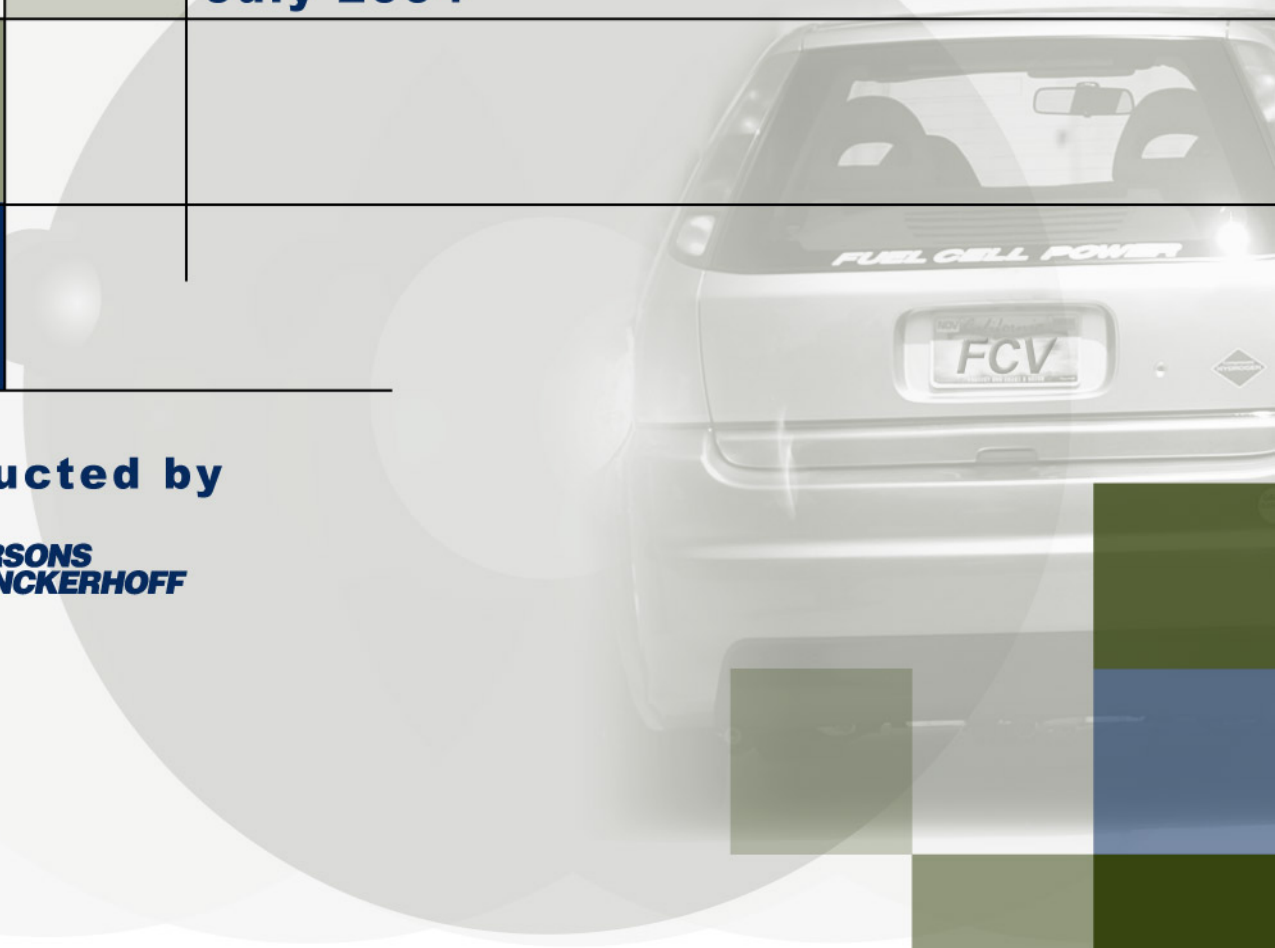
CaFCP COMMISSIONED

TECHNICAL REPORT

Support Facilities for Hydrogen-Fueled Vehicles

Conceptual Design and Cost Analysis Study

July 2004



Conducted by

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Support Facilities for Hydrogen-Fueled Vehicles
Conceptual Design and Cost Analysis Study

Technical Report

July 2004

Prepared for
California Fuel Cell Partnership
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In Association with

And

Important Information/Disclaimer

This report was prepared by an independent team of consultants led by Parsons Brinckerhoff, Inc. under contract to the California Fuel Cell Partnership. All Statements of fact, opinion, and assumptions contained in this report as well as all conclusions, results and recommendations reached herein are attributable to the consultant team and do not necessarily represent the opinions or views of the California Fuel Cell Partnership or any of its members.

None of the recommendations presented in this report are ready for implementation. The study summarized in this report is a preliminary investigation and provides only general information to facility designers. Because of study scope limitations on modeling, the study does not determine what modifications to buildings, if any, are necessary. Furthermore, the results and recommendations of this study are limited to the building facility designs, vehicle operations and suppositions, and the geographic region described in this study. Finally, since no commercial HFCVs exist today, and actual building configurations and use patterns may differ from those described in this report, none of the scenarios studied herein have been verified in any actual setting.

Ordering Information

Requests for copies of this report should be directed to the California Fuel Cell Partnership by

e-mail to info@cafcp.org or phone (916) 371-2870.

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1. Executive Summary

Project Overview

The California Fuel Cell Partnership (CaFCP) sponsored this study to better understand facility modifications and incremental costs that may be necessary to safely accommodate hydrogen fuel cell vehicles (HFCVs) parked in buildings. Earlier designs for buildings that accommodate gaseous fueled vehicles have included elaborate systems of hydrogen detection and mitigation such as hydrogen detectors, high ventilation rates, static-free floors and walls, explosion proof devices, special vehicle grounding, and other measures to deal with possible hydrogen leaks.

Such modifications have often been based on a general understanding of leaking hydrogen behavior and incorporated a wide range of high-cost modifications to mitigate a wide range of potential risks. This study provides a more focused analysis on the consequences of hydrogen leaks under specific conditions and in one geographic location in order to begin to relate potential hazards with building requirements. This report provides an excellent point of departure for future iterative evaluations as the HFCVs, hydrogen storage and building developments progress.

As there are limited established building codes or standards to guide designers and builders of HFCV facilities, this report provides a series of case studies, which examine selected issues related to accommodating HFCVs in buildings. The study results provide general information to facility designers in developing facility plans and identify some of the important leak scenarios that might be encountered with HFCVs. However, since no commercial HFCVs exist today, and actual building configurations and use patterns may differ from those described in this report, none of the scenarios studied have been verified in any actual setting. Therefore, the recommendations presented for each case study should not be misinterpreted to be ready for implementation without further analysis of site-specific conditions and full understanding of the vehicles' design, and review with local fire officials.

Case study facility designs were developed for four facilities:

- Commercial multi-story above-ground parking
- Commercial multi-story below-ground parking
- Residential, two-vehicle garages
- Commercial maintenance/repair/service station

For each case study, a baseline building design was developed incorporating functional requirements and applicable conventional building codes. Computational fluid dynamic (CFD) modeling was used to analyze a limited set of hydrogen leak scenarios inside the four types of facilities. Each of the facilities were treated as bare wall/ceiling facilities, i.e., finished, but with nothing in the facilities but the vehicle. The study also brought together government and industry expertise in the fields of fuel cells, fuel cell vehicles, hydrogen, safety, and facilities to provide input on developing scenarios for vehicle leaks. Preliminary results were also reviewed with local fire officials.

Vehicle Assumptions

The configuration of an HFCV affects the characteristics of possible leaks and governs the design choices for facilities. Since there are only experimental and pre-prototype HFCVs for today's consideration, it was not possible to identify commercial HFCV configurations for this study.

Therefore, the study was based on parking a 5-passenger "sedan" with a compressed hydrogen gas reservoir carrying capacity of 6kg. This hydrogen fuel cell vehicle (HFCV) is designed to comply with SAE J2578 and J2579 standards for hydrogen and fuel cells, which include provisions for safety systems onboard the vehicle. An assumption was made that the HFCV is equipped with safety mechanisms that are designed to detect and limit the amount of leaking hydrogen in certain prescribed conditions. Such assumed mechanisms include the implementation of a hydrogen detector in each wheel well. Each detector is designed to signal a procedure that will shut down hydrogen flow and isolate the vehicle tank upon detecting 1% hydrogen. Another assumed mechanism includes the use of an on-board computer that is capable of shutting down hydrogen flow upon receiving a signal detecting a larger than 20 cubic feet per minute (CFM) flow, 'leak', when the vehicle is dormant. In addition, this HFCV is assumed to be equipped with a valve that isolates hydrogen in the tank upon engine (fuel cell) shut down. The assumed isolation mechanism is designed to monitor and test for leaks upon vehicle shutdown and prior to startup by the on-board computer. These assumptions formed the basis for leak scenarios and played an important role in analysis of the potential impact on building configurations. Such assumptions were based on interpretation of SAE J2578 which requires leak detection and fail-safe shutoff but neither specifies the type of sensor nor the location.

Although there are several ways in which hydrogen could also be released directly from the vehicle fuel tank when the fuel cell engine is off, these release modes were considered too unlikely or to be of such small quantities to be included as a facility design basis. A pressure relief device (PRD) provides a fail-safe against over-pressuring the hydrogen tank. PRDs are intended to be very reliable; however if one releases, the contents of the tank are rapidly released. Experience suggests that if a PRD does release, the likely release mode is due to heating during fueling events, which do not occur in the four facilities in this study. This phenomenon is called "creep" and is currently being addressed by PRD-1 for natural gas applications from CSA (Canadian Standards Organization), who in addition is also developing a standard to address PRDs for Hydrogen specific applications. A fuel tank rupture was also not considered as a design constraint for the facilities because of robust construction of such tanks that have been witnessed today and the improbability of outside elements penetrating the tank wall while parked indoors.

Modeling Approach

The study used CFD analysis to model the movement of hydrogen leaking from a failing component on the "vehicle" chosen for this study. CFD estimates the shape and behavior of a hydrogen cloud or plume as time elapses, given facility dimensions, localized source of hydrogen, air movement speed and direction, and hydrogen properties.

Dr. Michael Swain of the University of Miami performed the CFD modeling for this study. The modeling is supported by many years of gaseous fuel dispersion analysis in vehicle applications. The modeling team has verified the performance of the model by measuring gas dispersion in test garages. Helium is used to simulate hydrogen in the test garage because it is non flammable and its properties are closest to hydrogen. Model predictions for helium have been compared with actual results to calibrate the model.

The modeling results are plotted as profiles of constant hydrogen concentration. The results identify the region in a hydrogen plume with 4.1% concentration, the lower flammability limit (LFL), and 1% hydrogen. The objective of the modeling was to evaluate the shape of a hydrogen plume under various ventilation conditions for each of the 'bare-wall' facilities. The modeling was also used to determine at what time the plume would reach a 1% concentration at vehicle wheel wells where sensors could detect the escaping hydrogen and signal the shut off of the hydrogen at the isolation valve. The configuration of the hydrogen plume was also evaluated at the ceiling when concentrations approaching 1% were predicted.

Most of the modeling scenarios were based on a 20-CFM leak from underneath the vehicle. The combination of a 20-CFM leak combined with properly functioning hydrogen detectors on the vehicle can correspond to a single mode failure of the selected vehicle's safety system that would be operative with the fuel cell engine on. Parametric evaluations of leak rates were also performed. Facility designs were based on these scenarios for protecting against a single mode failure.

Codes and Standards

The review of existing and potential codes and standards at the time of writing did not result in major hydrogen-related recommendations for the facilities. An analysis of codes covering ignitable gases, such as NFPA 497A-Section 2, NFPA 88A, NFPA 30, and Article 500 of NFPA 70, show that open parking structures, due to high air circulation rates are unlikely to contain combustible fuel mixtures. Underground garages require high air circulation rates to protect against the accumulation of carbon monoxide (CO).

Even after ventilation rates for CO removal are taken into account, ventilation requirements for maintenance garages that house gaseous fueled automobiles and buses are typically more stringent than those for residential garages. These public facilities are likely to house more vehicles and also present more opportunities for leaks caused by accidents during maintenance activities. A review of NFPA 52, Compressed Natural Gas Vehicular Fuel Systems Code, exempts residential garages from many requirements of facilities that house greater volumes of ignitable gas. It is not yet clear if hydrogen vehicles may also be excluded from the guidance.

There is little guidance currently written for hydrogen vehicles in maintenance facilities. The requirements for maintenance facilities currently address gaseous fuels but will likely need adapting to hydrogen in several areas. Specifically, NFPA 88B, the guidance for repair garages, references NFPA 52 in handling of fuels but no counterpart document exists for hydrogen.

As mentioned, in the previous section, vehicle related codes and standards are currently being developed/ updated for hydrogen specific applications. Established standards such as PRD-1 and NGV-2 have been developed by CSA and CGA (and adopted in the US and Canada) to address concerns with safety of natural gas PRDs and natural gas vehicles with compressed storage cylinders onboard, respectively. PRD-1 was developed specifically as a response to address the concerns with the reliability and uniform component testing. After the standard was released, it proved to be very effective by eliminating the release mode found in PRDs prior to the development to this standard. A new standard called HGV-2 (Hydrogen Gas Vehicle) is being created by CSA for hydrogen specific storage cylinders. Both of these aforementioned standards are presently being updated (as of this publish date) to specifically address hydrogen properties also at higher pressures than NGV (which is currently at 5000 Psi) storage containers- up to 10,000 Psi working pressure.

Facility Case Studies and Recommendations

The study prepared conceptual design layouts of the four facility types. The layouts identified architectural, structural, mechanical, and electrical systems that typically are included in conventional facilities designed to accommodate today's gasoline and diesel vehicles.

Practical parameters were selected for usage of facilities and surroundings (including elevators and other equipment). The project assumed no fueling or de-fueling activities in the facilities. Climate parameters were set to Sacramento Area plus/minus a few degrees at both ends of temperature

and humidity range. It should be noted that the buildings are assumed to be compliant with present building codes. There are many "legal" structures in the US that were built many years ago and "grandfathered" (that is, not updated to current standards). Such latitude for new building and "grandfathering" for existing buildings could result in situations that were not considered in these case studies.

Multi-Story Public Parking Facilities

The configurations of the below- and above ground parking facilities, model scenarios, and recommended facility modifications are summarized in Tables S-1 and S-2. No modifications to the baseline structures were recommended. Existing ventilation in the below ground structure would dilute a 20-CFM hydrogen leak so that a flammable mixture would only exist in close proximity to the vehicle. Similarly, natural ventilation would dilute hydrogen leaks for the above ground parking facility.

Vehicle safety systems can also serve to reduce hazards associated with a hydrogen leak. In situations with low air circulation, the hydrogen cloud could be expected to diffuse into the vehicle's wheel wells, and if sensors are located there, could initiate the system to shut off the hydrogen supply. Other control strategies could also limit the amount of hydrogen that leaks from the vehicle (see discussion of residential garage). Depending on the location and characteristics of the leak and wind conditions, hydrogen might not reach sensors in wheel wells. Walls would also affect the characteristics and direction of the leak plume, possibly containing the leak closer to the vehicle (and hydrogen sensors).

Table S-1. Design Parameters and Modifications for Below Ground Parking Facility

Below Ground Parking Facility	
Design Basis 3 stories, helix ramp, single elevator core Heating and ventilation ducts Mechanical and electrical rooms 95 vehicles per level ADA parking spaces	Key Code Requirements Two Stairs CBC, UBC Ventilation 1.5 CFM/ft^2 Sensor activated ventilation by CO level above 25 ppm is permitted Maintain positive ventilation in spaces adjacent to garage
Hydrogen Leak Modeling Scenario HFCV parked close to ventilation inlet 20 CFM hydrogen leak 1.5 ft/s air flow on left side of vehicle Modeling Results Hydrogen cloud at 4.1 %, 2 ft to right of vehicle Hydrogen cloud at 1% , 5 ft to right of vehicle Hydrogen cloud reached steady state after 50 sec 1% vertical plume does not reach inlet to ventilation	Facility Modifications None required if continuous ventilation is maintained.

ADA = Americans with Disabilities Act, CBC = California Building Code, UBC = Uniform Building Code
Suggested modifications are based on the study's assessment of code requirements, model results, and consultation with the Sacramento Fire Marshall.

Table S-2. Design Parameters and Modifications for Above Ground Parking Facility

Above Ground Parking Facility	
Design Basis 3 stories, sloped floor ramp, single elevator core Heating and ventilation ducts	Key Code Requirements Two Stairs CBC, UBC Walls with uniformly distributed openings on

Mechanical and electrical rooms Retail and office space at ground level 85 vehicles per level ADA parking spaces	two or more walls making up 20% of the total perimeter, UBC No mechanical ventilation required
Hydrogen Leak Modeling Scenarios HFCV parked in garage Three wind speeds: 1, 1.5, 2 mph on left side of vehicle Modeling Results For 1 mph wind, hydrogen cloud >1% remained under car. Leak would reach detectors in 10 sec. For 1.5 mph cloud and greater, cloud was pushed beyond vehicle (about 2 ft). Hydrogen cloud reached steady state after 50 sec. If vehicle power were not shut off, vehicle containing 6 kg of hydrogen would leak for 2 hours.	Facility Modifications None required

ADA = Americans with Disabilities Act, CBC = California Building Code, UBC = Uniform Building Code
1 mph = 1.47 ft/s. Suggested modifications are based on the study assessment of code requirements, model results, and consultation with the Sacramento Fire Marshall.

The configuration of the residential garage, model scenarios and potential facility modifications are summarized in Tables S-3. No modifications to the baseline structures would appear to be necessary for vehicles equipped with safety systems that detect hydrogen leaks according to the chosen scenarios. CFD modeling of one configuration showed that a 1% hydrogen concentration would reach the wheel well within 28 seconds where detectors could initiate a shut off of the fuel supply. Since not all vehicles will be equipped with hydrogen detectors, or be configured like the chosen vehicle design, additional modeling provided data on the time for a 5% hydrogen concentration to accumulate at the garage ceiling. This information may be used by carmakers to develop strategies to limit the amount of time that the vehicle operates at zero speed before shutting off the fuel supply

Table S-3. Design Parameters and Modifications for Residential Garage

Residential Garage	
Design Basis Two story, single family dwelling, wood frame Two car garage below bedroom, 400 ft^2 Electric garage door opener **Garage walls covered with drywall**	Key Code Requirements Continuous ventilation required for battery powered electric vehicles that vent hydrogen during charging, CBC Classified area (no ignition sources) 18 inches above floor (NFPA 30)
Hydrogen Leak Modeling Scenarios HFCV parked in closed garage Two undercarriage configurations 5, 15, 20 CFM hydrogen leaks Modeling Results For 20-CFM leak, 1-% plume reaches wheel wells in 7 sec. 1-% plume also spreads across garage ceiling. 4.1% concentration is 2 ft above vehicle. Three continuous leak rates were modeled to determine time to reach 5% hydrogen at ceiling. 5 CFM – 1740 sec 15 CFM – 725 sec 20 CFM – 545 sec	Facility Modifications None Recommended for vehicles equipped with detectors that detect hydrogen leaks.

ADA = Americans with Disabilities Act
CBC = California Building Code
UBC = Uniform Building Code
Suggested modifications are based on the study assessment of code requirements, model results, and consultation with the Sacramento Fire Marshall.

The configuration of the maintenance facility, model scenarios and suggested facility modifications are summarized in Tables S-4. No modifications to the baseline structures were recommended. The high rates of ventilation would dilute the assumed 20-CFM leak and result in a flammable mixture only in close proximity to the vehicle. The potential for flammable mixtures forming at the ceiling of the facility was also assessed. The time required for a hydrogen leak to result in 20% of the LFL at the ceiling was determined for different vehicle leak rates. Options for improving the ventilation in the building are presented in the report.

Table S-4. Design Parameters and Modifications for Maintenance and Service Facilities

Maintenance and Service Facility	
Design Basis New dealership maintenance facility 10 maintenance bays 3 of the bays intended for hydrogen and gasoline vehicle maintenance 240VAC battery chargers, DI water supply	Key Code Requirements Ventilation 1.5 CFM/ft^2 Maintain positive ventilation in spaces adjacent to garage, NFPA 30 Separation of maintenance area from office space
Hydrogen Leak Modeling Scenarios HFCV with continuous 20 CFM leak -Hydrogen cloud around vehicle HFCV with continuous 24 and 36 CFM leak -Hydrogen plume at ceiling, time to reach 0.82% at 18 inches below ceiling Modeling Results 20 CFM leak results in hydrogen cloud (4.1%), which remained under vehicle or within 2 ft of vehicle. 36 CFM leak results in 0.82% plume at 18 inches from the ceiling after 200 to 500 sec, depending on location of vehicle. Over 6000 sec elapsed before the 24 CFM leak resulted in a 0.82% plume at 18 inches from the ceiling.	Facility Modifications None require Consider reconfiguring the ventilation system to optimize dilution of a hydrogen leak

ADA = Americans with Disabilities Act, CBC = California Building Code, UBC = Uniform Building Code
Suggested modifications are based on the study assessment of code requirements, model results, and consultation with the Sacramento Fire Marshall.

Study Limitations

The results and recommendations of this study are limited to the building facility designs, vehicle operations suppositions, and the geographic region described in this study. The analysis is affected by building layout, which would vary with climate conditions, and the architectural layout of facilities.

The arrangement of ventilation systems, hydrogen leak rate, and building geometry would also affect the CFD modeling results and possibly the study results. The results are also limited to the hydrogen fuel cell vehicle leak scenarios and the vehicle equipment assumed for hydrogen leak

control described in this report. The study also incorporated the most recent information on codes and standards for hydrogen, which are also under development.

Until validation and demonstrations of the results reported here are verified, no recommendations or final conclusions can be inferred regarding either the vehicle or parking structure designs.

Conclusions

CFD modeling results of the controlled conditions described revealed that in all four vehicle parking cases the hydrogen cloud at the LFL concentration did not extend beyond two feet immediately surrounding the vehicle.

In the cases of the parking and maintenance facilities, the confinement of the gas cloud was attributed to typical airflow rates at ground level due to natural or mechanical ventilation. This airflow resulted in diluting the leaking hydrogen cloud to less than flammable concentration levels. In situations with low ventilation rates, the CFD model results showed the cloud spreading to the wheel wells where it could be detected if the vehicle were equipped with appropriately functional hydrogen sensors, and leak control could be maintained with the accommodating equipment.

The authors concluded that no facility modifications were required to accommodate HFCVs for the vehicle configuration identified in this study. These results depend on vehicle safety systems limiting the leak rate to 20 CFM when the fuel cell engine is on and hydrogen sensors that are capable of dependably detecting 1% levels of hydrogen near the leak source are included. Hydrogen sensors identified for the vehicle could detect leaks in situations with low ventilation. It is premature to suggest other strategies to limit the potential hazard when vehicles are parked, but this report does provide information that will be useful in exploring other options.

