sheet plywood blowout panel breach. Figure 10b shows a comparison of deflagration simulations with experimental data from the scaled warehouse for a 3 sec ignition delay for the case of a well-sealed warehouse with and without breach of the plywood pressure blowout panel. Peak overpressure was approximately 13 kPa when the pressure relief panel breaches as compared to 25 kPa with the reinforced panel that does not breach. Results of the simulations are in good agreement with the experimental data and indicate that pressure relief panels can provide an effective means to reduce deflagration pressure rise.

Figure 11a shows comparisons of deflagration overpressure simulations with experimental data for the cases when ignition occurred 3 cm above the forklift and 10 cm below the top of the warehouse ceiling. For the experiments where ignition occurred 10 cm below the top of the warehouse ceiling the ignition delay time was increased from 3.0 to 3.5 sec to ensure the hydrogen mixture at the release point was flammable. The experimental data shows that the peak overpressure was approximately 24.6 kPa when ignition occurred above the forklift in the well-sealed warehouse as compared to 19.0 kPa when ignition occurred 10 cm from the ceiling. Simulations for ignition above the forklift in the well-sealed warehouse are in good agreement with the data while simulations for ignition 10 cm below the top of the ceiling show a peak overpressure of approximately 23.5 kPa as compared to 19.0 kPa in the experiments. One possible explanation for the disagreement is that a single sheet plywood blowout panel was used for the ignition 10 cm below ceiling tests while a 3-sheet plywood blowout panel was used for the tests where ignition occurred 3 cm above the forklift. The single sheet plywood panel may have undergone greater deformation and allowed a greater amount of leakage during the experiment. Figure 11b shows a comparison of data with simulations for ignition 10 cm below the top of the warehouse ceiling (3.5 sec ignition delay time) where the amount of warehouse leakage in the simulation is varied. The simulations show that small increases in leakage area can significantly reduce the ignition deflagration pressure inside the warehouse. Another possible explanation is that the FLACS simulation for ignition 10 cm from the top of the warehouse ceiling (3.5 sec ignition delay) shows that the flame propagated across the ceiling as well as down the release plume toward the model forklift. This is contradictory to the flame imaging experiments for ignition 10 cm below the ceiling, which show that flame propagated across the ceiling but does not burn down from the ceiling along the hydrogen plume towards the model forklift. The FLACS flame propagation model may not account for differences in the flammability limits of hydrogen depending on whether the flame propagates upward or downward.

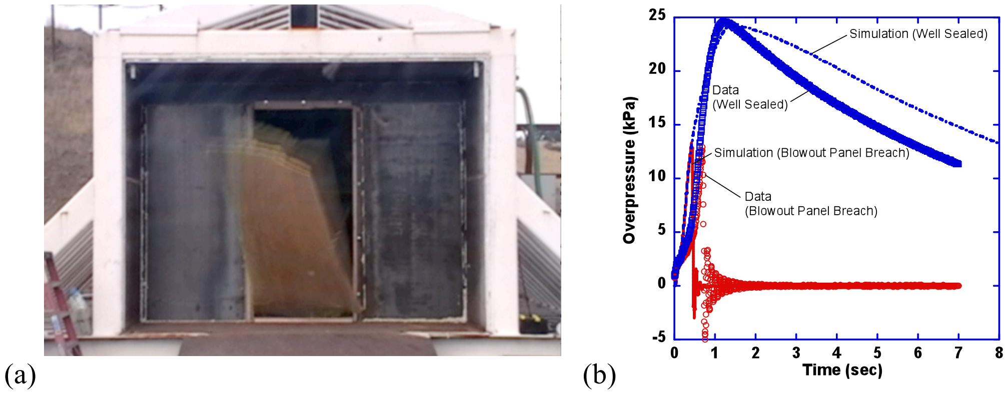


Figure 10. (a) Single frame of a high-speed video showing breach of plywood blowout panel on front of the scaled warehouse after ignition of hydrogen release from model forklift. (b) Comparison of simulation and experimental data for a well-sealed warehouse with and without plywood blowout panel breach (3 sec ignition delay time). Ignition location is 3 cm above the forklift and time is measured from the beginning of spark ignition.