2. Background

2.1 Objective of the Study

In its continuing efforts to advance hydrogen fuel cell vehicle market penetration, the California Fuel Cell Partnership (CaFCP) initiated this project, "Support Facilities for Hydrogen-Fueled Vehicles", to conceptualize viable options for cost-effective generic facility design to safely house hydrogen fuel cell vehicles (HFCVs) in four types of facilities: 1) Commercial maintenance/repair/service station, 2) Commercial multi-story above-ground parking, 3) Commercial multi-story below-ground parking and 4) Residential, two-vehicle garage.

This report evaluates conventional facilities and identifies recommended modifications based on an assumed hydrogen fuel cell vehicle with specified safety equipment, and a hydrogen leak scenario. The facility modifications are identified at the conceptual design level which includes a basic floor plan and assessment of code, mechanical, and electrical requirements.

The CaFCP selected Parsons Brinckerhoff (PB) to conduct the study. Assisted by hydrogen experts from the University of Miami and Tiax, LLC, PB formed the study team. The CaFCP provided guidance and oversight of the study. The study team coordinated its efforts, and received valuable advice from the State of California Fire Marshal, the City of West Sacramento Fire Officials, Society of Automotive Engineering (SAE), hydrogen fuel cell vehicles manufacturers, energy and hydrogen suppliers, and the United States Department of Energy (DOE).

Use of This Report

Case studies that analyzed the potential leaks from hydrogen fuel cell vehicles when parked in buildings were developed. The case studies included four facility types and the process involved several steps taken to identify potential facility modifications that would enable these facilities to accommodate hydrogen fuel cell vehicles.

The results are unique to the assumptions and circumstances of the case studies. Assumptions were based on inputs from the CaFCP and they are applicable only to these case studies; however, the analysis process and modeling results may be helpful in the analysis and design of other facilities. The recommendations for facility modifications apply only to the vehicle and facility combinations discussed in this report. Readers could use the knowledge gained from these case studies to understand potential hydrogen behavior inside facilities. Readers could also use this report as an example of process and results that helped designers determine effective modifications to the facilities to accommodate hydrogen fuel cell vehicles. Because the case studies, process, and results are unique and use specific assumptions and circumstances, minor or major modifications to such assumptions would most likely alter the process and results. For example, alternate facility or vehicle designs, leaking rates, locations of parked vehicles (even within a foot or two), or probabilities of component failures may significantly alter the process and results of these case studies. Therefore, readers of this report are encouraged to examine the process and results as applied to these case studies only and may interpolate the knowledge gained to guide them in developing their own case studies or facilities modification designs.

This report describes conventional designs for facilities to potentially be utilized to house HFCVs. Designers of specific facilities may use the information in this report as information to help create conceptual designs for future facilities or to modify facilities and to discuss future codes and standard requirements that may help facilitate the commercialization of HFCVs. However, until validation and demonstrations of the results reported here are verified, no recommendations or final conclusions can be

inferred regarding either the vehicle or parking structure designs. This report does, however, provide a useful launching point for future iterative evaluations as the HFCVs, hydrogen storage and building developments progress.

The report provides design layouts of the four facilities and presents detailed analysis of hydrogen leaks, based on a specific leaking scenario, inside each facility using the computational fluid dynamic (CFD) analysis method. The report also identifies various existing and planned hydrogen codes and standards for facilities and vehicles, known at the time of writing.

2.3 Study Parameters and Assumptions

2.3.1 Hydrogen Fuel Properties and Usage in Fuel Cell Vehicles

The fuel selected for this study conforms to the properties of fuel in the majority of existing and planned hydrogen fuel cell vehicles, i.e. compressed hydrogen gas with 99.95% or higher hydrogen content. The other 0.05% could be a combination of other compounds such as nitrogen, carbon monoxide, carbon dioxide, argon, and oxygen. Fuel pressure could be as high as 10,000 pounds-per-square-inch (psi).

The study used the following published information regarding hydrogen properties:

> Hydrogen is the element with the lowest molecular weight which also makes it lighter than other gases. Hydrogen/air mixtures are flammable at concentrations ranging from 4.1 to 74 percent hydrogen, at least from the standpoint that inadequate information exists but that it has been shown to have significant impact on the properties of other flammable gases. This flammability range is achieved under controlled laboratory circumstances. In real world situations, hydrogen often does not ignite at concentrations of 4.1 percent in air. The variability in flammability limit may be due to atmospheric conditions, humidity, and other factors. It is detonable at concentration from 18.2 to 58.9 percent air by volume. Hydrogen can be ignited by a small amount of energy (0.017 mJ at 1 atm) and can auto-ignite upon contact with temperatures of 932 degrees Fahrenheit (500 degrees Celsius). Hydrogen is also capable of catalytic ignition at much lower temperatures. Hydrogen is non-toxic and non-corrosive but can cause material embrittlement if exposed for an extended period of time. Other hydrogen properties include flame temperature of 4000 degrees Fahrenheit and a boiling temperature of negative 422 degrees Fahrenheit.[1]

2.3.2 Hydrogen Fuel Cell Vehicles

Several vehicle manufacturers identified HFCV parameters that could be used as assumptions for this study. The parameters are intended to represent a fair picture of the current "State of the Art" compressed HFCV. However it should be noted that these designs will evolve as HFCV move to commercialization.

The generic HFCV considered during the study is a 5-passenger sedan type vehicle with a compressed hydrogen carrying capacity of 6 kg at 10,000 psi pressure. As shown in the general schematic (figure 2.1), the Hydrogen Containing System consists of six components: (1) Fuel Tank, (2) Pressure Relief

[1] USDOT – Office of research, Demonstration, and Innovation - Clean Air Program – Design Guidelines for Bus Transit Systems Using Hydrogen as an Alternative Fuel

Device (PRD), (3) Isolation, or Shut-off, Valve (IV), (4) Pressure Regulator, (5) Fuel Cell System (FCS), and (6) connecting pipes and fittings - Figure 2.1.

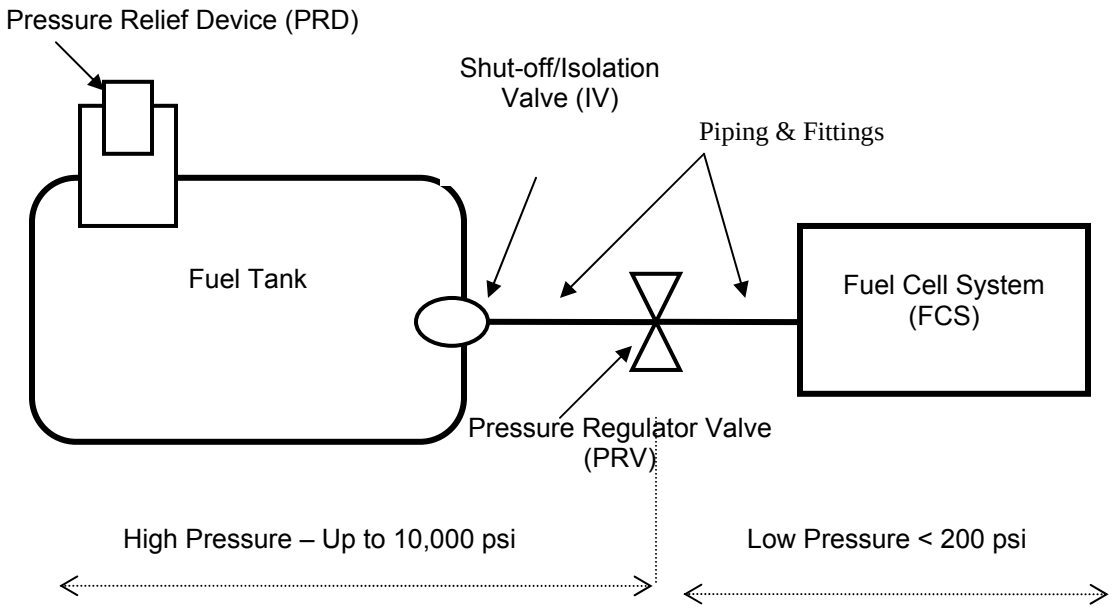


Figure 2.1 – Block Diagram of HFCV Hydrogen Containing System (HCS)

A pressurized HFCV fuel tank may be made of aluminum with fiber wrapping. Fuel tanks typically are designed and tested. The hydrogen storage tank includes one fill point, and one pressure relief point. These points are considered the only ways that hydrogen may leak out of the fuel tank. The pressure relief point includes a pressure relief device (PRD) that is designed to relieve excess tank pressure.

The fittings subsystem is made of connecting hoses, fittings, lines, coupling, and manifolds that distribute the hydrogen among the fuel tank, isolation valve (IV), and fuel cells system (FCS). While the fittings connecting the pressure regulator and FCS typically contain low-pressure hydrogen (<200 psi), the fittings between the fuel tank and the pressure regulator usually contain hydrogen at high pressure (~10,000 psi).

The design and construction of HFCV systems should comply with the intent of Society of Automotive Engineering (SAE) J2578 and J2579 standards, among others, which guide the development of safety systems on-board hydrogen fuel cell vehicles. Such standards, or guidelines, include technical evaluations on methods to reduce the possibilities and/or rate of leaking hydrogen to the atmosphere.

At the present time vehicle manufacturers have safety mechanisms to reduce the possibilities and/or rate of leaking hydrogen. For example, on compressed HFCVs such mechanisms may include a hydrogen gas sensor located in each of the 4 wheel wells. Each sensor is set to detect 1% hydrogen concentration by volume when they are operating. When operating, any sensor that detects 1% hydrogen can send a signal to the fuel cell system that causes isolation of hydrogen flow through the activation of the isolation valve (IV) and the release of the remaining small amount of hydrogen into the atmosphere. Other safety systems may include the utilization of on-board computer detection of a large differential between the amounts of hydrogen leaving the hydrogen tank compared to that being required to operate the fuel cell system. Upon such detection, the on-board computer isolates the hydrogen in the tank through the IV. The integrity of the shut-off/isolation valve and the entire hydrogen system can be checked for leakage by the on-board computer during regular shutdown/startup procedures every time the vehicle is turned off

and on. Proper operation of this on-board hydrogen safety system requires the vehicle to be operating in the on position, "vehicle on". For the purposes of this study it was determined that the type of system identified above would be utilized as one of the assumptions regarding the proposed design of the study vehicle. Because hydrogen fuel cell vehicle operation in true commercial settings has been minimal, long-term operations and safety performance could not be established and verified. Therefore, this study used the available unconfirmed safety and performance records as reported by vehicle manufacturers, operators, and developers.

2.3.3 Facilities Design

The facilities designs used in the study are based on common engineering and construction practices for typical conventional gasoline vehicle facilities. The designs were based on the following general parameters:

Geographic location of the facilities is in the region from Sacramento to San Diego. This region includes most of the areas likely to see short-term commercial deployment of HFCVs, and because it covers a range of geographic conditions ranging from desert environments with hot climate and low humidity to regions which receive heavy snow in the winter.

The climate of the facilities is similar to Sacramento Area plus/minus few degrees at both ends of the temperature and humidity range (25° F – 100° F, 30% - 100%). The selected climate parameters represent most of the region without any specific extremes such as dry deserts (less than 30% humidity and more than 100° F simultaneously).

Practicality, functionality, and reality were the determining factors in selecting any/all of the criteria/parameters set forth for all of the facilities. Practical parameters included items such as surrounding environment, auxiliary equipment inside the facilities, and usage of the facility. For example, a parking garage in a dense urban area would likely not be a street level single story facility, but rather, a multi story (below and/or above ground level), and would include retail and/or office space above or adjacent to it. Another general consideration is the fact that all parking facilities must include a specific number of parking spaces designated for people with disabilities. In a multi-level environment, at least one elevator would normally exist in such a facility.

The study assumed that no fueling or de-fueling activities would take place in any of the facilities.

In addition to the general parameters, specific facility design criteria included the following:

Commercial maintenance/repair/service station:

This study includes a maintenance facility in a state-of-the-art automobile dealership in an urban location. The facility has approximately ten bays, three of which could be used for HFCVs, but which also are able to accommodate conventional vehicles. In addition to the ten maintenance bays, the facility contains offices and other amenities. The maintenance bays require heating but not cooling.

Parking Facilities

The parking facilities studied include a three-level above-ground design in an office park environment, and a three-level below ground facility in an urban area. Each parking level contains approximately eighty-five (85) parking spaces, including spaces for disabled persons. The below ground concept

assumes another facility (office or retail space) at street level. The above ground facilities take into consideration typical setbacks with adjacent structures.

Two car residential garage

The study considered a typical attached, below living space, residential two-car garage in a single-family dwelling.

2.4 Hydrogen Leak Modeling

The study used the computational fluid dynamic (CFD) analysis method in modelling leaking hydrogen. Given facility parameters such as size and air movement speed and direction inside each facility, along with hydrogen properties, CFD approximates the shape and behavior of the hydrogen dispersion as time elapses by applying and solving a set of complex differential and algebraic equations. To visualize the shape of the cloud, the CFD calculation results are plotted in two dimensions.

Throughout the report we assume steady state leak rates for our modelling efforts (e.g. 20 CFM) over a period of time from a vehicle with 6 kg of compressed hydrogen storage. This leak rate corresponds to a fuel cell power output of about 50 kW. Therefore, the modelled leak rate could reflect the performance of any number of hydrogen storage options including 5000 and 10,000 psi storage.

Conducting the hydrogen leak modeling required establishing hydrogen leak scenarios that would fairly represent a probable rate of hydrogen leakage in each facility type.

The selected scenario is based on the following assumed HFCV parameters:

- Hydrogen leaks from HFCV components because of component failure (flammable discharges of hydrogen are not normally released to the atmosphere).

  Single-mode failure (one component failing at a time) is more likely to occur than multi-mode failures. Our initial scenarios were single mode failures with corresponding onboard vehicle corrective action in several cases. Analysis of these failures resulted in no modifications required for a facility. However, the study team recognized that future vehicles might not be configured with similar safety systems.

- It is unlikely that the structural integrity of the hydrogen fuel tank would fail.

- It is unlikely that the pressure relief device (PRD) would release because there is no fueling/de-fueling of vehicles taking place and all PRDs on current FCV comply with the PRD-1 standard.

- HFCV design and construction comply with the intent of SAE J2578 and J2579 standards.

The sequential steps in selecting the leaking scenarios and rates included:

1. Confirm that the hydrogen fuel cell vehicles (HFCV) are the only source that could leak hydrogen in the facilities. HFCV design and construction typically do not permit hydrogen to leak unless there is a component failure. Some vehicle design and construction onboard the current

developmental units on the road allow venting of hydrogen during vehicle shutdown only after diluting the hydrogen to a less than 25% concentration of the low flammability limit (LFL) of 4.1%.

2. Identify the maximum amount of hydrogen on any single vehicle as 6 Kilograms (Kg) pressurized at 10,000 pounds per square inch (psi).

3. Identify the hydrogen containing elements of any vehicle as illustrated in Figure 2.1. Although no detailed design parameters were available, all vehicle manufacturers participating at the CAFCP confirmed that the block diagram is a reasonable representation of a vehicle hydrogen system design and construction.

4. Examination of each component of the hydrogen containing system onboard the vehicle revealed the following:

    a. The low-pressure side components starting from the Pressure Regulator through the fuel cell system contain sufficient pressure to cause a significant hydrogen leak in the event of a failure of a component in that section. Therefore, the low-pressure side components (fuel cell system and piping and fittings) were considered a possible hydrogen leak source for the purpose of this study.

    b. The hydrogen fuel tank was eliminated as a possible source of leakage because of the robust construction of such tanks, and the additional protection surrounding the tank in the current developmental HFCVs. Any leak from the tank could occur only upon rupturing due to outside elements penetrating and weakening the tank walls or because of abnormally high pressure inside the tank.

        Outside elements penetrating the tank walls, while possible during operation of the vehicle on the road, is unlikely to occur while parked in any of the facility types in the study. The possibility of tank penetration occurring while driving the vehicle prior to parking it was considered unlikely because it was assumed that the HFCV design would include additional protection enclosures surrounding the tank that minimizes the chances of outside elements penetrating the tank. Such design and practices currently exceed existing practices of protecting fuel tanks in gasoline vehicles.

    The robust construction of the fuel tank was further confirmed based on the results of various destructive tests under severe circumstances, such as a 52 mile-per-hour vehicle collision. The study also recognized the fact that, while HFCVs have not been in service sufficiently long to establish statistical records, there have been no reported incidents of hydrogen fuel tanks rupturing under normal circumstances when no external elements were involved.

    Additional factors that were considered in eliminating tank rupture as a likely scenario included historical performance data for other compressed gaseous or cryogenic fuels such as natural gas, liquefied petroleum gas, and butane. Historical data indicate that tank rupturing probabilities are extremely low. (However, few tanks have been constructed for onboard storage of hydrogen at 690 bar [10,000 psi] and operated on public roads for several years.)

    c. The study excluded PRD release as unlikely.

PRD release is defined as a sudden release from the device under normal circumstances, which would result in releasing hydrogen from the tank at a high rate.

The study concluded that PRD release is unlikely because PRDs have not typically released when no fueling/de-fueling is taking place. The heating of the PRD during fueling/de-fueling is considered a good test of PRD integrity and is the single most common reason for PRD release. The probability of PRD release during fueling/de-fueling, although low, is much greater than when vehicles are simply parked. Since this study does not address fueling/de-fueling operations, the probability of PRD release was excluded.

The theory of hydrogen PRD releasing because of excessive heating was also referenced in a survey of PRD releases in CNG buses. Although the survey listed CNG PRD releases of various manufacturers/types without conclusively identifying the cause of such releases, the survey alluded to high temperature as a possible cause of such releases through eutectic alloy melting, creeping, or plastic deformation of the PRD. The survey predicted that a hydrogen PRD would also likely release because of high temperature cycling. This is due to the fact that most "PRDs" are eutectic type devices which are in effect "fusible plug" which are meant to release at a rated high temperatures. The survey concluded that more detailed analysis studies of the mechanical/material of PRD is needed to conclusively determine the causes of PRD releases.[2]

The study also considered that there have been no reported incidents of hydrogen PRD releases on parked vehicles during the limited operation and development experience of HFCV.

The study noted that there were three PRD releases reported during the Chicago Transit Authority's (CTA) Fuel Cell Bus Demonstration Project in the late 1990's. While the CTA PRD releases occurred during operations (not fueling or parking), the released PRDs were of different design from today's PRDs, and are no longer used. In addition, the CTA buses design and construction were different from today's vehicles. The study assumed that vehicle design is based on lessons learned from CTA's demonstration project. The releases in this study occurred prior to the 1998 release of PRD-1, where there was a design flaw found in one of the manufacturers of these devices. This particular design has since been recalled and removed from the market.

d. The Pressure Regulator was considered a component that could cause a hydrogen leak.

e. Piping and fittings were considered components that could cause a hydrogen leak.

[2] Pressure Relief Device Failure Analysis - William P. Chernicoff - Volpe National Transportation Systems Center - Research and Special Programs Administration - U.S. Department of Transportation - Cambridge, Massachusetts.

2.5 Hydrogen Facilities Codes and Standards

The study identified and analyzed most of the existing and planned hydrogen codes and standards intended for facilities. Although the identified codes/standards were considered in the recommendation for potential facility modifications, because national and international development of hydrogen codes and standards for facilities has been very limited, such standards did not have a major impact in study recommendations. The codes/standards include:

- NFPA 30A – Code for Motor Fuel Dispensing Facilities and Repair Garages
- NFPA 50A – Standard for Gaseous Hydrogen Systems at Consumer Sites
- NFPA 50B – Standard for Liquefied Hydrogen Systems at Consumer Sites
- NFPA 52 – Compressed Natural Gas Vehicular Fuel Systems Code
- NFPA 57 – Liquefied Natural Gas vehicular Fuel Systems Code
- NFPA 88A – Standard for Parking Garages
- NFPA 88B – Standard for Repair Garages
- USDOT/FTA Compressed Natural Gas Safety in Transit Operations
- USDOT/FTA Dispersion of CNG Following a High-Pressure Release
- USDOT/FTA Design Guidelines for Bus Transit Systems Using Compressed Natural Gas as an Alternative Fuel
- USDOT/FTA Design Guidelines for Bus Transit Systems Using Liquefied Natural Gas as an Alternative Fuel
- USDOT/FTA Liquefied Natural Gas Safety in Transit Operations
- USDOT/FTA Use of Hydrogen to Power the Advanced Technology Transit Bus (ATTB): An Assessment
- USDOT/FTA Cylinder Issues Associated with Alternative Fuels
- United States and California department of Labor Occupational Health and Safety Administration (OSHA) Standards
- California Code of Regulations

2.6 Limitations of the Study

Due to the scope of this study being a preliminary investigation to highlight some of the areas in building facilities where additional considerations may need to be focused, several limitations were placed on the study.

Such limitations might include climate, practical knowledge of hydrogen release characteristics, and reliability of safety of all operating systems, such as elevators and electronics particularly in residences, and the myriad ignition sources possible. Some of the limitations that have impacted the study include the status of hydrogen fuel cell vehicle technology development and the associated limited data of operation and performance in true commercial settings.

Because hydrogen fuel cell vehicle technology is in the development stage at this writing, study assumptions regarding vehicle safety systems are based on existing information on developmental vehicles. In addition, the lack of HFCV operations in true commercial settings resulted in the use of reliability and durability data of vehicle safety systems used in developmental vehicles.

Facilities parameter limitations reflect the basic four facility types within a specified geographic area without vehicle fuelling and de-fuelling operations. In addition, the study's scope did not include additional CFD modeling to verify the effectiveness of potential facility modifications and dealt exclusively with empty facilities, i.e., facilities that did not contain other vehicles (such as in parking structures or maintenance facilities) or other equipment (such as in maintenance facilities or home garages).

Furthermore, the onboard vehicle hydrogen storage was taken to be a high pressure system (10,000 psi) to illustrate the results from hydrogen leaks under conditions where larger volumes of hydrogen could be released in a shorter time period. No other storage methods were considered. No ignition sources were assumed to be present within the close proximity of the vehicle, including hot brake rotors which may serve as a catalytic surface because NFPA does not consider the vehicle (conventional and/or CNG ones) or any of its subsystems to be an ignition source. This condition may not be applicable to hydrogen.

3. Multi-Story Public Parking Facilities

The study examined two public parking facility types; underground and above-ground. Above ground facilities are typically built in areas where property values or space constraints favor a higher vehicle parking density than surface parking. Above ground parking structures are typically dedicated to parking. Below ground parking structures are typically integrated into structures where land values are very high. A building is almost always built on top of a below ground parking facility.

3.1 Underground

3.1.1 Design

The design basis for the underground parking facility is a three-story structure capable of accommodating approximately 95 vehicles on each level, including American with Disabilities Act (ADA) parking spaces. Its design represents typical conditions found in underground parking structures. The facility included two staircases, one elevator shaft, heating and ventilation ducts, and mechanical and electrical rooms – Figure 3.1.

The facility design includes a cast-in-place concrete foundation and structural frame. The floor-plates could be pre-cast or cast-in-place concrete. The parking floors are level and vehicles travel between floors via a single helix ramp located at one end of the structure. In order to balance efficiency of cost with ease of use, vehicular circulation is limited to one loop (with parking around the perimeter and in the center), but the loop is wide enough to allow two-way circulation.

Pedestrians move between floors either by elevator or stair. A single elevator core, containing six elevators, is located in the center of the floor-plate to provide equal access to the entire floor without the added cost of multiple cores. Two stairs are provided and separated per California Building Code (CBC) and Universal Building Code (UBC) requirements. The modeled facility provides parking spaces for patrons with disabilities according to guidelines defined by the Americans with Disabilities Act (ADA) at each level directly adjacent to the central elevator core.

The garage was designed with mechanical ventilation in accordance with Universal Building Code (UBC) and International Mechanical Code (IMC) requirements. Such requirements include the capability to provide a maximum ventilation rate of 1.5 CFM/SF. An optional configuration, not considered in this study, allows for intermittent ventilation if the facility is equipped with sensor activated ventilation that maintains a maximum CO concentration of 25 parts-per-million (ppm). Adjacent spaces must be maintained with positive pressure relative to the garage for this configuration.

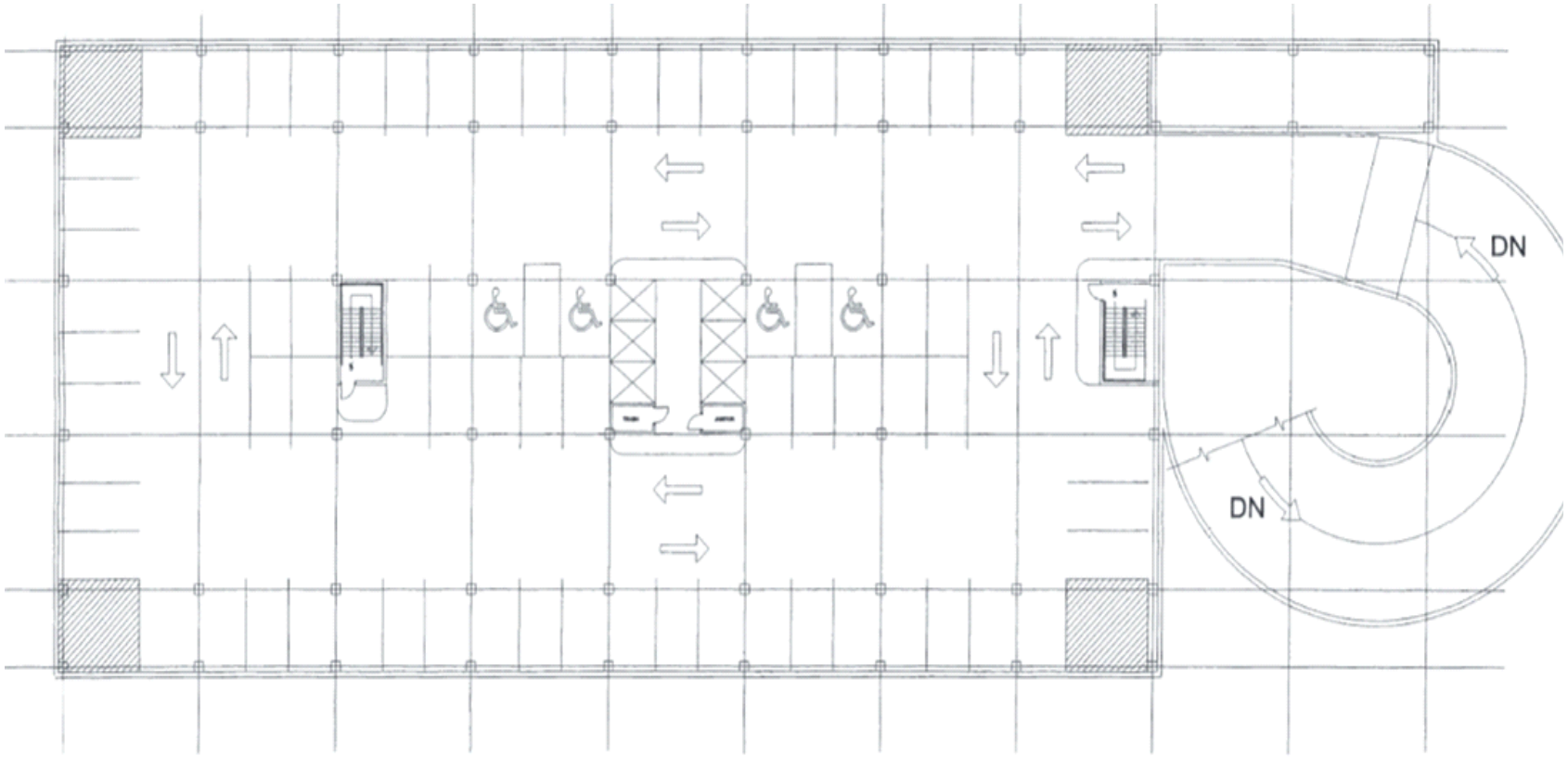


Figure 3.1 Layout of Underground Parking Facility

3.1.2 Hydrogen Leak Modeling

The study team modeled hydrogen leaking from the undercarriage of an operational "on" HFCV. The HFCV is equipped with an on-board detection system, and the hydrogen-leaking rate is 20 CFM. This modeling series simulated the scenario of a continuous 20 CFM hydrogen leak from a "vehicle on", with on-board safety system that shut off the hydrogen leak when a 1% concentration reaches the wheel well. Vehicle/facility configurations, shown in Table 3.1, were modeled.

Table 3.1 CFD Model Scenarios for Underground Parking Facilities

Model #	Location	Vehicle Configuration	Air Flow Speed	On-board Safety System	Leaking Rate
UG1	Main Floor	Wheel wells and lip	1.5 ft/sec	Yes	20 CFM
UG2	Near ventilation exhaust outlets	Wheel wells and lip	2 – 4 ft/sec	Yes	20 CFM

Prior to conducting hydrogen leak modeling, the study team modeled the airflow resulting from the facility's ventilation system at one foot above the floor in an empty structure. The facility ventilation system meets code requirements and standards for human comfort. The results of modeling the airflow at one foot above floor are illustrated in Figure 3.2.

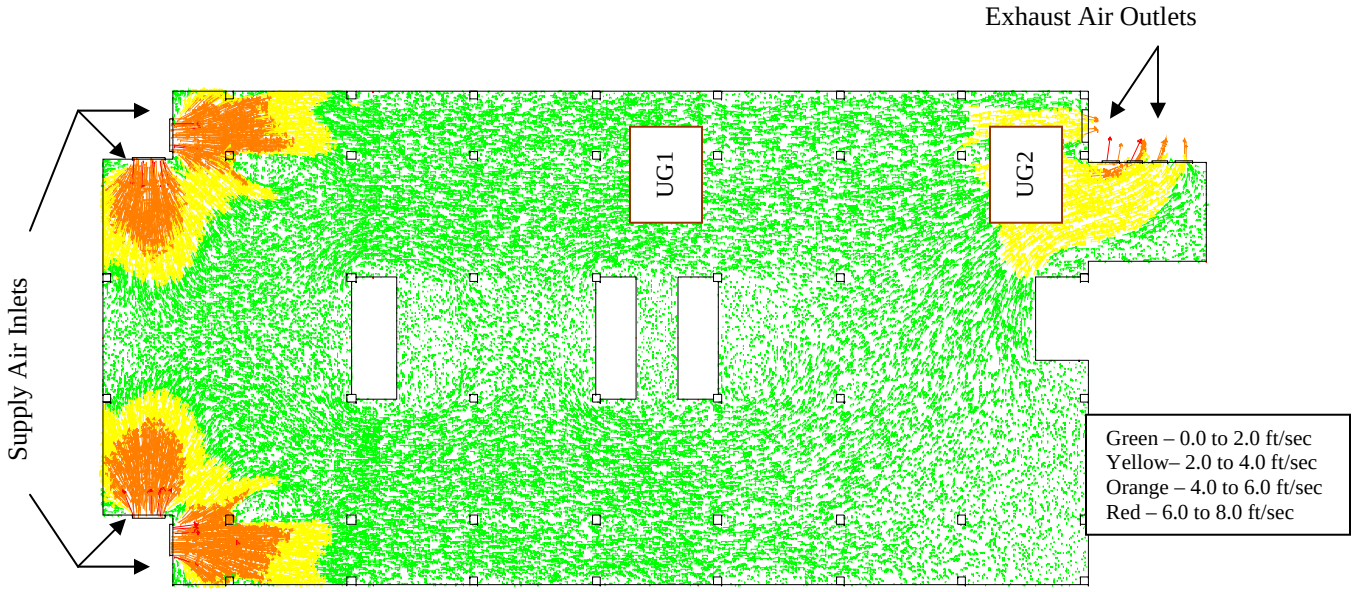


Figure 3.2– Airflow velocity at 1 foot above floor in underground parking facility

The airflow was modeled to determine the impact of such airflow on leaking hydrogen behavior, in terms of shifting the hydrogen away from the vehicle and/or diluting the hydrogen cloud to below combustible levels. The impact of other vehicles in the facility was not modeled.

Figure 3.2 illustrates the air velocity at 1 foot above the facility floor. The green colored area reflects 0.0 to 2.0 foot-per-second (ft/sec) air velocity, yellow as 2.0 to 4.0 ft/sec, orange as 4.0 to 6.0 ft/sec, and red

as 6.0 to 8.0 ft/sec. , The airflow modeling indicated that the air velocity at 1 foot above the floor is greater near the ventilation supply inlets and exhaust outlets than in the rest of the facility.

Figure 3.3 shows that a 1.0 mph wind is not sufficient to diffuse the cloud from under the vehicle. In the case of a HFCV that is equipped with functioning on-board hydrogen leak detectors, it is assumed that the onboard sensors would detect a hydrogen concentration at 1% and would signal the system to shut off the hydrogen leak. Figure 3.3 shows that after 10 seconds of leakage the on-board sensors have more than ample hydrogen concentration available to initiate a signal and shut off the hydrogen flow.

The air flow modeling was repeated with hydrogen leaking from the under side of a vehicle at 20 CFM with a 1.5 ft/sec airflow at 1 foot above the floor with air flowing from left side of vehicle. After 50 seconds with a hydrogen leak, a 4.1% hydrogen concentration extended approximately 2 feet beyond the right side of the vehicle, and a 1% hydrogen concentration extended approximately 5 feet beyond the right side of the vehicle covering an area equal to vehicle's size – Figure 3.3

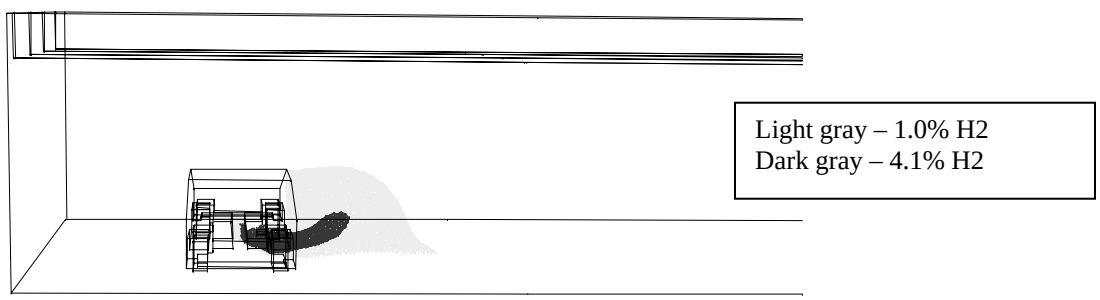


Figure 3.3- 1.5 MPH wind, 20 CFM hydrogen leak (after 50 seconds)

Modeling was stopped after 50 seconds because the simulation indicated that the combustible hydrogen cloud reached a steady state condition.

One possible explanation of the hydrogen concentration confinement to within five feet of the vehicle is the 1.5 ft/sec air velocity, which may be sufficient to dilute the hydrogen beyond the five feet distance. Although not modeled, the modeling computer expected the concentration levels and cloud shape to maintain the same condition until the tank was emptied.

The study team examined the possibilities of the hydrogen cloud entering the ventilation exhaust outlet if the vehicle was parked close enough to the outlet. This analysis determined if the facilities mechanical systems could draw enough hydrogen from a leaking vehicle to form a combustible mixture inside the ventilation ducts.

This model analyzed the placement of a leaking vehicle in the parking space closest to the exhaust outlet (return duct) of the parking garage ventilation system. The model indicated that after 50 seconds of leakage (Figure 3.4), the combustible cloud (4.1% hydrogen) did not enter the ventilation system of the garage. After 50 seconds, the modeled scenario has reached steady state in which the combustible portion of the hydrogen cloud will retain its shape and not extend into the ventilation system. The hydrogen cloud closest to the exhaust outlet is diluted to a concentration lower than the combustible limit due to the high air velocity created by the ventilation system.

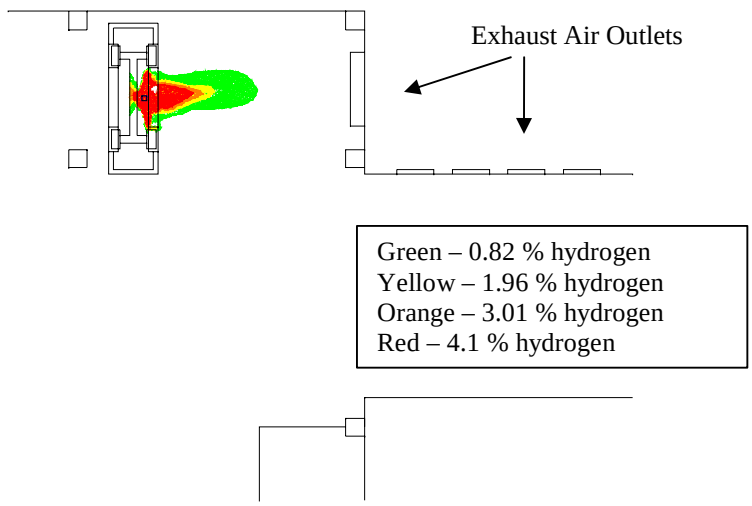


Figure 3.4 - Vehicle with 20 CFM hydrogen leak in parking spot closest to inlet of parking garage exhaust system (after 50 seconds).

Analysis of the results of the underground modeling indicate that, except for the immediate area surrounding the vehicle (within two feet), leaking scenarios of 20 CFM from vehicles parked anywhere in the facility did not produce a combustible hydrogen cloud.

Modeling of 20 CFM leaking hydrogen from a vehicle equipped with hydrogen leak detection and isolation safety systems indicated that a 1.5 – 4 ft/sec. air velocity caused the hydrogen concentration to be diluted and swept from the vehicle's undercarriage. Such dilution and displacement of hydrogen has prevented the hydrogen detectors in the wheel wells from detecting the hydrogen and allowed the hydrogen to continue leaking. Since we assumed that the on-board computer could only respond to leak rates greater than 20 CFM, the on-board vehicle safety system was not a factor in isolating the hydrogen from leaking into the facility. The same 1.5 – 4 ft/sec airflow velocity that diluted the hydrogen under the vehicle to less than detectable limits by the on-board safety system also confined the potentially combustible hydrogen cloud to within two feet of the vehicle's surroundings.

Therefore, one could conclude that, in this particular model, 1.5 – 4 ft/sec. airflow under a leaking HFCV will confine the hydrogen combustible cloud to within two feet of the vehicle's surroundings regardless of whether the vehicle is equipped with on-board safety systems or not.

In the case of wind velocity less than 1.5 mph, or if a wall existed in the close proximity to the downwind side of the vehicle, the modeling results indicated that the hydrogen cloud would collect under the vehicle. With the study's assumptions that the HFCV is equipped with an on-board safety system, the modeling results indicate that the on-board safety systems would detect hydrogen and respond by isolating the leak before a combustible hydrogen cloud is formed anywhere in the facility, including under the vehicle.

3.1.3 Recommended Modifications

CFD modeling results indicated that the air ventilation system's ability to maintain at least 1.5 ft/sec. velocity at 1 foot above the floor is a key factor in reducing the potential accumulation of combustible hydrogen clouds beyond two feet of the vehicle regardless of the vehicle's on-board safety system.

Since existing design and construction codes and standards for ventilation systems at parking facilities typically result in air velocity of at least 1.5 ft/sec. at 1 foot above the floor, a potential conclusion of this modeling indicates that no special modifications are necessary to accommodate leaking hydrogen fuel cell vehicles. Such a finding is applicable only to the assumptions and scenarios in this modeling. Other scenarios or assumptions such as facility configuration, leaking rates, or air velocity will change the modeling results and conclusions.

A 1.0 mph wind is not sufficient to diffuse the cloud from under the vehicle. In the case of a HFCV that is equipped with functioning on-board hydrogen leak detectors, it is assumed that the onboard sensors would detect a hydrogen concentration at 1% and would signal the system to shut off the hydrogen leak. Figures 3.3 and 3.6 show that after 10 seconds of leakage the on-board sensors have more than ample hydrogen concentration available to initiate a signal and shut off the hydrogen flow.

3.2 Aboveground

3.2.1 Design

Similar to the underground facility, the aboveground parking facility is a three-story facility capable of accommodating approximately 85 vehicles on each floor including ADA parking spaces. The facility includes two staircases, one elevator shaft, heating and ventilation ducts, and mechanical and electrical rooms. The facility incorporates retail or office space above – Figure 3.5.

Since moving vehicles create a significant amount of vibration, the structural frame and foundation are usually constructed of cast-in-place concrete. The general vehicular flow pattern is a single loop with parking around the perimeter and in the center.

However, by virtue of this facility being above ground it is afforded greater flexibility in construction and design than its underground counterpart. That is why existing examples of aboveground facilities vary more between themselves than in underground facilities. There are more options or means by which vehicles can be moved from floor to floor in the aboveground facility than the underground facility. These differences are primarily because of space restrictions, high cost of excavation and general limitations of sub-grade construction which do not restrict the design of the above-ground facility.

In an underground garage, a localized system would most likely be used, such as a straight, switch-back or helix ramp for vertical vehicular circulation. An aboveground garage can use these systems as well, but also could employ a spilt-plate or ramped floor system, where a section of the facility's floor is gently sloped or inclined from one floor level to the next. Vehicles park on this sloped plane similarly to the level areas. In order to represent and test a design that is different from the underground facility, but remains a typical condition, this study chose a sloped floor in the above ground facility.

The aboveground facility's design accommodates the vertical circulation of pedestrians somewhat differently from its underground counterpart. Here the elevator core is decentralized, pushing the elevator and one stair well to one side of the structure and another stair to the opposite side. The separation between stairs is per CBC/UBC and parking dedicated to the disabled is adjacent and compliant to ADA requirements.

An issue that is less pertinent to underground structures, but relevant to aboveground structures is composition & design of the exterior wall. Belowground structures generally construct the exterior wall integrally with foundation and it is most often composed of cast-in-place concrete. Aboveground parking

facilities can be constructed with nearly an infinite variety of exterior wall types or skins, but that skin is basically independent of the structure (other than using the structure for support) and determined primarily by the facilities context. That is to say that the skin or exterior wall needs to maintain certain physical properties such as weight, rigidity, openness, etc., but the form or shape that the exterior wall takes is more a function of fitting into its surroundings than its purpose as a parking facility. Unless there is some highly unusual exterior wall configuration, because of the skins independence from structure, its specific form is inconsequential to this study.

The garage was designed in compliance with the UBC requirements for an open garage. Such requirements include uniformly distributed openings on two or more sides making up a minimum of 20% of the total wall perimeter, and 40% of the wall perimeter, for each level. Interior wall and column lines must be at least 20% open. With this classification of open garage, no mechanical ventilation was required.

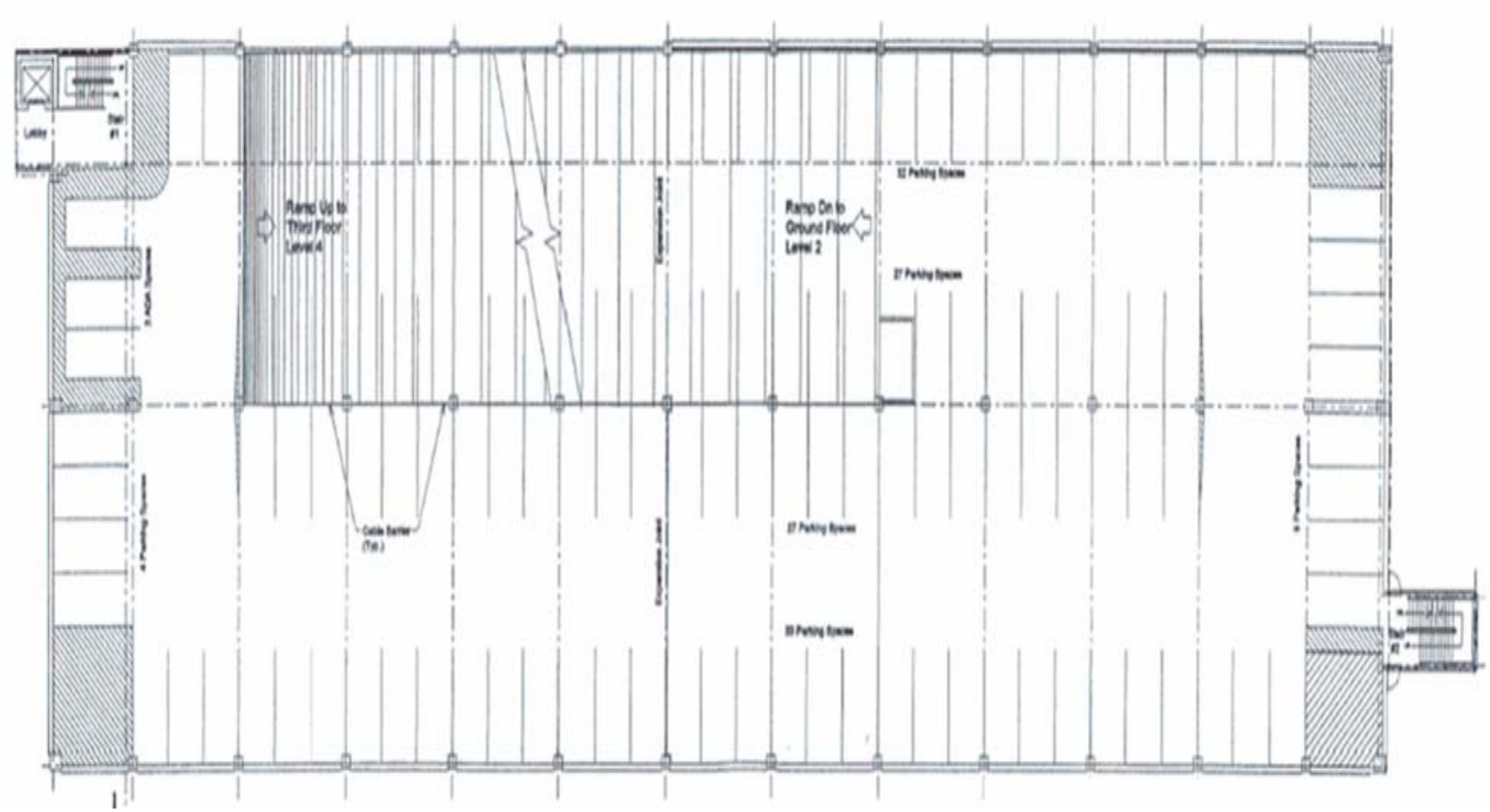


Figure 3-5 –Above Ground Parking Facility Layout

3.2.2 Hydrogen Leak Modeling

The modeling simulated the scenario of 20 cubic foot per minute (CFM) hydrogen leaking from an operating "on" HFCV. The "on" designation means that the HFCV is equipped with properly functioning on-board hydrogen leak detection and isolation systems.