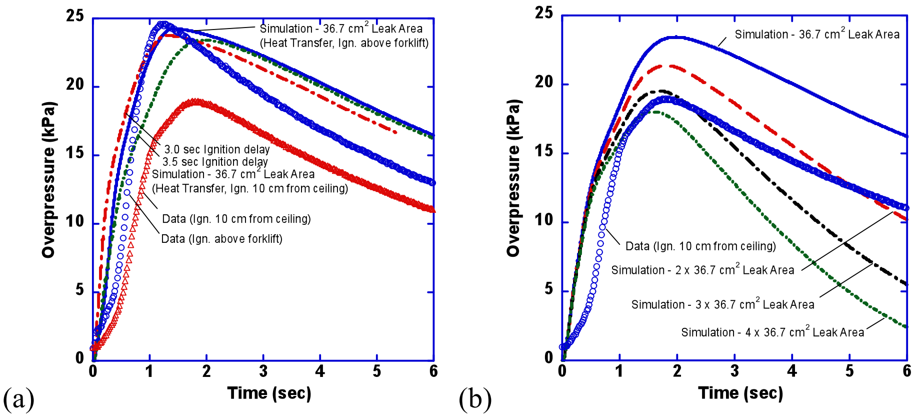


Figure 11. (a) Comparison of simulation results and experimental data for ignition 3 cm above forklift (3.0 sec ignition delay time) and ignition 10 cm from warehouse ceiling (3.0 and 3.5 sec ignition delay time). (b) Comparison of simulation results with experimental data for ignition 10 cm from warehouse ceiling (3.5 sec ignition delay time) where the amount of warehouse leakage was varied in the simulations.

4.0 FULL-SCALE WAREHOUSE SIMULATIONS

Full-scale forklift-in-warehouse release simulations were performed with the FUEGO/FLACS models to evaluate whether the full-scale warehouse release and deflagration would behave in the same manner as observed in the scaled warehouse experiments. The geometry of the scaled SRI warehouse including the forklift and its location was converted to a full-scale warehouse model by multiplying all of the lengths in the model by a factor of 2.8. This full-scale warehouse had a ceiling height of 7.62 m (25 ft) and was 12.863 m long by 10.202 m wide with a volume of 1000 m^3. A total of 0.8 kg of hydrogen was released from the forklift tank at 35 MPa through a 6.35 mm opening into a 0.0118 m^3

enclosure with a vent opening on the side of the forklift of 674.1 cm^2. The NETFLOW compressible network flow analysis code was again used to model the transient nature of the tank blowdown (assuming 50% blockage by the grill); the results were applied for the FUEGO boundary condition at the exhaust opening on the side of the forklift. Full-scale front and back wall vents were incorporated into the model and active forced ventilation, passive (natural) ventilation, and completely (100%) sealed simulations were also performed. For the active ventilation simulations the full-scale ventilation rate of 0.03 m^3/min/0.34 m^3 (1 ft^3/min/12 ft^3) of room volume was used in the simulations.

Table 1 shows comparisons of simulated peak ignition deflagration overpressure in the scaled and full-scale warehouse releases for a 3 sec ignition delay time. For the well-sealed (100%) warehouse conditions the peak ignition deflagration overpressure with wall heat transfer for the full-scale warehouse is 24.5 kPa as compared to 26.7 kPa in the (1/2.8) scaled warehouse geometry. The results for the full-scale warehouse show that forced flow ventilation has little effect on deflagration overpressure as compared to the case where the vents are left open without forced flow. A similar effect of forced ventilation on the deflagration overpressure for the scaled warehouse experiments was observed (see Fig. 9b). Figure 12 shows that the effect of forced ventilation on the flammable volume of hydrogen in the full-scale warehouse is small. This is consistent with the experimental and modeling results for the scaled warehouse experiment that are shown in Fig. 8b.