Three different wind speeds under the vehicle were modeled with the assumption that the wind direction was from the driver's side of the vehicle. Speeds of 1.0 mph, 1.5 mph, and 2.0 miles per hour (mph) were modeled - Table 3.2

Table 3.2 CFD Model Scenarios for Aboveground Parking Facilities

Model #	Vehicle Configuration	Air Flow Speed	On-board Safety System	Leaking Rate
AG1	Wheel wells and lip	1 mph	Yes	20 CFM
AG2	Wheel wells and lip	1.5 mph	Yes	20 CFM
AG3	Wheel wells and lip	2 mph	Yes	20 CFM

Figure 3.6 shows that a 1.0 mph wind is not sufficient to diffuse the cloud from under the vehicle. In the case of a HFCV that is equipped with functioning on-board hydrogen leak detectors, it is assumed that the onboard sensors would detect a hydrogen concentration at 1% and would signal the system to shut off the hydrogen leak. Figure 3.6 shows that after 10 seconds of leakage the on-board sensors have more than ample hydrogen concentration available to initiate a signal and shut off the hydrogen flow.

Figures 3.7 and 3.8 show the maximum sizes of the 4.1% and 1.0% concentration hydrogen clouds with 1.5 and 2.0 mph wind respectively. The model results are shown after 50 seconds of leakage and represent steady-state behavior of the clouds. The steady state clouds would maintain the same shape until the vehicle runs out of hydrogen. For a vehicle containing 6 kg of hydrogen, this would be approximately one-hour and 45 minutes. Model results indicate that higher wind velocities would cause more mixing of the hydrogen and air, thus reducing the combustible cloud sizes as indicated in Figure 3.7 and 3.8 (1.5 mph and 2.0 mph).

However, if a wall existed in close proximity to the passenger side (downwind) of the vehicle, the hydrogen would not be dispersed from under the vehicle. The hydrogen would collect in the wheel wells, and in the case of HFCV that is equipped with on-board hydrogen leak detection, the on-board sensors detectors are expected to detect hydrogen in excess of 1% concentration and initiate shut off the hydrogen leakage by isolating the hydrogen tank.

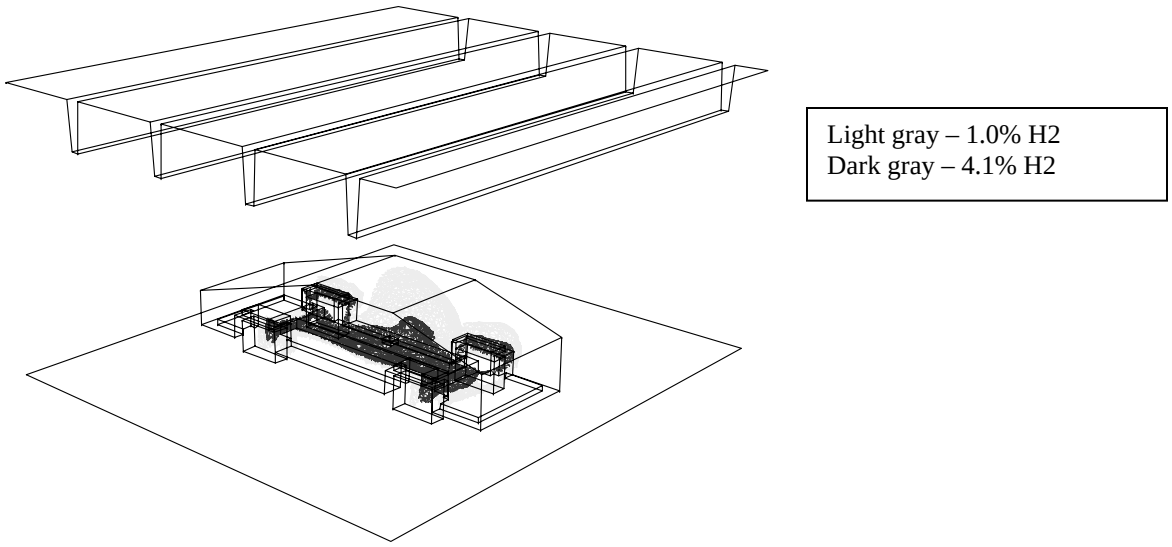


Figure 3-6 - 1 MPH wind, 20 CFM hydrogen leak (after 10 seconds)

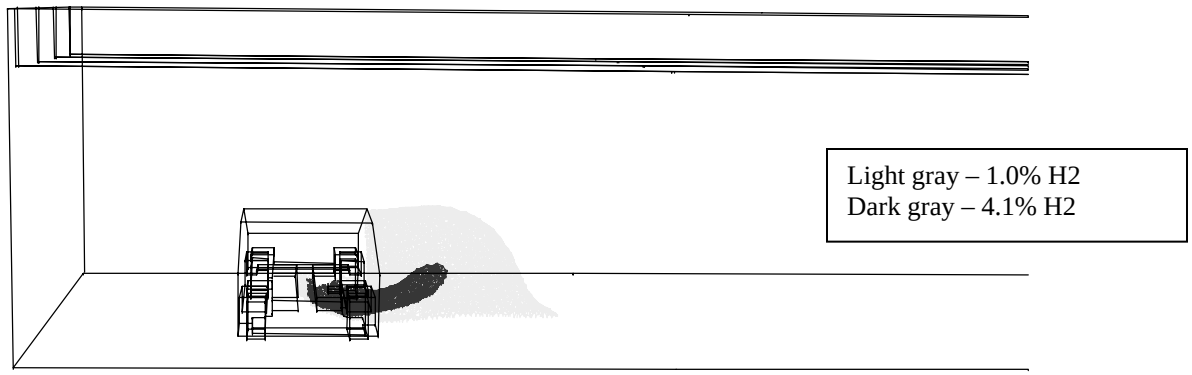


Figure 3.7- 1.5 MPH wind, 20 CFM hydrogen leak (after 50 seconds)

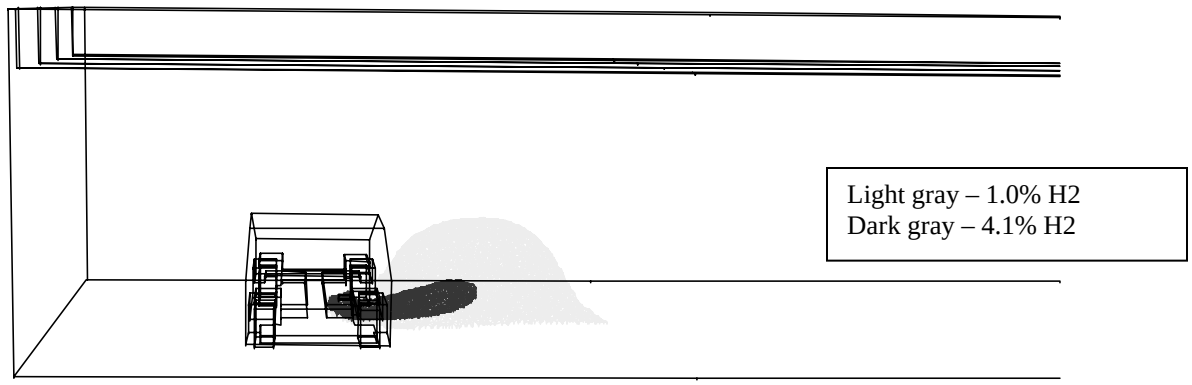


Figure 3.8- 2 MPH wind, 20 CFM hydrogen leak (after 50 seconds)

3.2.3 Recommended Modifications

Based on the modeling results, no modifications for the above-ground parking facility are recommended in the case of wind velocity in excess of 1.5 mph. because potentially combustible hydrogen concentration were contained within two feet of the vehicle.

In the case of wind velocity less than 1.5 mph, or if a wall existed in the close proximity to the downwind side of the vehicle, the modeling results indicated that the hydrogen cloud would collect under the vehicle. With the study's assumptions that the HFCV is equipped with an on-board safety system, the modeling results indicate that the on-board safety systems would detect hydrogen and respond by isolating the leak before a combustible hydrogen cloud is formed anywhere in the facility, including under the vehicle.

Therefore, given the scenario assumptions and modeling results of such scenarios, the study concludes that no facility modifications are necessary.

Other conclusions would be drawn with the use of different scenarios and assumptions. For example, modeling a hydrogen leak from a HFCV that is either not equipped with an on-board safety system, or has a safety system that is not properly functioning, the results could indicate that a combustible hydrogen cloud would form in the facility if the wind speed is less than 1.5 mph. Effective facility modifications would then be based on examining the modeling results and recommending modifications that would reduce the risk of forming a combustible hydrogen cloud. Because the scope of this study was limited to few scenarios and assumptions, the study did not perform additional modeling scenarios.

4. Residential Garage

4.1 Design

The modeled residential garage is an attached, below living space residential two-car garage in a single-family dwelling. The elevation, second floor layout, and garage layout are shown in figures 4-1, 4-2, and 4-2A. These drawings provide dimensional specifications for CFD modeling. They also indicate the location of doors and windows which could provide a pathway for leaking hydrogen.

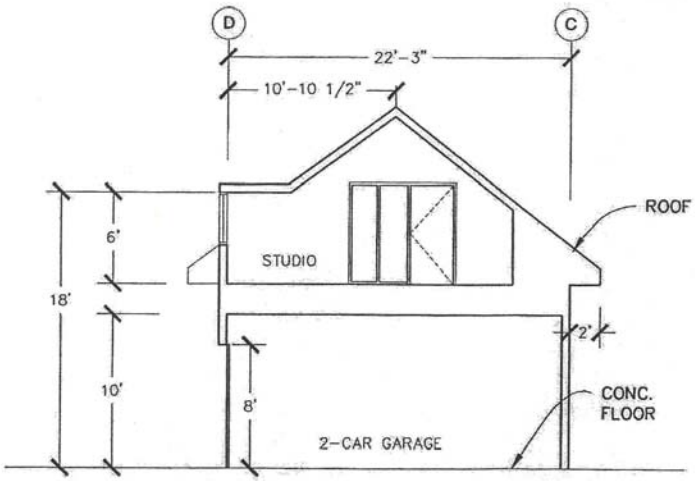


Figure 4-1– two-vehicle Residential Garage -Elevation

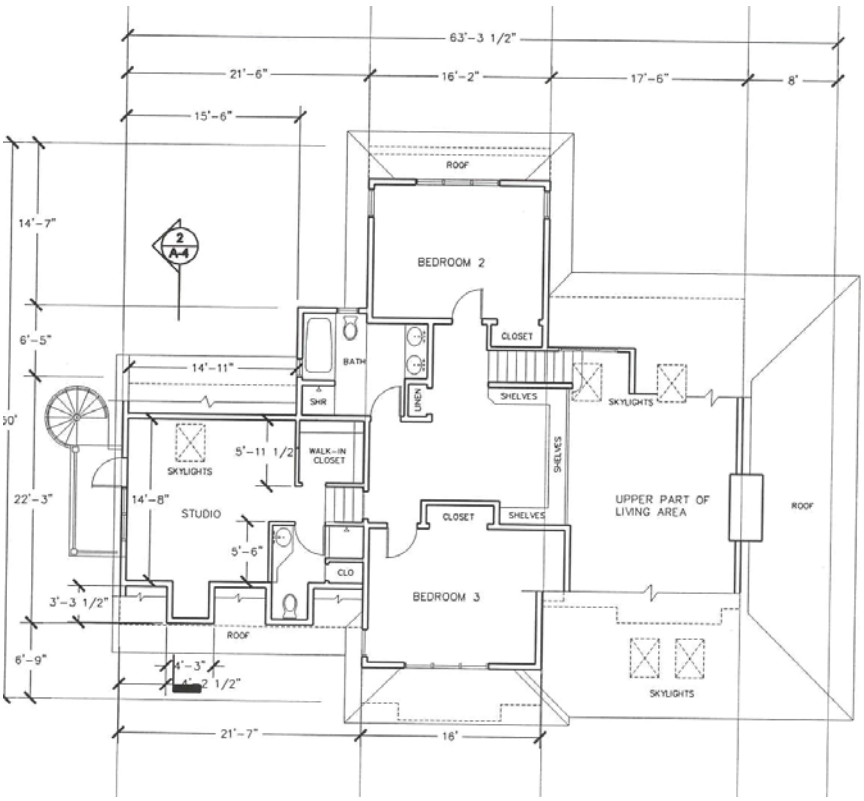


Figure 4-2 - Two-vehicle Residential Garage & Living Space - Second Floor Layout

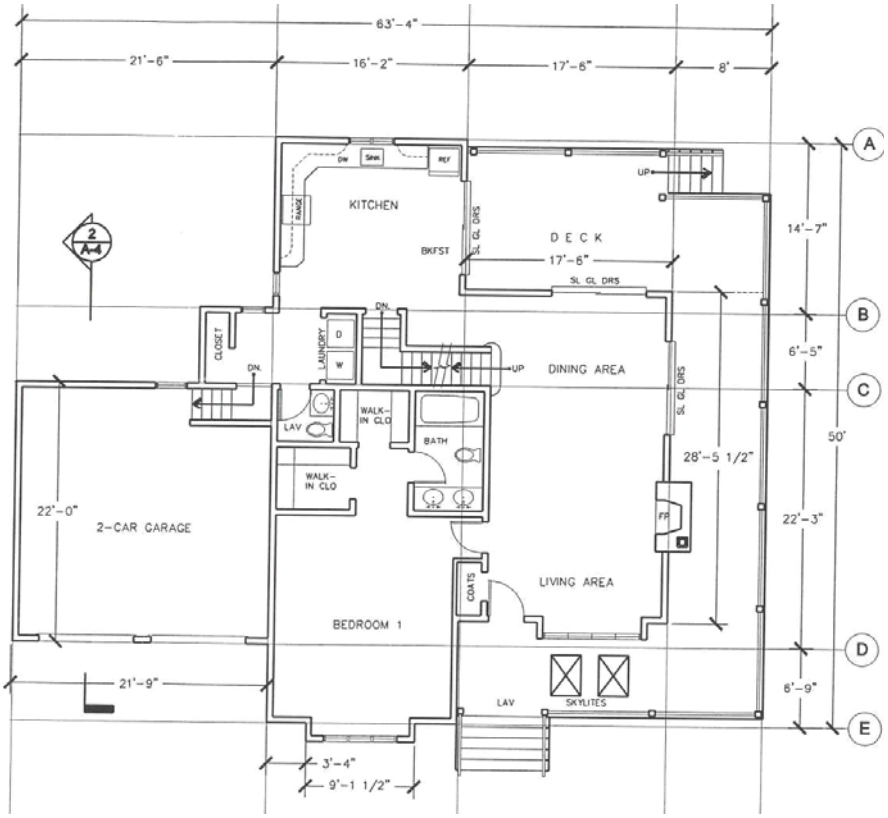


Figure 4-2A - Two-vehicle Residential Garage & Living Space - Ground Floor Layout

The nature and form of residential construction is the most varied of the three buildings in this study. Therefore, many of the buildings in California will vary from the specific building design presented in this Section more than the buildings in Sections 3 and 5. The variation among residential housing is especially pronounced in a large and diverse state like California where there is no dominant architectural style, culture, configuration, climate or geographic condition. However, because of automotive physical dimensions and operational envelops, certain assumptions can be made of residential garages (i.e. 400 square foot, 10 foot high ceiling, may contain water heater, shelving, and gardening equipment). Also, to some extent in California, there is a predominance of wood frame, stud construction used in residential building that is often independent of style, culture, configuration, climate or geographic condition.

Designed as a suburban, free standing, two story home, the house modeled for this study, has hipped roofs and a wrap-around porch. On the ground floor the house's major occupied spaces, like living room, dining room, kitchen, bedroom and garage are organized around a central core consisting of bathrooms and a stair. Entrance to the home is either off the porch, between the living room and ground floor bedroom or through the garage. The second floor is also organized around a core, but here the core provides access to the upstairs bedrooms. One of these bedrooms is directly above the garage and has a balcony with an exterior spiral staircase down to the ground. The bedrooms are effectively in the hipped roof of the house. Though no residential design is typical, house designs similar to this are found throughout California.

Since this study is concerned with conditions as they pertain to storing a hydrogen fuel cell vehicle (HFCV) in a residential garage, most of in the particularities of residential design are inconsequential to this study. Thus the house design used as a model for this study is primarily concerned with the garage,

which is of conventional proportion (approximately 400 square foot), and the bedroom which is located directly above it. The entire structure is framed in wood studs (often referred to as "stick framing").

The primary building design factors that could be affected by a hydrogen release include the following:

- The garage meets NFPA and NEC 70. Ignition sources are 18 inches above floor level. For this design, the ignition sources are outlets. The water heater, washer, and electric dryer are located inside the house.
- The garage is equipped with an electric garage door opener. The motor and a light are located in the ceiling in the center of the garage.
- Florescent lights are located in the garage ceiling. Light switches are located adjacent to the entrance door to the house.
- The door to the house has an automatic close feature as required by code.
- The garage ceiling and walls are covered with wallboard.
- A bedroom window is located above the garage door.
- No heating or ventilation system is included in the garage.

4.2 Hydrogen Leak Modeling

Five leak scenarios were modeled to assess a situation where the vehicle leaks in the garage with the fuel cell engine on. The parameters for the leak scenarios are shown in Table 4-1. The purpose of the first two CFD analyses was to assess the time for a hydrogen cloud to reach the vehicle's wheel well where sensors could shut off the leak. The remaining three analyses evaluated the time for a continuous leak to reach the garage ceiling, while the on-board safety systems were off and the garage doors closed.

Table 4-1. CFD Model Scenarios for Residential Garage

Model #	Garage Door	Vehicle Configuration	On-board Safety System	Leaking Rate
1	Closed	Flat undercarriage	Yes	20 CFM
2	Closed	Wheel wells and lip	Yes	20 CFM
3	Closed	Wheel wells and lip	No	5 CFM
4	Closed	Wheel wells and lip	No	15 CFM
5	Closed	Wheel wells and lip	No	20 CFM

The first hydrogen leak modeling exercise of the residential garage simulated a twenty (20) cubic foot per minute (CFM) leak from a vehicle parked inside a closed, two-vehicle garage. The simulation was run for 180 seconds. The simulation also assumed that the vehicle's undercarriage has a flat contour with no wheel wells. The simulation shutoff hydrogen flow when a 1% concentration reached the hydrogen sensors located on the undercarriage in front of the back wheels and behind the front wheels. Although today's vehicles are normally contoured with wheel wells and a 3" lip surrounding the undercarriage, this simulation of a flat contour with no wheel wells represents a conservative model with regard to the amount of hydrogen released from the vehicle. Without wheel wells or the undercarriage lip, the leaking hydrogen can escape quickly from underneath the vehicle to the garage.

A second simulation of 20 CFM assumed a regular vehicle contour (including wheel wells and an undercarriage lip) with the sensors located at the highest point in the wheel wells. These modeling

scenarios stopped the flow of hydrogen when a 1% concentration reached the wheel well. The simulation continues after the hydrogen flow stopped to assess the dispersion of the hydrogen cloud.

The last three scenarios were conducted to identify the shape of the hydrogen plume in the garage and to determine the time it will take for a five percent (5%) concentration of hydrogen to reach the center point of the ceiling of the garage for a continuous leak. The reason we picked the parameter of 5% hydrogen at the garage's center ceiling point is to ensure the presence of 4.1% hydrogen concentration between the leaking vehicle and the ceiling of the garage. These three additional scenarios assumed hydrogen leak rates of five (5) CFM, fifteen (15) CFM, and twenty (20) CFM. These scenarios utilized the vehicle's contoured undercarriage design that includes wheel wells and a 3" lip. These scenarios also utilized the conservative assumption that the garage doors were closed, thus allowing the least amount of ventilation as possible.

Results

The first two modeling scenarios showed the distribution of the predicted hydrogen cloud with two different vehicle undercarriage geometries. The shapes of the predicted hydrogen clouds are shown in Figure 4-3 through 4-8. These simulations showed that a 1% hydrogen cloud would reach the wheel well in 7 or 28 seconds depending on the vehicle geometry. The 1% concentration at this time would be two feet above the vehicle.

Results of the first modeling (20 CFM – "vehicle on" – flat contour) indicated that after fifteen (15) seconds from the start of the leak, the hydrogen formed a cloud that extended from the side of the vehicle, where the leak originated, to the ceiling of the garage. The lower flammability limit of hydrogen (4.1%) was present in the surrounding ten (10) square foot (SF) (5'X2') area approximately two feet above the vehicle and extended in an inverted funnel shape to the source of the leak - Figure 4-3.

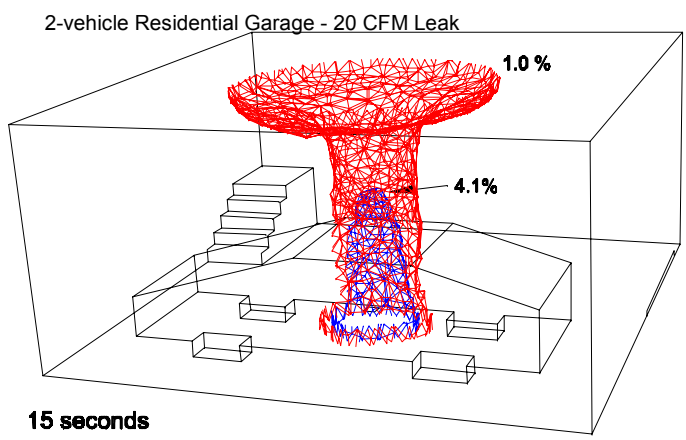


Figure 4-3- Two-vehicle Residential Garage - 20 CFM Leak – 15 Seconds

A 1% hydrogen cloud was also predicted to start to spread across the ceiling of the garage. The model predicted a 1% hydrogen concentration by the passenger side (right side) rear wheel after 28 seconds. The simulation stopped the flow of hydrogen and the cloud spread across the entire ceiling of the garage,

but the 4.1% concentration surrounding envelope remained approximately in the same area as in the 15 seconds case (in a 10 SF area approximately two feet above the vehicle) - Figure 4-4.

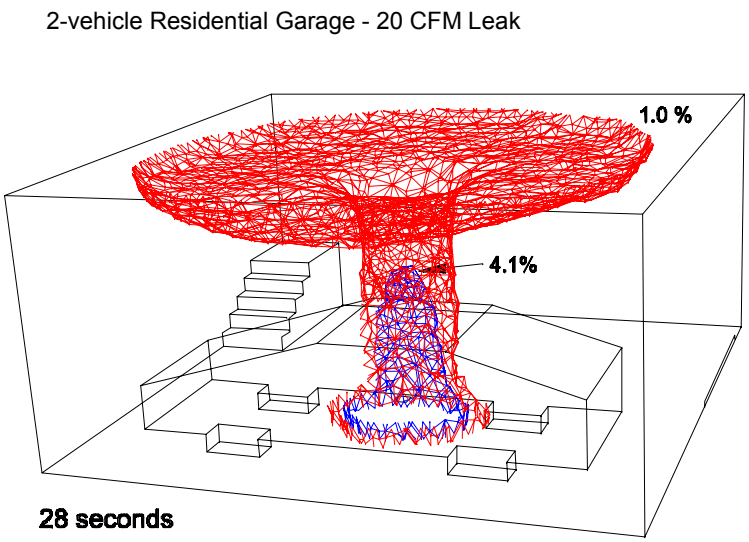


Figure 4-4 - Two-vehicle Residential Garage - 20 CFM Leak – 28 Seconds

The modeling simulated the spread of hydrogen if the vehicle were equipped with hydrogen sensors and safety systems to shut off the flow when 1% hydrogen was detected at the wheel well. The simulation continued on after the 17 seconds with no additional hydrogen flow from the vehicle. Figures 4-5 through 4-7 show the dissipation of the hydrogen cloud.

The simulation indicates that at 45 seconds from start of the leak (17 seconds after shutoff valve activation), the 4.1% concentration was present in an area approximately 1'X1' near the source of the leak, and the 1% cloud that spread across the ceiling started to diminish – Figure 4-5.

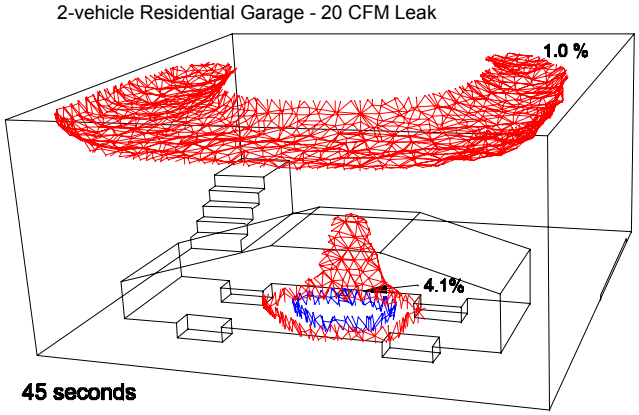


Figure 4-5 - Two-vehicle Residential Garage - 20 CFM Leak – 45 Seconds

At 60 seconds from start of the leak (32 seconds from activation of the shutoff valve), the hydrogen cloud had returned to the same shape as it was at 45 seconds – Figure 4-6.

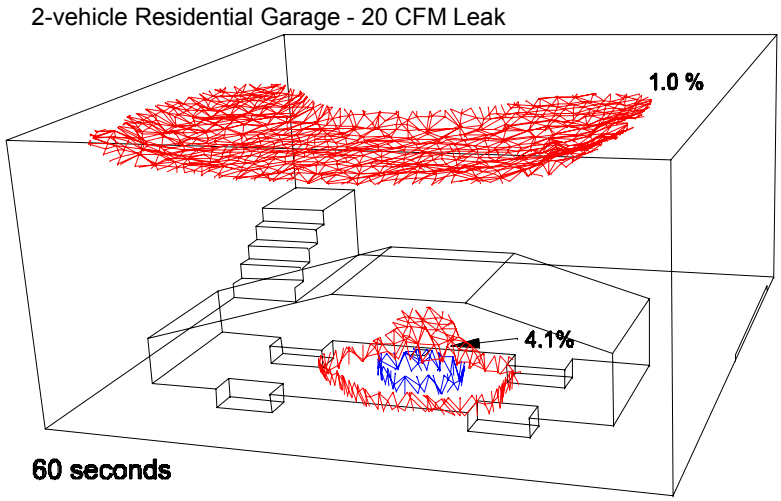


Figure 4-6 - Two-vehicle Residential Garage - 20 CFM Leak – 60 Seconds

At 120 seconds after the initial leak, the highest indicated hydrogen concentration in the garage was 1%, and only near the source of the leak – Figure 4-7.

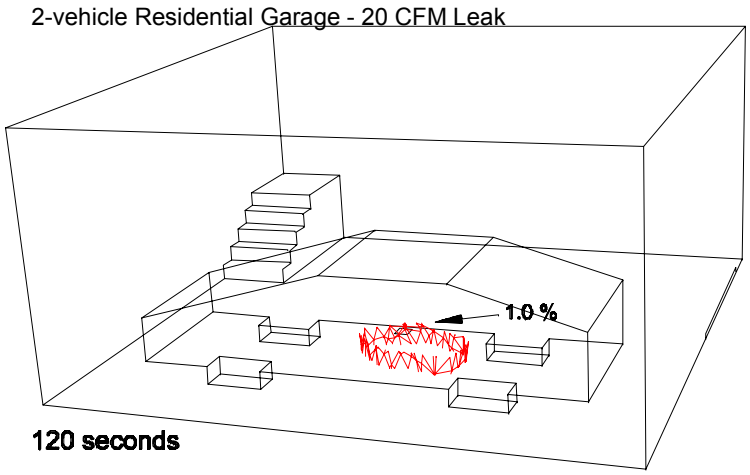


Figure 4-7 - Two-vehicle Residential Garage - 20 CFM Leak – 120 Seconds

Finally, at 180 seconds, the hydrogen has dispersed enough that there was no more than a 1% concentration of hydrogen at any point in the garage – Figure 4-8.

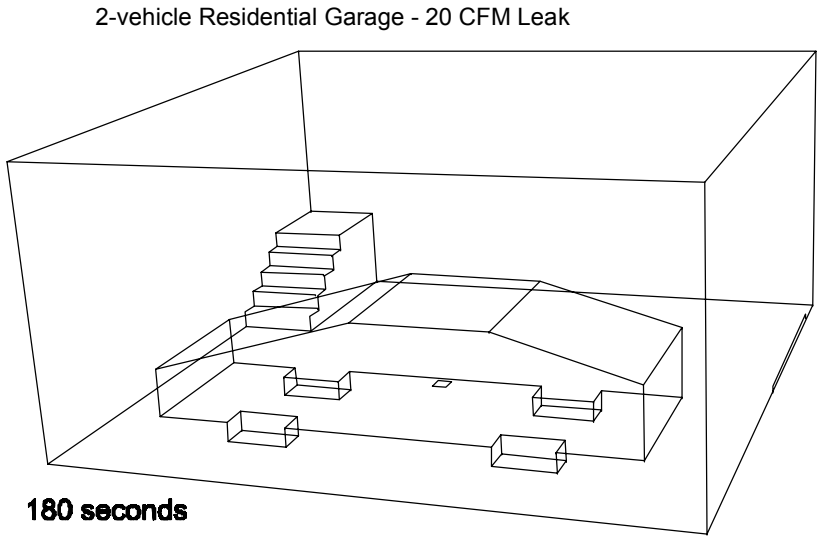


Figure 4-8 - Two-vehicle Residential Garage - 20 CFM Leak – 180 Seconds

The second modeling run of 20 CFM "vehicle on" with a contoured vehicle undercarriage revealed that the rear wheel well hydrogen sensor detected the leaking hydrogen in approximately 7 seconds from the start of the leak. At that time, the hydrogen concentration of 4.1% had just started to form underneath the vehicle with no noticeable concentration outside the perimeter of the vehicle's undercarriage. The reduced detection time of this scenario from the first scenario can be attributed to the vehicle's undercarriage contour especially the 3" lip and wheel wells. The contoured undercarriage configuration reduced the volume of hydrogen leaked from under the vehicle into the garage. Since hydrogen is a buoyant gas it will seek the highest point. The highest point under the vehicle was the wheel wells where the hydrogen was collected and then detected by the sensors once its concentration reached 1%.

The first two modeling predicted the behavior of a hydrogen leak sensors shut off the fuel supply when 1% hydrogen is detected at the wheel well. This analysis showed that the flammable portion of the hydrogen cloud remained in close proximity to the vehicle and then dissipated within 100 seconds if the hydrogen supply were shut off.

The study team conducted further analyses to assess the impact of a leak if the vehicle was not equipped with hydrogen sensors at the wheel well or if the sensors were malfunctioning (multi-mode failure). Three leak rates were modeled: 5, 15, and 20 CFM. This information provides automakers with the information to assess the consequences of a leak and also develop strategies to limit the amount of fuel that can leak from the vehicle when it might be parked with the fuel cell engine on.

Modeling continuous 5, 15, and 20 CFM leaks indicated that the 5% hydrogen concentration reached the center point of the enclosed garage at 1740, 725, and 545 seconds respectively. At these times, the potentially combustible 4.1% cloud filled the entire space between the leak and the center point of the garage. A narrow shaped cone of 6% hydrogen concentration was also detected between the source of the leak and the 5% concentration – Figure 4-9.

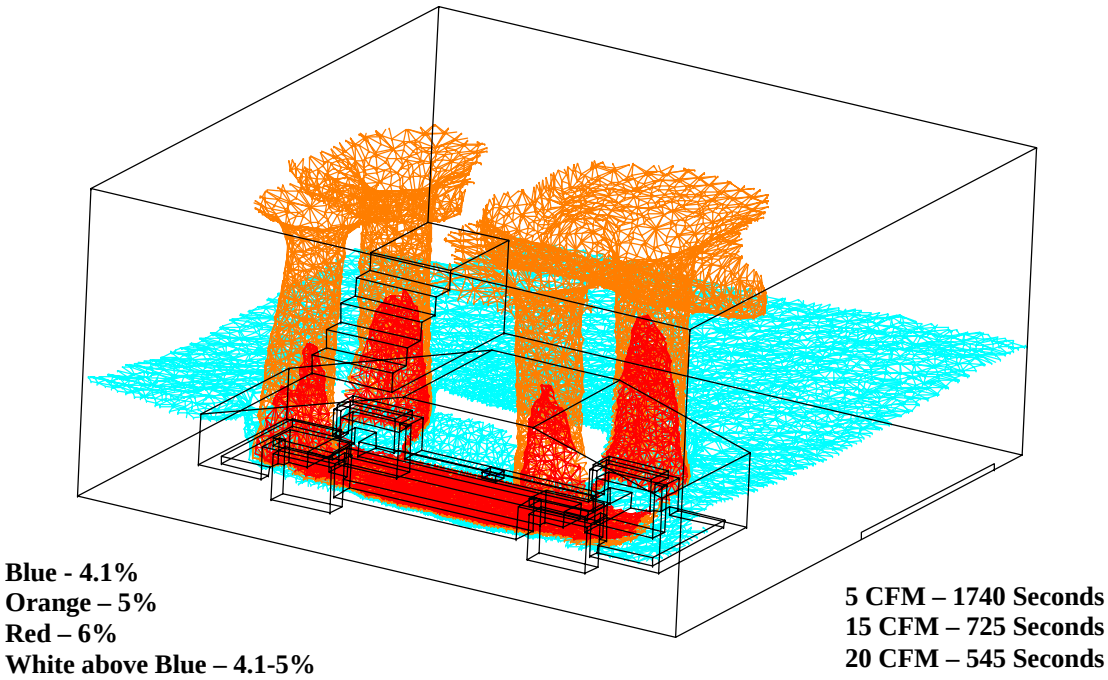


Figure 4-9 - Two-vehicle Residential Garage – 5, 15, and 20 CFM Leak – No on-board safety system

4.3 Recommended Modifications

Based on the results of the 20 CFM "vehicle on" modeling (Scenarios 1 and 2), the study recommends no modifications are necessary at the residential garage because the on-board safety system limited the potentially combustible hydrogen leak to within the vehicle's undercarriage perimeter and only for 7 seconds. In the case of a flat contour vehicle, the on-board safety system detected the leaking hydrogen after 28 seconds and the combustible cloud existed only within a 10 SF area approximately two feet above the vehicle.

The modeling results for the 5% hydrogen concentration at the ceiling center point indicated that without the on-board safety system or facility modifications, a combustible concentration would exist in the closed garage if a 20 CFM leak continued for 9 minutes or more (12 minutes for 15 CFM and 29 minutes for 5 CFM).

Although the effectiveness of facility modifications to mitigate a 5% hydrogen concentration scenarios could not be verified without additional modeling, the study recommends that any potential facility modifications should focus on early detection and timely mitigation of leaking hydrogen sources so that the concentration would not reach combustible limits. The cost of facility modifications is presented in Section 6. Additional analysis of the continuous leak scenarios is also presented. Information on the effect of a continuous leak and potential further modifications can be used by automakers to evaluate vehicle design strategies and make recommendations to their customers on building modifications.

While the results of the CFD modeling indicate that on-board hydrogen detection and isolation would reduce or eliminate leaking hydrogen from escaping to the garage, this study did not perform cost-benefit analysis of such on-board systems. In addition, the study's scope did not include investigating the feasibility, reliability, or availability of such on-board systems and technologies.

The study scope focused mainly on facility modifications under specific scenarios. The study team selected the scenarios based on discussion among team members (please refer to Section 2 for scenarios selection methodology and approach). Therefore, the outcome of this study is applicable only to the selected scenarios and should not be interpreted as general recommendations for facility modification. Additional modeling and examination of vehicle parameters (cost, feasibility, availability, and reliability of on-board safety system) may indicate that modifying the facility is more feasible than installing on-board safety systems and visa versa.

5. Maintenance and Service Facilities

5.1 Design

The design basis for a commercial service facility was part of a state-of-the-art dealership facility with ten (10) bays total and at least three (3) bays capable of accommodating HFCVs as well as conventional vehicles.

Each HFCV bay requires a space of approximately 2' D X 2' W X 4' H to accommodate a high voltage (240 VAC) battery charger. The HFCV bays also require accommodation for DI water. The HFCV bays do not require any grounding connectors or cables. Only light maintenance or replacement of major component type service would be done at the dealership. Maintaining HFCV requires unique tools, parts, equipment, special environmental chambers for storing them are required. Static control rooms are not required to service HFCVs or to store unique spare parts. Additional space requirements at HFCVs bays included a dynamometer and load tester (estimated to be a box about 2'x2'x1'). (The dynamometer is often present in maintenance facilities in California due to smog testing requirements for conventional vehicles – Figure 5.1)

The layout and promenade through the 10 bay maintenance facility is as simple and straight forward as its utilitarian function. The facility is divided in two sections at column line "C". Here a fire wall separates the maintenance shops from all other functions of the facility. This separation is per California Building Code (CBC) and Uniform Building Code (UBC), which require the separation of dissimilar use types. The vehicular entrance to these bays is on the short wall of the shop; on column line "I," between column lines 2.3 and 2.6. On the other side of the separation wall, the facility accommodates functions such as reception, offices, storage, break area and bathrooms. Pedestrian access points are located on each exterior face of the rectangular building plan. Customer parking is provided along the long side of the facility at column line 3, with two disabled parking spaces near the main entrance, per the Americans with Disabilities Act (ADA) guidelines. All the functions of the maintenance facility are accommodated on one floor at ground level, eliminating the need for costly ramps, elevators or stairs.

Efficiency, safety, flexibility and functional requirements were the most important factors in determining the design of a maintenance facility. The building was designed with a steel structure, metal panel envelope (exterior wall and roof), cast-in-place concrete floor and foundation. The foundation can be constructed as a slab on grade with or without footings, as soil conditions, environment and local building codes dictate. Steel and panel building system can be pre-engineered, partially prefabricated and assembled on site. They are erected rather quickly and efficiently. A columnar structure was selected because they tend to be more open, flexible, accepting of modification and adaptation than heavy wall systems such as masonry or concrete. This flexibility combined with the long spans and fire resistance (with fire proofing) offered by steel facilitate safety and function required by an automotive maintenance facility. A pitched roof (22 feet to 19 feet high) allows the building to shed water easily. A roof monitor (a skylight that projects slightly above the roof) at the ridge provides natural light and ventilation. The pitched roof also enables the prompt release of lighter-than-air hydrogen though these vents. A flat roof would provide more opportunity for hydrogen to be trapped between exposed structural elements in the ceiling.

The exterior or skin of the building in this model is a metal panel system but could easily change materials to suit its context. For instance, if this facility were in or near a historic district, its skin could rather easily be made of brick, stucco or shingles. As long as the interior envelope / surfaces of the facility are consistent, such external, contextual, aesthetic specifications did not affect this study.

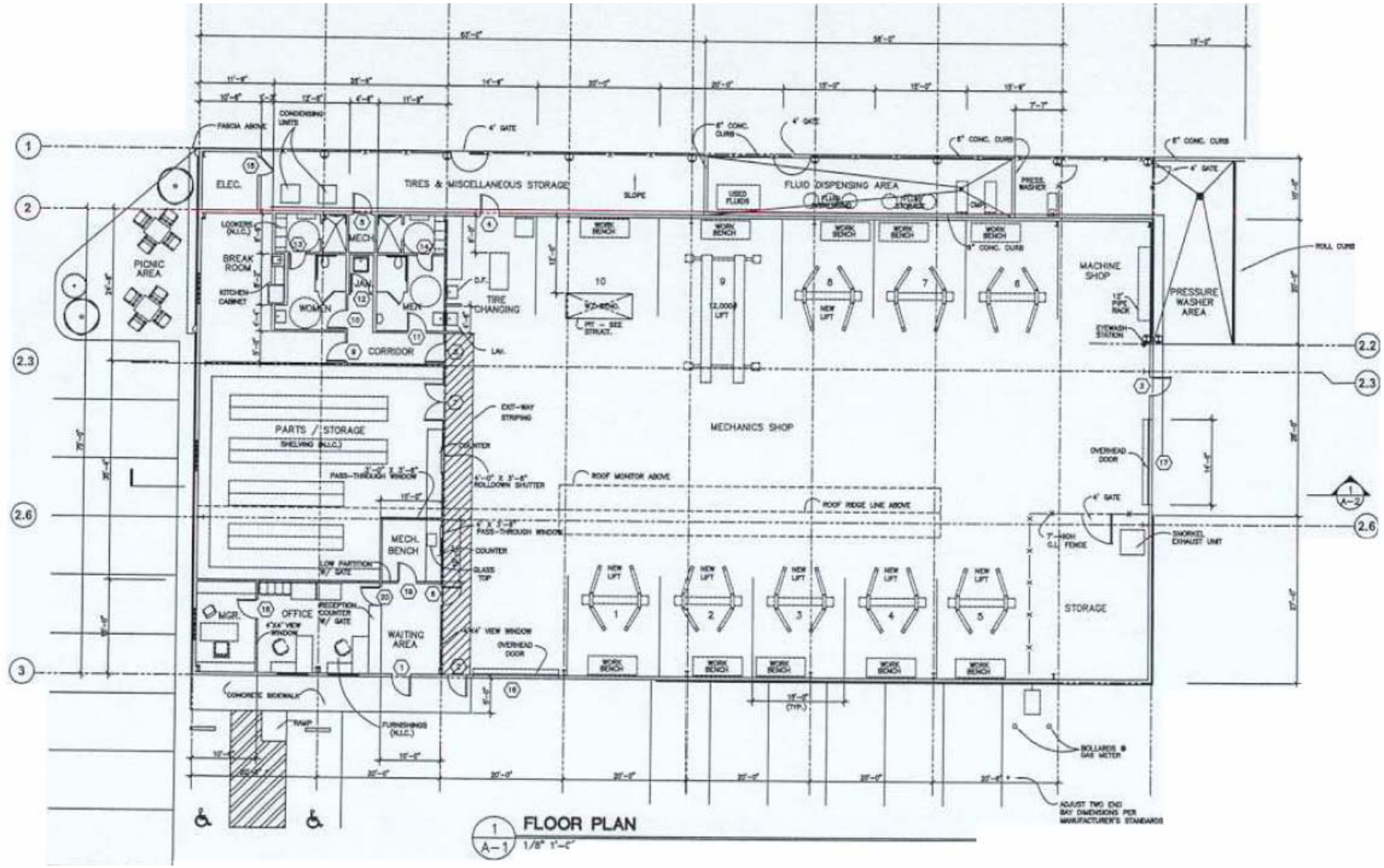


Figure 5.1- Maintenance Facility Layout

5.2 Hydrogen Leak Modeling

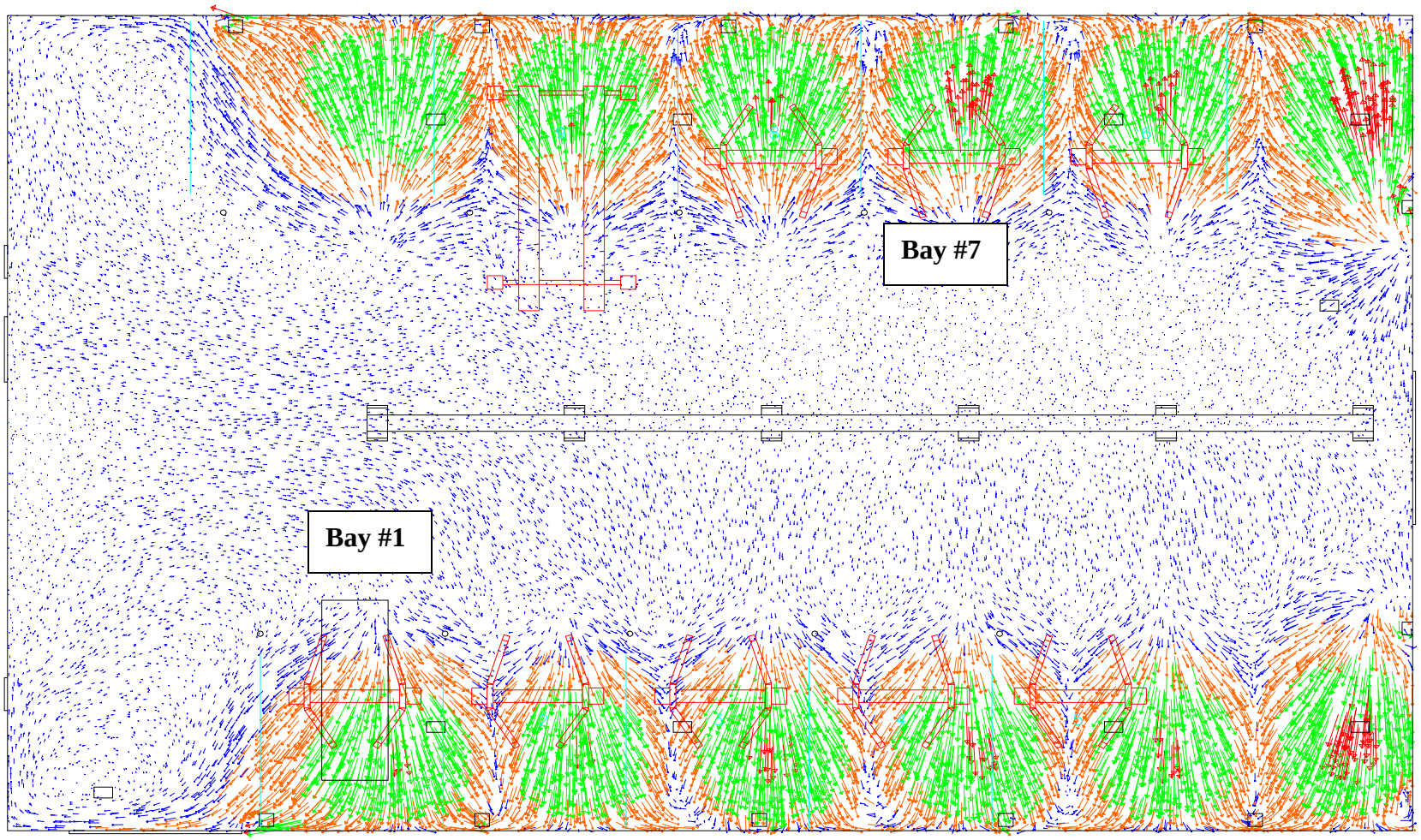
Two scenarios were modeled. The first modeling simulated the scenario of a continuous 20 CFM hydrogen leak from a "vehicle off", or on-board safety system not functioning. Such a modeling was conducted to accommodate the possibility of the on-board safety systems not properly functioning during vehicle maintenance.