Table 1. Comparison of simulated peak ignition deflagration overpressure from forklift releases in scaled and full-scale warehouses for 3.0 sec ignition delay time and ignition 3 cm above the top of the forklift.

	100% Sealed (no heat transfer)	100% Sealed (heat transfer to walls)	Natural Ventilation (vents open)	Active Ventilation (vents open with forced flow)
Scaled-Warehouse (S.F. = 1/2.8)	29.8 kPa	26.7 kPa	4.9 kPa	4.2 kPa
Full-Scale Warehouse	27.2 kPa	24.5 kPa	14 kPa	15.5 kPa

A series of full-scale warehouse simulations were also performed for the 0.8 kg forklift release where the volume of the warehouse was increased from 1000 m^3 to 1500 m^3 and 2000 m^3 while keeping the ceiling height of the warehouse constant at 7.62 m (25 ft). For these simulations the width and length of the 1000 m^3 warehouse were scaled by a constant factor for each case to reach the desired warehouse volume. The location of the forklift remained midway between the front and back walls of the warehouse and at a fixed distance of 3.039 m from the nearer sidewall in all cases.

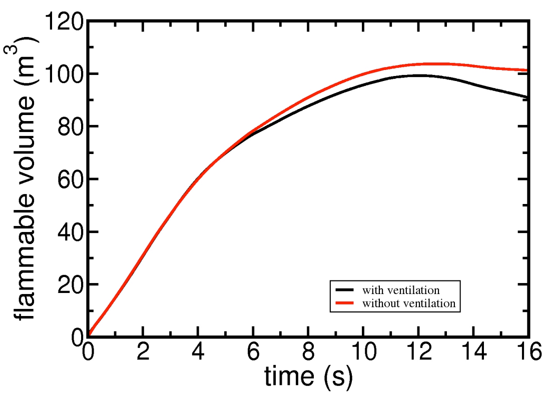


Figure 12. Simulation results showing time evolution of flammable volume of hydrogen (4% - 75% mole fraction) from forklift release of 0.8 kg H_2 in the full-scale warehouse for cases with and without forced ventilation.

Figures 13 and 14 show the flammable hydrogen clouds (4% - 75% mole fraction) for a 0.8 kg forklift release in warehouses of volumes 1000 m^3, 1500 m^3, and 2000 m^3 with a 7.62 m ceiling and without ventilation at 3 sec and 6 sec after the start of the release, respectively. Fig. 15 shows the predicted peak overpressure for ignition of these clouds at ignition delay times of 3 sec and 6 sec, corresponding to the times of the flammable volumes shown in Figs. 13 and 14. The results indicate that the peak deflagration overpressure decreases in an almost linear manner with increasing warehouse volume.

1000m^3 1500m^3 2000m^3

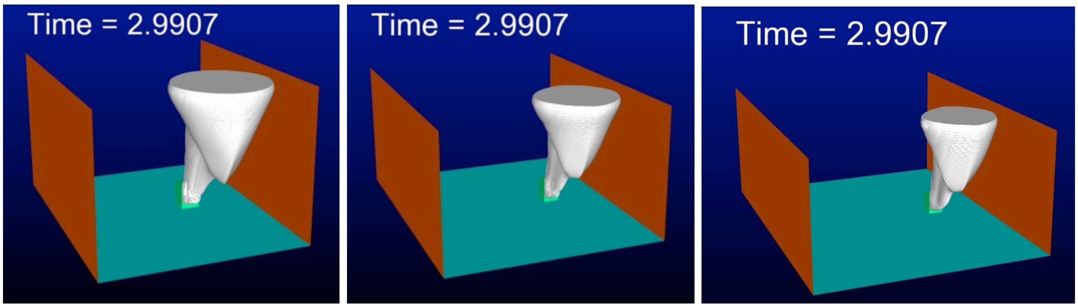


Figure 13. Simulations showing flammable hydrogen cloud (4% - 75% mole fraction) 3 sec into the 0.8 kg forklift release for full-scale warehouses with a 7.62 m high ceiling and volumes of 1000 m^3, 1500 m^3, and 2000 m^3 (without ventilation).