A second hydrogen leak scenario was modeled to identify the amount of time it would take for a 0.82% hydrogen concentration to reach approximately 18 inches below the ceiling and to estimate the shape of hydrogen cloud in the facility during that time. This scenario was selected because it mimics CNG facilities practices and therefore, would be easily understood and accepted by fire and building officials.
The parameters for the leak scenarios are shown in Table 5-1.

Table 5-1. CFD Model Scenarios for Maintenance Facility

Model #	Bay #	Vehicle Configuration	Air Flow Speed	On-board Safety System	Leaking Rate
1	1	Wheel wells and lip	2-3 ft/sec	No	20 CFM
2	1 & 7	Wheel wells and lip	2-3 ft/sec 3-4 ft/sec	No	24 and 36 CFM

Prior to conducting hydrogen leak modeling, the study team modeled the airflow resulting from the facility's ventilation system the at one foot above the floor.
Ventilation rates were based on maintenance facility codes as defined in Universal Building Codes (UBC) and standards for human safety and comfort. Results of modeling the airflow at one foot above floor are illustrated in Figure 5.2.



Blue – 0-1 ft/sec Orange – 1-2 ft/sec Green – 2-3 ft/sec Red – 3-4 ft/sec

Figure 5.2– Air Velocity Vector at 1 Foot above Floor – Maintenance Facility

Results of the 20 CFM modeling indicated that the combustible cloud of 4.1% concentration remained mostly under the vehicle and within two feet of the vehicle's surrounding area. Although the shape and pattern of the hydrogen cloud oscillated over time, the steady-state was reached at approximately 250 seconds and was again repeated at approximately 270 seconds. The cloud's shape and pattern oscillated between the shapes at 250 and 270 seconds thereafter (Figure 5.3 and 5.4).

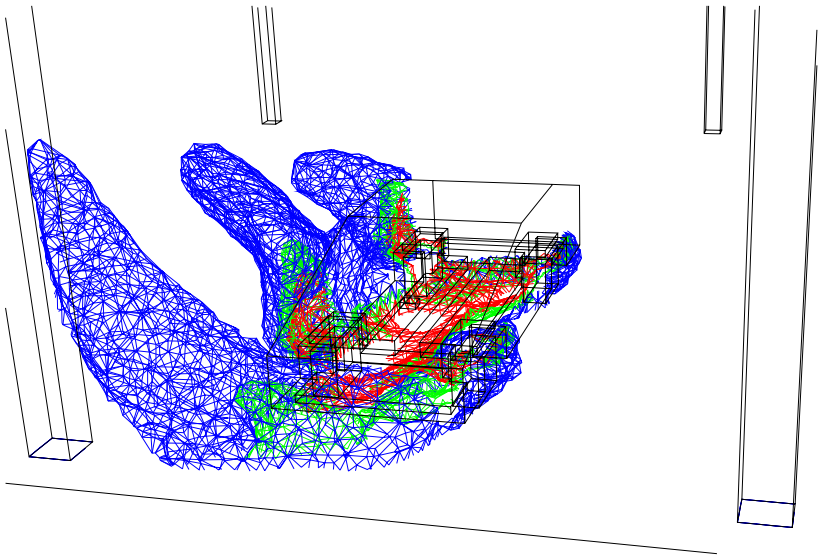


Figure 5.3 - 20 CFM hydrogen leak under vehicle after 250 seconds – Bay #1

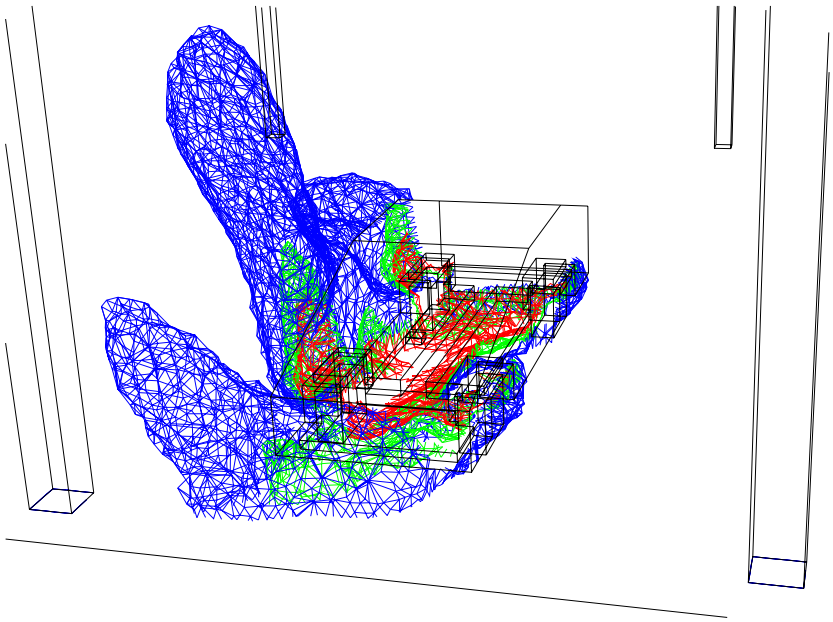


Figure 5.4 - 20 CFM hydrogen leak under vehicle after 270 seconds – Bay #1

The oscillation of the hydrogen cloud could be attributed to the configuration of the facility's mechanical ventilation system. Building codes for conventional and CNG maintenance facilities specify ventilation requirements, which were incorporated into the modeled facility. The ventilation forces air downwards

towards the vehicles and exhausts air close to floor level near the vehicles. As the hydrogen cloud tends to rise quickly and the facility ventilation suppresses such a rise, the hydrogen cloud oscillates unpredictably.

The modeling results indicate the ventilation system has a significant role in shaping the hydrogen cloud. Location of the vehicle also affects the shape of the cloud because the ventilation system air striking the vehicle roof and moving to the sides of the vehicle is impacted by the location of the vehicle

To identify the shape of hydrogen cloud in the facility and the amount of time it would take for a 0.82% hydrogen concentration by volume to reach approximately 18 inches below the ceiling, the study conducted various modeling runs at two bays using two leakage rates of 24 and 36 CFM.

The two bays were selected based on the results of air flow modeling throughout the facility which indicated that of the nine vehicle bays, the two selected bays had different air flow patterns.

The air flow pattern in the first bay (bay #1) caused air under the vehicle to flow toward the front of the vehicle. In the second bay (bay #7) air under the vehicle flowed toward the rear of the vehicle.

The differences in flow patterns produced differences in behavior of the hydrogen cloud (Figure 5.5 through 5.8). The first bay (#1) had oscillations in flow being rather unstable early in time and settling into a more stable pattern than the second bay. The oscillations in flow in the second bay (#7) increased in amplitude with time and, depending on hydrogen leak rate and time elapsed, the 0.82% concentration cloud reached within 18 inches of the ceiling. This occurred at 24 CFM hydrogen leak rate after 6125 seconds – Figure 5.9.

A 36 CFM hydrogen leak in the first bay (#1)produced a 0.82% concentration of hydrogen 18 inches from the ceiling after 200 seconds of leakage – Figure 5.10. The cloud did not reach within 18 inches of the ceiling until after 500 seconds of leakage due to oscillations.

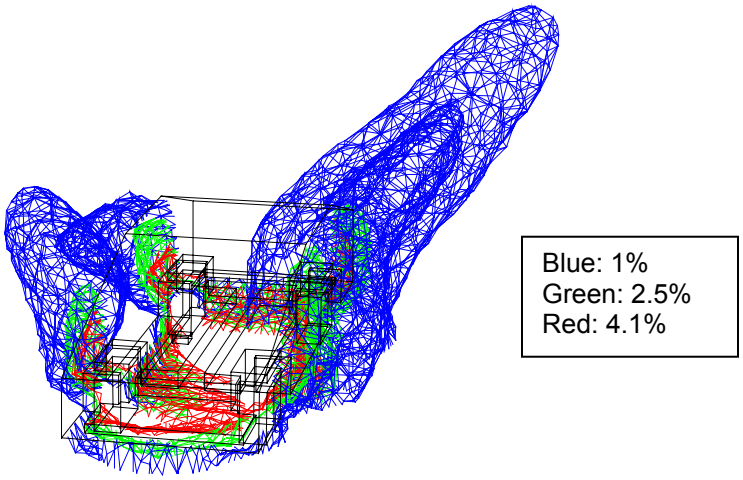


Figure 5.5- 24 CFM leakage, after 925 seconds – Bay #7

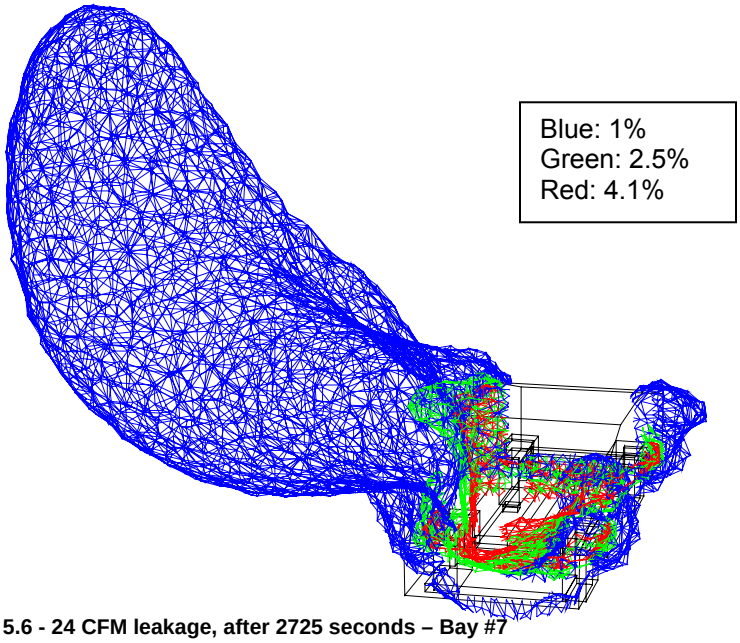


Figure 5.6 - 24 CFM leakage, after 2725 seconds – Bay #7

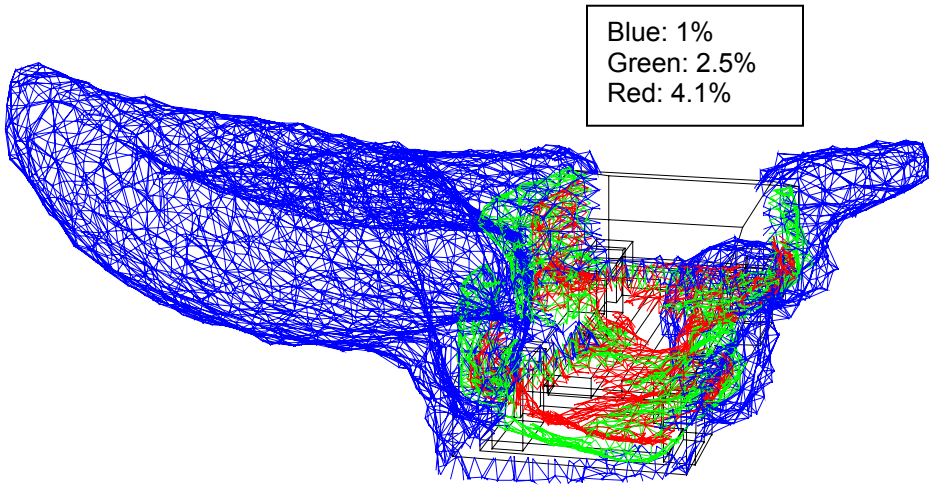


Figure 5.7- 24 CFM leakage, after 4325 seconds – Bay #7

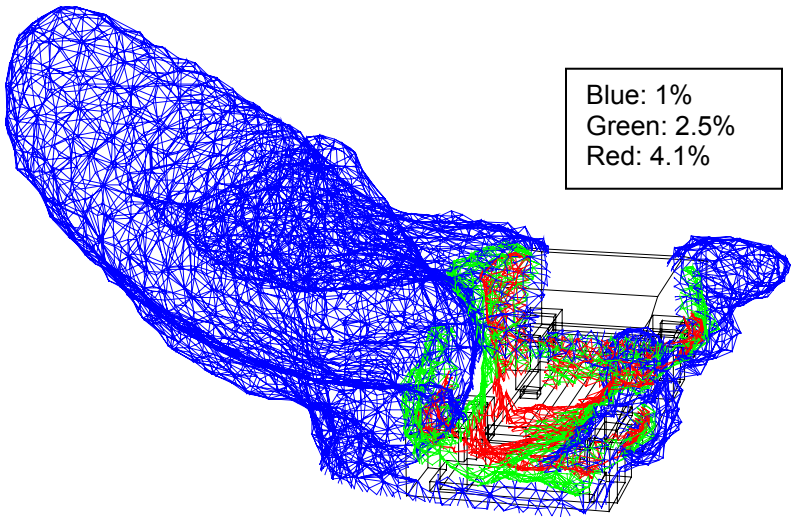


Figure 5.8- 24 CFM leakage, after 6475 seconds – Bay #7

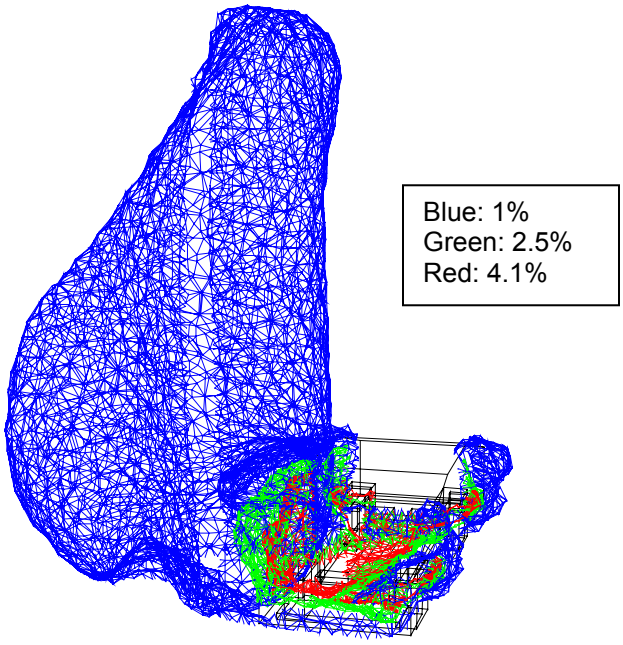


Figure 5.9- 24 CFM leakage, after 6125 seconds, cloud is 18 inches from ceiling – Bay #7

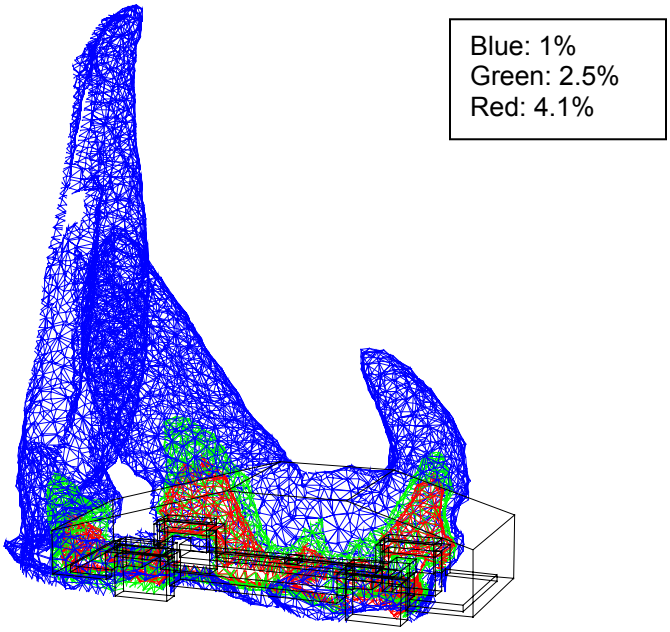


Figure 5.10- 36 CFM leakage, after 200 seconds, cloud 18 inches from the ceiling – Bay #1

5.3 Recommended Modifications

Because modeling results of the assumed scenarios indicated that at no instance did a potentially flammable 4.1% hydrogen concentration existed beyond two feet of the leaking vehicle, the study concludes that no facility modifications are necessary. It should be noted that modeling other scenarios (i.e. different facilities, vehicles, leaking rates, etc.) might have resulted in different conclusions. Without conducting such additional modeling, the study cannot conclusively determine what modifications, if any, are necessary. Because of scope limitations (discussed in Section 2), the study did not conduct additional modeling.

The modeling results for the maintenance facility indicated that the hydrogen cloud behaved in an unstable manner. It oscillated unpredictably based on the air movement in the facility and the location of the leaking vehicle. Such instability makes it difficult to predict the likelihood of the cloud's behavior under different circumstances and to determine an effective method of detecting/mitigating the hydrogen cloud.

The study identifies, for cost/benefit analysis purposes only, potential HFCV facility modifications that are perceived to be effective. Two transit agencies, Chicago Transit and SunLine, have implemented variations of such modifications at their hydrogen fuel cell bus maintenance facilities. Such modifications have been largely based on CNG industry practices in facility modifications for natural gas vehicles. CNG industry practice includes installing natural gas detectors 18 inches below the ceiling. The detectors initiate an audible alarm and increase ventilation rates upon detection of 20% low-flammability-limits (LFL) of natural gas. Upon detection of 80% LFL, the detectors cause the electric power to be disconnected from non-essential devices, and depending on the facility configuration, cause some doors to open and/or close. In case of natural gas explosions, facility doors are designed to blow to the outside rather than to contain the explosion. Other potential modifications that are used in natural gas and hydrogen fuel cell bus maintenance facilities include isolating the buses' bays with physical barriers (walls and doors), installing collecting hoods over the bus to collect and vent leaking hydrogen. The effectiveness of such potential modifications could not be substantiated by examining the CFD modeling results in our case.

The CFD modeling results indicated that such modifications are not necessary and/or effective in the cases modeled by this study. In the case of installing hydrogen detectors at 18 inches below the ceiling, for example, CFD modeling results indicated that depending on the location of the vehicle, the 0.82% hydrogen cloud (20% of hydrogen LFL) may not reach 18 inches below the ceiling. In addition, when the 0.82% hydrogen reached 18 inches below the ceiling, the potentially combustible hydrogen cloud (4.1%) remained within 1 foot of the vehicle. Increasing the building ventilation rate would not improve safety substantially as the 4.1% hydrogen cloud was predicted to remain within 1 foot of the vehicle.

Because the hydrogen leak modeling results form the basis of our recommendation that no facility modifications were necessary, the benefit of the optional modifications that have been previously practiced could be viewed as negligible. Cost estimates for designing and implementing such optional modifications at the modeled facility are summarized in Table 5.2. Since potential modifications vary in detail from one facility to another, the summary table in Table 5.2 assigns a weight factor for all categories including cost.

Item # 8 in Table 5.2 "Add a hood over the entire vehicle to collect hydrogen as it rises", for example, has a weight factor of 2 (out of 10) for effectiveness. This indicates that installing a hood over the entire vehicle would be effective modification because leaking hydrogen would be collected in the hood rather than escape to the ceiling. Because designing and installing a hood over the vehicle is not considered too cumbersome, a weight factor of 4 (out of 10) was assigned to "Ease of Implementation" category.

Similarly, cost of installing a hood over the vehicle was assigned a weight factor of 4 (out of 10) which indicates relatively low to moderate cost.

Installing a hood over the vehicle, however, introduces challenges that designers must address. Some of these challenges include the height of the hood to accommodate vehicles on lifts. In addition, if the designated bay is designed to accommodate gasoline vehicles, installing a hood over the vehicle could hinder the typical ventilation system's ability to move air downwards, which would violate gasoline vehicle building codes. In such a case, this bay must be designated as hydrogen vehicles only. In busy maintenance facilities settings, designating bays for specific vehicles would reduce the efficiency of the facility thus increase cost of maintenance. Another challenge of installing a hood over the vehicle is the potential of collecting hydrogen inside the hood to an explosive limit because the hood would act as a collecting point of leaking hydrogen.

Table 5.2 Summary of Effectiveness, Feasibility, and Cost Estimates for Modifying Maintenance Facilities

	Hydrogen Mitigation Options							
	1 - Least cost / Most Practical							
	10 - Most Cost / Least Practical	Effectiveness		Ease of Implementation		Cost (Weight value)		
	Although not categorized, all options include installation of hydrogen sensors, fire detectors, and mitigation mechanism	New Facility	Existing Facility	New Facility	Existing Facility	New Facility	Existing Facility	Notes
1	- Consider that no action may be required since the 4.1% concentration is contained under the vehicle.	3	2	1	1	1	1	
2	- Change the supply air direction to move air down in the center of the building & out along the floor toward the wall, instead of out and down the wall.	4	4	2	3	2	3	
3	- Increase the number of low level exhaust inlets such that there is an inlet between each vehicle maintenance bay, or possibly directly in front of each bay.	3	5	3	5	3	5	
4	- Move the low level exhaust intakes to a position near the interior of the building.	5	5	6	8	7	9	
5	- Add local exhaust beneath the vehicle with a flexible duct attached to one of the low level exhaust ducts.	4	4	2	3	2	3	Install in sleeve extending up exhaust duct. Most effective in combination with additional exhaust drops and redirected supply air
6	- Increase the total supply and exhaust volume to inhibit upward movement of hydrogen.	3	3	3	4	4	5	
7	- Improve the downward distribution of supply air to provide more uniform downward flow to inhibit the upward movement of hydrogen.	3	3	5	5	6	6	
8	- Add a hood over the entire vehicle to collect hydrogen as it rises.	2	2	4	4	4	4	Need to accommodate vehicle on lift. Need accommodate low level exhaust for gasoline. Could produce an explosive hdyrogen mix
9	- Add a curtain containment around the bay for hydrogen vehicle maintenance, similar to warehouse strip doors.	2	2	2	2	3	3	Could produce an explosive hdyrogen mix
10	- Add a fan or duct discharge to diffuse and direct the hydrogen cloud.	2	2	4	5	4	5	

6. Cost Benefit Analysis

The building modifications recommended in this study were based on vehicle performance parameters defined in Section 2. Modeling was conducted to assess the effect of a 20 CFM hydrogen leaking rate assuming that working hydrogen sensors were located in the wheel wells. In some scenarios the performance of a functioning hydrogen detector was required to eliminate a hazardous situation while in other scenarios the building's ventilation system eliminated the hazard form the leak.

Vehicle designers need to consider the HFCV and its support as a system, understanding that trade-offs between safety systems on the vehicle influence the cost and necessary safety modifications for buildings. This section provides information on the modifications that may be undertaken to improve the safety of buildings. Additional information on the modeling of the residential garage is also discussed because CFD modeling showed that a flammable hydrogen mixture could reach an ignition source in the garage if the vehicle is not equipped with safety systems that would detect and shut down a leak discussed in Section 4.

This section focuses on a qualitative identification of the economic and logistical impacts of potential facility modifications. The effectiveness of such modifications has not been verified.

Potential Hydrogen Releases

Hydrogen can leak into a facility from a vehicle because of failures in the vehicle safety system. The hydrogen leak rate is related to the severity of the system's failures. Under certain circumstances, as the leaking rate increases, the time required to form an ignitable hydrogen mixture in the facility decreases.

In addition, as the leaking rate increases, so does the ignitable hydrogen mixture concentration and energy content. Vehicle and facility designers need to take into account the potential consequences of a leak, (not analyzed here other than presenting the leak rate which reflects energy release)

In estimating the potential hazard, the study identified the likelihood of leaking scenarios and the amount of energy that could be released in each scenario.

Figure 6.1 illustrates safety events with a qualitative estimate of the likelihood of occurrence for various events (scenarios), hydrogen release rates and potential energy released for each event.

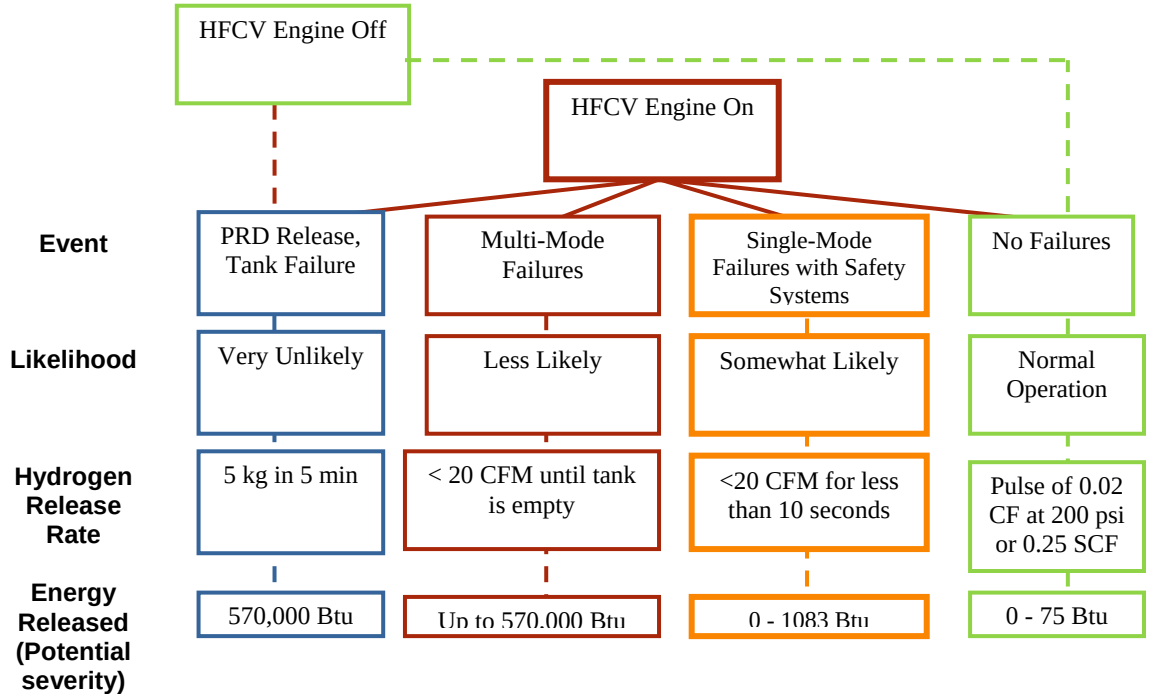


Figure 6.1 – HFCV Failure Modes Likelihood and Associated Risk

Several events are illustrated under two conditions; Vehicle Off and Vehicle On. Because the hydrogen is isolated in the fuel tank when the vehicle is off, the only likelihood of any hydrogen leak is through the pressure relief device (PRD) and/or through a rupture of the hydrogen tank. This study considered the release of either the PRD and/or fuel tank failure very unlikely. Because the hydrogen release rate would be very high (5 kg in less than 5 minutes) the risk associated with such release/failure is also considered very high.

When the vehicle is on (on-board vehicle safety systems functioning properly), the study considered a multi-mode failure (a hydrogen leak and one or more other failure such as on-board safety system) with up to 20 CFM leaking rate until the tank was empty as unlikely. Such a scenario could result in up to 570,000 BTU of energy release (red).

The study considered single-mode failure (only hydrogen leak) when vehicle is on (on-board safety systems functioning properly) as somewhat likely. Under this scenario, a 20 CFM leak would most likely be detected by the vehicle's safety system which would isolate the hydrogen in the tank in less than 10 seconds. Therefore, the maximum amount of released energy would be 1,083 BTU.

Under normal operation (no failures), upon vehicle shut down, the shut-off valve would isolate the hydrogen in the tank and the remaining hydrogen in the system (downstream from the shut-of valve) would normally be vented to the atmosphere. Such a small amount of hydrogen could contain up to 75 BTU, and poses no significant risk (green).

Residential Garage

No modifications were recommended for the scenarios modeled in this study for the residential garage because modeling results indicated that the hydrogen plume would reach the wheel wells in a short time where detectors could shut off the flow of hydrogen. However, hydrogen detectors may not be available on all vehicles if available they may not always be in working order.

Commercially available vehicles will operate in severe environments where hydrogen sensors may not be practical. In addition, the ability of the customer to perform ongoing maintenance of these sensors has not been determined.

When on-board safety systems were not considered, Modeling results of continuous 5, 15, and 20 CFM leaks indicated that the ignitable hydrogen mixture was formed at the ceiling of the garage in approximately 1740, 745, and 545 seconds respectively. Figure 6.2 illustrates the time required to form a 5% concentration cloud at the ceiling of the garage (The reason we picked the parameter of 5% hydrogen at the garage's center ceiling point is to ensure the presence of 4.1% hydrogen concentration between the leaking vehicle and the ceiling of the garage). Also shown is the time for a 1% plume to reach the ceiling. The corresponding amount of energy in the hydrogen for the total release up until the leak reaches a 5 percent concentration is shown on the right side of the axis. Up to 0.5 kg of hydrogen, which would release 60,000 Btu if ignited in a air mixture, is released.

The assessment of the plume formation in the garage provides engineers useful information in providing the targets needed to design the vehicle in a safe manner. The vehicle can be designed to minimize to the greatest extent possible any risks from leaks and support recommendations that would result in minimal or no facility modifications

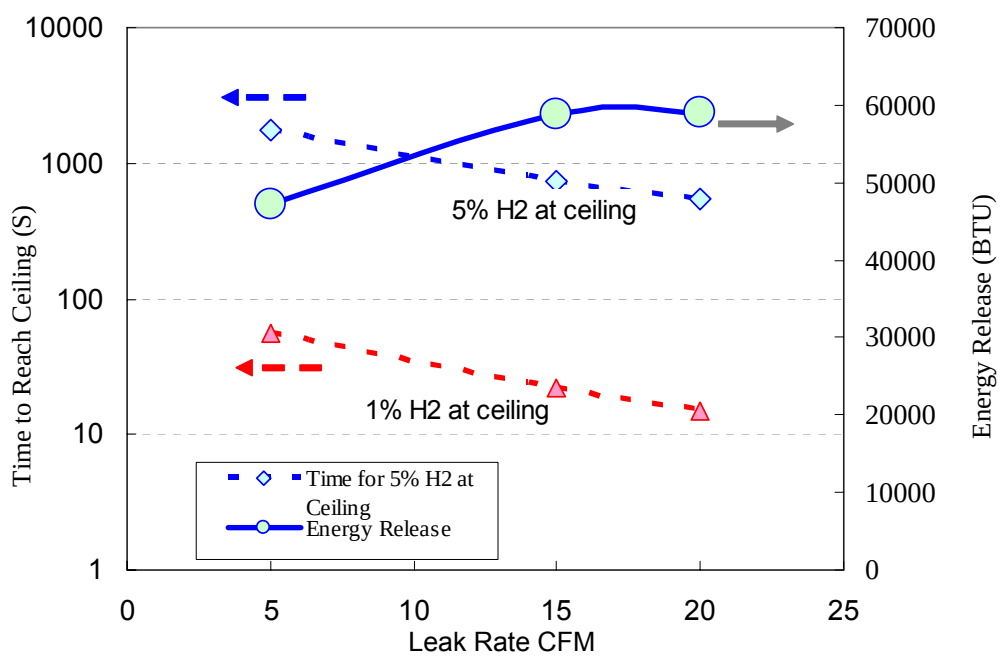


Figure 6.2 - Time required for hydrogen plume to reach garage ceiling – Residential garage modeling results

Facility modifications are based on early detection and fast mitigation of leaking hydrogen and the reduction or elimination of ignition sources. The objective of such modifications is to reduce the perceived hazard associated with potentially combustible hydrogen.

Ideally, facility modifications should prevent hydrogen concentration in the facility from reaching the ignitable limit. However, verifying the effectiveness to prevent ignitable hydrogen ignitable mixtures from forming of each of the facility modification discussed here requires extensive additional modeling.

For the purpose of the cost/benefit analysis, Figure 34 illustrates potential modifications that may be able to prevent and/or delay the ignitable mixture from forming in the garage regardless of the leak rates and/or scenarios. The estimated cost/benefit analysis could be used as guidance to understand the relationship between investing in facility modifications and the potential advantages/disadvantages that may be realized. For example, to reduce the possibility of forming an ignitable mixture in the garage through increased air ventilation, installing an active fan, with inlet and outlet wall openings, that operates upon hydrogen detector activation or garage door closure is about $3,400 ($2,500 for detector, $600 for inlet and outlet wall openings, and $300 for fan). The potential benefit of such a modification is to increase the time required to form an ignitable hydrogen mixture in the garage. In addition to the capital cost of $3,400, the disadvantages (or cost) include preventative maintenance of the detectors and the loss of heat in the garage. This modification's effectiveness depends on the hydrogen leaking scenario (i.e. leaking rate, location of leak, temperature inside the garage) and the fan's ability to maintain the hydrogen concentration below the ignitable limit which could not be quantified without additional modeling.

However, since the potential for a modification to prevent the formation of an ignitable hydrogen cloud is somewhat limited, the residential customer may find limited value or benefits from such modifications. Not operating the vehicle in the garage may also be an appropriate safety measure.

In addition, the study's scope did not include investigating the feasibility, reliability, or availability of such on-board systems and technologies. Due to economics of scale, and the desirable feature for vehicles to park in any residential garage, it may be cost effective to develop vehicle safety systems or control procedures rather than rely on the residential garage modifications identified here. Further investigation will be needed as vehicles move closer to commercially viable designs.

Table 6.1 Residential Garage – Vehicle Safety Options

Vehicle Safety Systems	Cost	Other Benefits
Detect hydrogen leak on vehicle before flammable mixture can reach ceiling	Cost of sensor and wiring. Sensor maintenance, calibration and troubleshooting false alarms.	None
Limit hydrogen release on stopped vehicle	Control logic could be programmed on the vehicle to shut down fuel.	None
Summary: Vehicle safety options would most likely reduce the risk associated with a failure on the vehicle resulting in reduced or elimination of facility modification requirements. The cost can range from no hardware costs to installing and maintaining sensors on the vehicle.		

Examples of such potential facility modifications along with their cost estimates are illustrated in Table 6-2. Although the effectiveness of facility modifications to mitigate a 5% hydrogen concentration scenarios could not be verified without additional modeling, the study recommends that any potential facility modifications should focus on early detection and timely mitigation of leaking hydrogen sources so that

the concentration would not reach combustible limits. Benefits other than hydrogen detection of these options are presented in Table 6.3.

Table 6.2 Cost estimates of residential garage modification

Modification	Facility	Design Cost* Estimate	Construction Cost* Estimate	Annual Operation Cost
Install hydrogen detectors in center of ceiling. Sounds alarm only	New	Less than $100	$2,500	$1,000
	Existing			
Install hydrogen detectors in center of ceiling. Integrate with facility's safety system.	New		$2,800 assuming safety system exists	$2,000
	Existing			
Install Wall Openings	New	Less than $100	$300 per opening	Less than $100
	Existing			
Install active fans and vents	New	Less than $300	$500 per fan/vent	Less than $300
	Existing			

* Design and construction cost assumes electrical power connections to detectors.

Material cost estimate is based on average cost of material as published by several manufacturers or distributors catalogs including the Internet. Labor cost estimate is based on average wage rate, as published by the United State Department of Labor, and prevailing margin of 150% for personnel used in the installation and an engineering estimate for the number of hours needed to perform the work.

Table 6.3. Cost and Qualitative Benefits of Residential Garage Modifications

Facility Modifications	**Cost Estimate**	**Other Benefits**
H2 detector	$2500 to $5000 per detector. Sensor maintenance, calibration (depending on sensor technology), and potential for false alarms	None
Openings in wall, garage door	$600 for inlet and outlet in wall, or $200 for garage door modifications. Heat loss in cold climates.	None
Move lights and garage door opener away from center of garage	For new construction, $200 for side mounted garage door opener. $200 for additional lighting on side of garage. Side mounted garage door opener worm drive will be less durable.	None
Passive ceiling fan for single story garage with no bedroom overhead.	$300 for fan and roof installation	Reduces heat build up on hot days. Reduces potential for condensation in winter.
Wall openings with active fan, garage door or sensor	$600 for inlet and outlet plus, $300 for fan, $2500 for sensor. Fan could	Ventilation could be integrated with house and

activated	also be activated by garage door opener. Power consumption will not be large because fan runs intermittently. Loss of heat in garage.	attic fans for summer cooling.
Wall openings with continuous ventilation	$600 for inlet and outlet plus, $300 for fan. Power consumption and noise from fan. Circulates cold air into garage in winter.	None
Sprinkler system, fire sensor activated	Construction cost: $1000 Fire sensor maintenance	Protects against other types of fires in garage.
Summary: Several measures could provide modest safety benefits for a home garage. These safety measures could help detect a hydrogen leak or remove hydrogen from the garage.		

* Design and construction cost assumes electrical power connections to detectors.

Material cost estimate is based on average cost of material as published by several manufacturers or distributors catalogs including the Internet. Labor cost estimate is based on average wage rate, as published by the United State Department of Labor, and prevailing margin of 150% for personnel used in the installation and an engineering estimate for the number of hours needed to perform the work.

Public Parking

Results indicate that no facility modifications are required for public parking facilities under the 20 CFM leak rate with or without the on-board safety systems. Existing ventilation, required for CO removal and human comfort in below-ground garages, and natural ventilation in above-ground garages, appears to eliminate hazards associated with most hydrogen leak scenarios.

Facility modifications did not appear to be necessary for most leak scenarios. Nevertheless, other leak scenarios or air circulation patterns could result in the presence of a flammable mixture. Table 6.4 illustrates the benefits of additional modifications to the facility.

Table 6.4. Cost/benefit Analysis - Parking Facility Modifications

Facility Modifications	Cost Estimate	Other Benefits
H2 detector	$2500 to $5000 per detector. Sensor maintenance, calibration (depending on sensor technology), and potential for false alarms	None
Fire detector	$2500 to $5000 per detector Detector maintenance	Protects against other building fires
Summary: Several additional measures could provide modest safety benefits, which will have costs associated with them. Existing air circulation already reduces the risk from hydrogen leaks (20 cfm).		

* Design and construction cost assumes electrical power connections to detectors.

Material cost estimate is based on average cost of material as published by several manufacturers or distributors catalogs including the Internet. Labor cost estimate is based on average wage rate, as published by the United State Department of Labor, and prevailing margin of 150% for personnel used in the installation and an engineering estimate for the number of hours needed to perform the work.

Commercial maintenance/repair/service station:

Code guidance for conventional and gaseous-fueled (CNG) vehicle maintenance facilities results in higher level of safety in these facilities.

For gaseous fuel facilities, the risk of flammable gas mixtures is typically reduced with sensor activated ventilation. In addition, when a leaking HFCV was modeled in these facilities, the typical high ventilation rates in maintenance facilities intended for human comfort and for reducing the possibilities of forming toxic and/or ignitable gases (other than hydrogen) reduced the possibilities of forming an ignitable hydrogen mixture. Therefore, the effectiveness of additional modifications, other than the ones specified for conventional and CNG vehicles, to accommodate HFCV is limited because of the high degree of safety that has been established. Similar to CNG facility code guidance, installing hydrogen detectors that would increase the ventilation rate in the facility upon detection of hydrogen might provide additional safety measures. The hydrogen detectors could be installed next to the natural gas detectors approximately 18 inches below the ceiling and should be calibrated to detect 0.82% (20% of hydrogen 4.1% low flammability limit).

Table 6.5 illustrates the cost of potential additional safety modifications that may be implemented at maintenance facilities. The qualitative benefits to the building operator are also indicated.

Table 6.5 – Cost/benefit analysis – Maintenance Facility Potential Modifications

Facility Modifications	Cost Estimate	Other Benefits
H2 detector with sensor activated ventilation	$2500 to $5000 per detector. Detector maintenance	None
Fire detector	$2500 to $5000 per detector Detector maintenance	Protects against other building fires
Passive ventilation	Depends on building configuration. No operating cost.	Possible air circulation benefits.
Isolate HFCV Bays	Up to $5,000 per bay Bay cannot be used by other than HFCV	None
Install hood over HFCV	$10,000 $5,000 for detector inside hood detector maintenance	None
Summary: Hydrogen and fire detectors can provide added safety for a maintenance facility.		

* Design and construction cost assumes electrical power connections to detectors.

Material cost estimate is based on average cost of material as published by several manufacturers or distributors catalogs including the Internet. Labor cost estimate is based on average wage rate, as published by the United State Department of Labor, and prevailing margin of 150% for personnel used in the installation and an engineering estimate for the number of hours needed to perform the work.

7. Codes and Standards

7.1 Introduction

In this section of the study, several current codes governing the design and construction of facilities are discussed in terms of their relevance to hydrogen vehicles and facilities. In addition, the hydrogen specific codes and standards for facilities that have been recently adopted by the International Code Council (ICC) are also discussed and analyzed in terms of their impact on the design and construction of hydrogen fuel cell vehicles and facilities as well as their impact on the outcome of this study.

Prior to the ICC adoption of hydrogen codes and standards in March 2003 (codes were officially adopted in December, 2002, but the final language was issued in March, 2003) facilities codes and standards did not explicitly cover the requirements for hydrogen vehicles in applications such as parking, fueling, and maintenance. Instead, references for vehicles were written for conventional transportation fuels like gasoline and diesel, and alternative fuels like natural gas and propane.

The purpose of the fuel-related codes is to create standards that ensure a safe environment that avoids flammable or explosive mixtures and ignition sources. Although there were no code documents specifically tailored for hydrogen vehicles and their applications prior to the ICC guidance, it has been assumed that future references would follow existing codes and would adapt them for hydrogen vehicle technologies. One example of such an adaptation process is the development of the ICC code document.

Section 7.2 of this report analyzes the current codes standards stet to determine which issues are relevant to the study of parking and maintenance facilities. Section 7.2.1 reviews issues related to classification of locations with gas containers or leak potential. In Section 7.2.2, codes that are specific to particular locations are discussed in terms of their applicability to hydrogen vehicles. Section 7.3 summarizes the discussion of Section 7.2 and concludes that current parking structures and maintenance facilities may have shortcomings in some areas when used for hydrogen fuel vehicles. In most areas, however, overcoming these shortcomings would require only minor modifications and cost increases beyond the norm for conventional or natural gas vehicles.

Section 7.4 presents a discussion and analysis of the recently adopted ICC codes and standards that have introduced hydrogen-specific regulations for building designs and construction. The subsections are organized according to the ICC areas of coverage. Section 7.4.1 covers the ICC adopted codes in the area of buildings; Section 7.4.2 discusses the fire code of the ICC; Section 7.4.3 discusses the fuel area; Section 7.4.4 includes discussion of the mechanical area; and Section 7.4.5 discusses the residential area of the codes. Other ICC subject areas such as electrical, plumbing, performance, urban wild life, and others did not include any hydrogen references and were not discussed in the study.

The new ICC codes provide a good framework to address most of the shortcomings in the older codes as they may apply in the hydrogen area, including hydrogen utilization in vehicles. However, the ICC codes do not address some areas of hydrogen application, especially the ones covered in this study; i.e. commercial and residential parking facilities. In addition, the ICC code coverage of maintenance facilities does not provide detailed design instructions, and leaves a wide range of interpretation to the designer and/or local enforcing jurisdiction. Such incompleteness in the ICC code is not unexpected because a good understanding of hydrogen applications lags behind other fuels.

The hydrogen-specific language that has been added to the ICC codes can be considered a major victory for the hydrogen industry, because the new codes recognize hydrogen as a commercial vehicle fuel. The

fact that the ICC adopted standards to regulate the design and construction of such fuel utilization is a testimony to hydrogen market penetration. It is expected that the ICC hydrogen-specific codes will be further refined as more experience is gained with hydrogen as fuel. Eventually, a complete design and construction document will result, which will provide guidance in a similar manner to the NFPA.

This study provides significant data and information that should be utilized during the next round of ICC code modifications. Further study may be appropriate to include additional ICC areas of focus; i.e. fueling and de-fueling of vehicles in facilities.

7.2 Prior to ICC hydrogen Guidance Code Requirements

In general, relevant codes and standards are either specific to an application or specific to a combination of a fuel and application. Because the National Fire Protection Association (NFPA) has had the most extensive codes that could be applicable to hydrogen fuel vehicles in parking and maintenance facilities prior to ICC hydrogen guidance, the standards studied in this analysis are mainly NFPA codes and are summarized in Table 7-1.

Table 7-1 - NFPA standards with applicability to hydrogen fuel vehicle parking and maintenance facilities, organized by fuel and application.