1000m^3 1500m^3 2000m^3

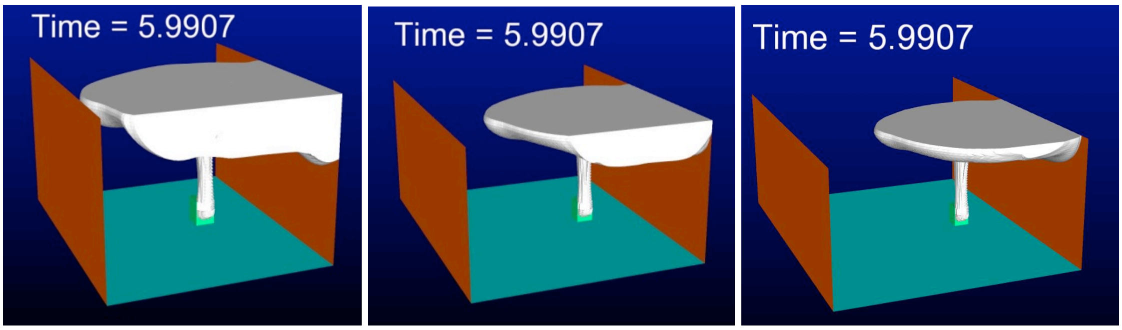


Figure 14. Simulations showing flammable hydrogen cloud (4% - 75% mole fraction) 6sec into the 0.8 kg forklift release for full-scale warehouses with a 7.62 m high ceiling and volumes of 1000 m^3, 1500 m^3, and 2000 m^3 (without ventilation).

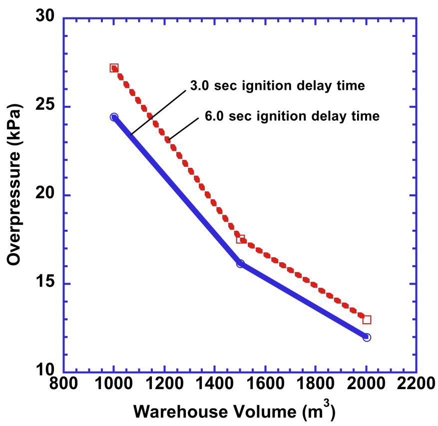


Figure 15. Simulations showing peak ignition overpressure in a well-sealed (100%) full-scale warehouse for a 0.8 kg forklift release where ignition occurs 3 cm above the top of the forklift and the ceiling height is 7.62 m. Results include heat transfer to the warehouse walls and show the effect of changing the ignition delay time and warehouse volume.

5.0 SUMMARY AND CONCLUSIONS

Simulation results of an unintended release from a hydrogen fuel-cell forklift vehicle in a full-scale warehouse have been performed for the case where the hydrogen gas is vented from the side of the forklift vehicle as a result of a medium sized leak or thermal activation of the pressure relief device (PRD). The same modeling approach used in the full-scale warehouse release was validated in a scaled model by comparing simulated results with measured results from a series of scaled-warehouse forklift release experiments performed at the SRI Corral Hollow Experiment Site. Results of the simulations were found to be in good agreement with the experimental data. The results of the modeling and experiments demonstrate that passive natural ventilation or pressure relief panels can be an effective means to mitigate deflagration overpressure arising from ignition of the hydrogen. Simulation results also indicated that increasing the warehouse volume beyond the requirements currently specified also reduces the overpressure. Both simulations and experiments show that forced ventilation has little effect on hydrogen concentration or deflagration overpressure in the early stages of the release.

6.0 ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program under the Safety, Codes, and Standards subprogram element managed by Antonio Ruiz.

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