Focus	Code	Fuel	Application
Building use	**NFPA 30A**	Flammable and combustible liquids	Automotive Service Station (Maintenance and Dispensing Facilities)
	NFPA 88A	Unspecified but includes CNG and LNG vehicles	Parking Structures (not including one or two-family dwellings)
	NFPA 88B	Unspecified except special provisions for CNG or LNG vehicles	Repair Garages
	NFPA 497	Various	Classification of hazardous locations
Fuel	**NFPA 50A**	Hydrogen	Bulk Hydrogen at Dispensing Facilities
	NFPA 70, Section 625 (NEC 625-30)	Hydrogen	Open Parking Site or Structure
	NFPA 52	Natural Gas	Dispensing Facilities (including home garages)
Fuel and Building Use	**NFPA 70, Section 625 (NEC 625)**	Flooded Battery EV (hydrogen while charging)	Home garages

Using existing codes and standards as a basis, as well as results from other studies, state or local governments will undoubtedly enact additional regulations that impact how hydrogen fuel vehicles and facilities are designed and used.

The construction and/or operation of facilities for vehicle parking and servicing are governed by fuel- and facility-specific codes. The codes specify various requirements including placement and type of equipment, ventilation, and obligations for sensors and alarms, as shown in Table 7-2. For example, for one type of fuel application, a sensor based on gas detection may be required to activate an alarm. However, in another application, no sensor or alarm may be required. It is important to determine which elements are required for hydrogen in parking and servicing applications in order to understand the potential costs of construction and operation.

In the following sections, these requirements are analyzed to determine their relationships to hydrogen in parking and maintenance facilities. Once it is known what type of restrictions and obligations may exist for hydrogen technology, changes from standard building procedures can be determined.

Table 7-2 - Potential fuel-related restrictions that may be found in codes

Location/Type of Equipment	Electrical/Heating Classification	Ventilation	Sensors and Alarms

▪ Location of vehicles/proximity to equipment[a]
▪ Total volume of fuel stored
▪ Existence of valves, flanges, other connectors that could leak
	▪ Classification of locations
	  ▪ Potential leak sources
	  ▪ Ceiling area
	▪ Open flame heaters
	▪ Electrical equipment
	▪ Lighting
		▪ Mechanical continuous
		▪ Non-mechanical continuous (open structures, windows, louvers)
		▪ Sensor activated
		▪ No restriction (no ventilation required)
			▪ Sensor based on gas detection, activates ventilation
			▪ Alarm based on gas detection
			▪ Sensor based on gas detection activates alarm and visible indication of gas levels
			▪ Other alarm strategies
			▪ No restriction (no sensors or alarms required)

[a] Potential ignition sources, ventilation, entryways.

This methodology has been successfully used for determining requirements for CNG fueling facilities prior to enactment of many of the current codes and standards.

For example, the Los Angeles County Metropolitan Transportation Authority (MTA) commissioned several studies in the early 1990s to determine the maintenance facility modifications required for CNG buses. Existing codes were examined, experiences and safety studies from other facilities were gathered and analyzed, and engineering rationale was applied to address issues not covered by existing codes and

standards[3]. Another study examined the potential hazards associated with CNG buses for the Toronto Transit Commission (TTC)[4]. A scale model of a TTC garage and buses was used to determine the types of leaks and resulting gas concentrations. It was determined that leaks either were small and resulted in concentrations lower than the lower explosion limit, or that they were so catastrophic that building ventilation was irrelevant. Another reference is the 1991 Natural Gas Vehicle (NGV) Safety Regulation Seminar Proceedings from a meeting in Toronto, Ontario[5]. In a presentation, P.G.M.P Verstegen of the Netherlands found that CNG cylinder safety relief valves on buses functioned properly in a maintenance facility fire. They concluded that there was no greater fire danger for CNG than for diesel buses. The information obtained from these and other studies, in addition to a survey of practices at existing CNG bus facilities, helped to determine which of the types of issues in Table 7-2 were relevant for the LA MTA maintenance facility.

The rationale for the resulting CNG facility configuration was a combination of issues shown in Table 7-3. Any evaluation of a facility requires a good understanding of the use of the facility itself, the equipment that is used inside it, and the potential requirements to be analyzed.

Table 7-3 - Issues evaluated for CNG maintenance facilities to determine design

Issue	Details
Architectural/Structural	Code compliance for construction, design loads
Mechanical	Ventilation, ignition sources and applicable restrictions
Electrical	NEC classification (Class, Group, Division), ventilation, stand-by power requirements

7.2.1 Classification of locations containing gases

The National Fire Protection Association (NFPA) Code 497, along with references from standards NFPA 30A and 70, describes the classification and safeguards for gases. Table 7-4 describes the codes that help to determine how to classify parking structures and maintenance facilities suitable for hydrogen vehicles based on codes for classifying hazardous locations.

[3] Stone & Webster Engineering Corporation. *Maintenance Facilities Modifications to Accommodate CNG Buses: Task 10 Final Report*. Prepared for the Los Angeles County Metropolitan Transportation Authority. March, 1994.
[4] Hatch Associates. *Site Assessment of NGV Bus Operations at the TTC Wilson Garage*. AT-92-02, prepared for the Vehicle Technology Office, Ministry of Transportation of Ontario. March, 1993.
[5] Ortech International. *NGV Safety Regulation Seminar Proceedings*. Sponsored by Energy, Mines, and Resources Canada, Toronto, Ontario, Canada. June 1991.

Table 7-4 - Codes governing ignitable gases and their locations

Code	Description	Relevance to parking structures and maintenance facilities
NFPA 497	Recommended practices for electrical installations in locations considered hazardous due to a combustible gas or vapor.	Hydrogen is a combustible gas.
Article 500 of NFPA 70 (NFPA 497A 2-1)	Defines classified and non-classified locations. Classified locations are those in which a combustible material may be present in sufficient concentrations to produce an ignitable mixture.	Locations with hydrogen equipment should be investigated to determine classification or non-classification.
Article 500 of NFPA 70 (NFPA 497A 2-1.3)	Recognizes degrees of hazards within classified locations. Division 1 is concerned with locations in which ignitable mixtures are likely to be in continuous presence. A location that would have an ignitable mixture only in abnormal conditions is considered Division 2.	The facilities under consideration for hydrogen vehicle parking and maintenance could be considered Division 2 since hydrogen would only be released due to a leak or accident.
NFPA 497A 2-2.1	Defines conditions necessary for ignition: a combustible gas or vapor must be present, there must be a sufficient quantity of an ignitable mixture created by gas mixed with air in proper proportions, and there must be release of energy intense enough to cause ignition to occur	Definitions may help to determine if parking structures and maintenance facilities have conditions necessary for ignition.
NFPA 497A 2-3.1	States that lighter-than-air gases tend to dissipate rapidly. Except in enclosed spaces, they seldom accumulate to form ignitable mixtures near grade level, where most electrical installations are located.	In an open parking structure, slow leaking hydrogen is not likely to form ignitable mixtures near ignition sources; in an enclosed parking garage or maintenance facility, a mixture is more likely to ignite if it accumulates near electrical installations.
NFPA 497A 2-6.1(a)	Defines non classified locations: release of ignitable mixtures is so infrequent that classification is unnecessary. The code states that “locations that are adequately ventilated, where combustible materials are contained within suitable, well-maintained, closed piping systems” are usually not classified.	Parking structures and maintenance facilities for hydrogen vehicles may be considered non-classified locations if they have adequate ventilation.
NFPA 30 (NFPA 497A 2-6.2)	Adequate ventilation is defined as “that which is sufficient to prevent accumulation of significant quantities of vapor-air mixtures in concentrations over 25 percent of the lower flammable limit.”	Determines that ventilation of this type may avoid classification of parking structures and maintenance facilities.

An analysis of these codes shows that open parking structures, due to high ventilation, are unlikely to harbor sufficient quantities of ignitable mixtures near ignition sources in the event of a minor leak. As a result, they probably should not be considered "classified locations" and therefore would not require any special installations designed for classified locations. Enclosed parking garages and maintenance facilities are more likely to accumulate ignitable mixtures if not ventilated enough to avoid a 25 percent lower explosive limit. Ventilation to avoid accumulation of explosive mixtures is irrelevant in the event of a catastrophic failure. The likelihood of this scenario may also determine the building specifications.

It is important to note that in addition to regulating ventilation rates, another method of avoiding ignitable sources is to limit the manner in which a leak can occur. In other words, a location can be non-classified due to ventilation but also due to a lack of gas source. NFPA 497A states that locations that are not adequately ventilated but where piping systems are "without valves, fitting, flanges, and similar accessories that may be prone to leaks" usually do not need to be classified (2-6.1(b)). Altering the hydrogen storage and processing equipment on the vehicle rather than altering the facility is an important option that could limit costs associated with building specifications.

7.2.2 Codes for particular types of locations

The NFPA has written codes for specific types of locations that are relevant to this study. They include parking garages (Section 7.2.2.1), areas for storage and distribution of natural gas (Section 7.2.2.2), residential garages used for refueling natural gas vehicles and residential garages used for electric vehicle charging (Section 7.2.2.3), areas for maintenance and servicing of vehicles (Section 7.2.2.4), and areas for storage of hydrogen (Section 7.2.2.5).

7.2.2.1 Requirements for Parking Garages

Currently, there are no codes for parking garages containing hydrogen vehicles. In fact, NFRPA 88A, Standard for Parking Structures, has no requirements for particular vehicle fuel types. General ventilation requirements for parking garages are considered adequate for natural gas vehicles, according to section A.5.3.2, the only mention of natural gas in the code.

The statement that ventilation for parking garages also addressed natural gas vehicles is helpful in the analysis for hydrogen. It means that the committee writing parking garage codes has looked into the nature of gases and has determined that no special precautions are necessary. The main issues for parking structures are:

- Heating equipment with flames must be located at least 18 inches above the floor and 18 inches below the ceiling (5.2.2). Other types of fixtures do not have restrictions as long as vehicles are using the area for parking only (maintenance areas have other restrictions).
- Mechanical ventilation is not required in open parking structures.
- Enclosed structures must be ventilated mechanically with at least 300 L/min-square meter (1 cubic ft/min-square foot) of floor area.
- Automatic sprinklers are required in enclosed structures where ceilings are less than 24 inches above grade. They are also required, along with a fire detection system (alarm) where a structure is enclosed under a building.

If the ventilation in an enclosed parking structure is sufficient, the area would be considered non-classified. The ventilation level currently listed in NFPA 88A is sufficient to accommodate natural gas vehicles and to avoid classification of the area. However, the ventilation required to avoid an ignitable mixture of natural gas is different from that required for avoidance of a hydrogen ignitable mixture. An engineering analysis is necessary to determine the ventilation required to avoid a concentration over 25

percent of the lower explosive limit. If that ventilation exceeds the current requirements, some modifications to the mechanical system will be necessary in enclosed parking structures.

Table 7-5 summarizes the codes that may affect the requirements for hydrogen vehicle parking structures.

Table 7-5 - Summary of parking garage requirements.

Code	Fuel	Requirement	Impact on parking garages
NFPA 497	Gases	Avoid accumulation of explosive gases.	Requirement to avoid leaks or avoid greater than 1% hydrogen volume (25% of LEL)
NFPA 88A	Liquid Fuels and Natural Gas	Ventilation not required for open structures.	No ventilation modifications in some parking garages
NFPA 88A	Liquid fuels (natural gas assumed but not mentioned)	Heating equipment with flames must be at height greater than 18 inches above the floor or 18 inches below ceiling.	The ceiling restriction was already added to address low density gas fuels. Height below ceiling could change for hydrogen.
NFPA 88A	Liquid Fuels and Natural Gas	Mechanical ventilation of 1 ft^3/min- ft^2 in enclosed parking structures.	Unclear if existing ventilation is sufficient for hydrogen vehicles.
NFPA 88A	Unspecified	Automatic sprinklers and fire alarms in underground structures under buildings.	At least the same requirements would apply to hydrogen vehicles.

From NFPA 88A, we can conclude that ventilation is not required for open parking structures. Ceiling restrictions for heating equipment with flames already apply to low density gases, but the exact height needs to be studied further to determine if changes are necessary to account for hydrogen characteristics. Ventilation requirements in enclosed structures already are very high, but need to be analyzed to determine if they are sufficient for avoidance of 25% of LEL. No further alarms or sensors are likely to be required.

7.2.2.2 Compression, storage, and dispensing facilities for natural gas

An analysis of NFPA 52, Compressed Natural Gas Vehicular Fuel Systems Code, provides two important pieces of information needed for understanding hydrogen vehicle parking requirements. First, it addresses natural gas vehicles, which are similar to hydrogen vehicles in many ways. Treatment of natural gas vehicles may be the basis for treatment of hydrogen vehicles. Second, NFPA 52 addresses fueling of natural gas vehicles in residential garages. A review of relevant codes and standards determined that this particular section of the NFPA Codes is the only guidance for gaseous vehicles in a residential garage.

One of the most interesting aspects of NFPA 52 is paragraph 1.4, which states that since advancements in technologies can lead to systems that differ from these governed by the codes, deviations that provide equivalent safety and meet the intent of the codes are permitted. This is significant since it gives the local jurisdiction the go-ahead to develop designs that differ from these addressed in the codes. It is debatable whether a change from natural gas to hydrogen vehicles is an advancement or a completely different technology. Nevertheless, the inclusion of paragraph 1.4 improves the chances for justification to apply or alter the codes found in NFPA 52 to fit a hydrogen vehicle location.

Another important aspect of NFPA 52 is that vehicles are not considered ignition sources (unless they have fuel-fired appliances like those found on recreational vehicles or catering trucks) (6.3.4). For practical purposes, this means that the existence of a hydrogen vehicle itself does not introduce any ignition sources to that location. This reduces the possibility of classifying the location where hydrogen vehicles park.

Facility Requirements

NFPA 52 describes ventilation requirements for compression, storage, and dispensing facilities. Parking facilities do not fit into this description unless such facilities have dispensing equipment on the premises. The ventilation requirements described in NFPA 52 may be considered as a conservative baseline for parking facilities. A comparison with parking structure ventilation requirements shown in NFPA 88A, however, indicates that parking structure requirements are stricter in air changes per hour (See Table 7-6).

Table 7-6 - Comparison of Ventilation Requirements for Natural Gas Compression, Storage, and Dispensing Facilities (NFPA 52) and Parking Garages (NFPA 88A)

Location	NG compression, storage, and dispensing	Parking garages for liquid and NG vehicles
Outdoor location	None	None
Indoor location	Venting to the outside. Inlets on outside walls near floor, outlets at the high point or roof.	Ventilating systems installed in accordance with A/C and Ventilation Systems Code NFPA 90A.
	Continuous mechanical, or mechanically activated by continuous NG monitoring detection to avoid more than 20 percent of LFL.	Continuous mechanical ventilation during hours of normal operation.
	At least 1 ft^3/min-12ft^2 of room volume.	At least 1 ft^3/min- ft^2 of room volume.

In addition to ventilation, compression, storage, and dispensing facilities require gas detection equipped to sound an alarm and a visibly indicate when gas concentrations are greater than 20 percent of the LFL (6.4.3.6).

NFPA 52 also implicitly considers smoking an ignition source as it requires large “No Smoking” signs. This behavioral prompt should also be considered as an option to avoid ignition sources in enclosed parking structures (residential garages) and possibly in open structures, as well.

Although NFPA 52 classifies some areas around compression, storage, and dispensing facilities for electrical equipment, ventilation creating positive pressure can reduce or eliminate the classified areas (6.12.1). This should not necessarily be taken as a requirement for parking areas, however, since the potential leakage of gas in compression, storage, and dispensing facilities is much greater than in a parked vehicle, and no such requirement exists in NFPA 88A.

From the review of NFPA 52 and comparison with NFPA 88A, the study finds that the codes on natural gas vehicles and their fueling facilities add several components to the list of considerations for hydrogen vehicles in parking facilities. First is the requirement for an alarm and visible indicator when gas concentrations exceed 20 percent of the LFL. Second is an air change requirement much lower than for parking garages. Third is further confirmation that open or well-ventilated areas do not require classification for electrical equipment. Although these considerations should be evaluated, the review has determined that requirements in the compression, storage, and dispensing facility section of NFPA can be seen as less important than the requirements in NFPA 88a, since a fueling facility is quite different from a parking structure. Therefore an alarm may be unnecessary in the parking facility.

7.2.2.3 Residential garages

Residential garages with natural gas fueling equipment

There are three important aspects of the residential refueling facility section of NFPA 52.

- Residential fueling facilities are exempt from electrical classifications.
- Residential fueling facilities are permitted indoors.
- If fueling indoors, a gas detector must be placed within 6 inches of the ceiling, must be set to operate at 20 percent of the LFL, and must stop the compressor.

The absence of classification and ventilation requirements is due to the small volume of gas typically present in a home refueling system. In addition, there is no gas stored in a home system except for the quantity on-board the vehicle. A home system essentially operates much like other gas appliances, such as ranges, ovens, and water heaters, except that humans have a more hands-on role in refueling the vehicle.

The vehicle is usually parked for several hours while it is filled with natural gas directly from a compressor. Since NFPA 52 applies to refueling, where there is a small chance for leakage in the transport of the gas, it is likely that simply parking a fully fueled natural gas vehicle would require no greater restrictions and likely fewer than NFPA 52. An engineering analysis will show whether the potential for leaks from a hydrogen vehicle is much different than that from a natural gas vehicle. If the potential, quantity, and quality of leaks are comparable between natural gas and hydrogen vehicles when parked, this section of NFPA should be sufficient to guide residential garage designs for hydrogen vehicles.

NFPA 52 suggests that the quantity of leakage is less important than the garage being designed with a sensor to detect the existence of the maximum concentration of gas during refueling. However, it is not possible to determine if the sensor requirement is only related to the refueling of the vehicle or also to the

potential for leaks from the vehicle. Thus, NFPA 52 does not provide an answer to the question of whether residential garages require sensors or not.

Residential garages with hydrogen-emitting electric vehicle batteries

The only code that has been written specifically to address hydrogen leakage in residential garages is Section 625 of NFPA 70, the National Electrical Code. Although hydrogen leakage from a hydrogen power vehicle is an anomaly and would only occur accidentally, hydrogen is normally emitted during the charging of certain types of batteries in older electric vehicles. This has been an issue of concern. Federal law requires that "provisions shall be made for sufficient diffusion and ventilation of gases from batteries to prevent the accumulation of explosive mixtures" (29CFR, 1920.305(j)(7)). As a result, the NFPA developed codes to address ventilation for electric vehicles. Although most batteries today are sealed and no longer generate hydrogen, the codes are still in existence and provide some guidance as to how NFPA might address hydrogen vehicle leaks.

The National Electrical Code and California Electrical Code require ventilation in rooms with open-vented electric vehicle batteries. The codes require ventilation in order to prevent build-up of hydrogen that could be generated when charging a battery. A concentration of greater than 25% of the lower flammability limit is considered hazardous. Hydrogen's lower flammability limit is 4% by volume (NFPA 497), so the ventilation ensures that the volume of hydrogen is less than 1% by volume.

The code requirements are described in National Electrical Code (NEC) Table 625-29(d), "Minimum Ventilation Required in Cubic Feet per Minute (cfm) for Each of the Total Number of Electric Vehicles that can be Charged at One Time." The California Electrical Code interprets this table to mean ventilation requirements per parking space (Rawson and Kateley). The table describes the ventilation required in terms of voltage and amperage of the charging system but the formula can be applied to a fixed space to determine the number of air changes per hour required for avoidance of hydrogen buildup. For a parking space of dimensions measuring approximately 1400 cubic feet, the smallest charging system of 120V and 15 amps requires ventilation of 37 cfm or 1.6 air-changes per hour (ACH). A large household charging system of 20 amps and 240V would require 99 cfm or 3.2 ACH. The highest ventilation rate listed in the California Electric Code is 8541 cfm for a 400 amp, 600V 3-phase system. For the same single parking space, this corresponds to 366 ACH, though this type of charging system is highly oversized for an individual light-duty vehicle and is listed here only to illustrate the entire range listed in the NEC. An alternative source states that the generally accepted ventilation rates range from 10 to 15 ACH (Petruno and Meade). Table 7-7 provides a comparison of ventilation required for different sized parking areas and charging systems using the values provided in the NEC.

The NEC does not state the assumed hydrogen flow rate for the ventilation requirements, although the WestStart-CALSTART study contributing to the code development tested controlled flow rates between 200 and 1000 liters per hour. The study also found that maximum hydrogen emissions from any of the electric vehicles in the study were approximately 1500 liters per hour (WestStart- CALSTART). Therefore it is reasonable to assume that the ventilation rates listed in Table 7-7 should be sufficient to protect a parking space from hydrogen emissions up to 1500 liters per hour.

Table 7-7 - Ventilation required for enclosed parking spaces with charging systems containing gas-emitting batteries.

	Airflow Requirement (ACH)	
Size of Room (cf)	**Single Phase 120 V, 15 amp**	**Single Phase 240 V, 15 amp**
	37 cfm	**74 cfm**
600	3.7	7.4
1000	2.2	4.4
1400	1.6	3.2
5000	0.4	0.9

Garage ventilation is usually accomplished by having an intake vent near the floor and an exhaust fan in the ceiling, as shown in Figure 7-2. Open parking spaces, such as those in parking garages where walls are open on at least two sides, do not require any additional ventilation (NEC §625-30).

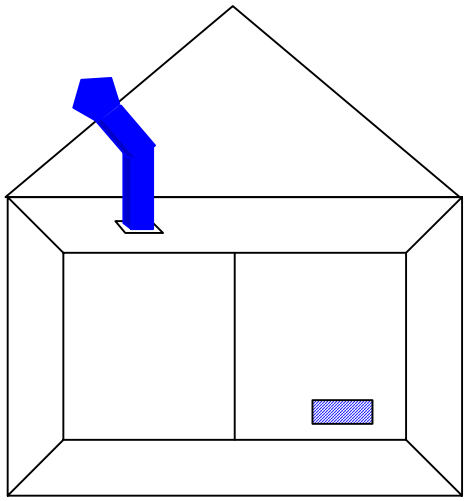


Figure 7-2 - Intake and exhaust fan placement in residential parking garage with electric vehicle charging requiring ventilation

7.2.2.4 Requirements for Maintenance and Service Facilities

Currently, NFPA 30A and NFPA 88B address safety for maintenance and service facilities but do not specifically refer to hydrogen vehicles. In fact, NFPA 30A (1996) addresses maintenance and dispensing facilities for vehicles fueled only with flammable and combustible liquids. It specifically states that the code does not apply to service stations that dispense compressed or liquid gases for automotive purposes. As a result, this code provides limited information with respect to handling gaseous vehicles at a maintenance facility.

On the other hand, NFPA 88B (1997) addresses requirements for repair garages and does offer some provisions specifically for CNG or LNG vehicles. Drawing from the safety issues in NFPA 88B, it is possible to identify issues that need resolving for hydrogen, as shown in Table 7-8.

Table 7-8 - NFPA 88B standards for repair garage that may need adaptation for hydrogen vehicles

Issue	Impact on facilities servicing hydrogen vehicles
Determination of class and division of area near ceiling for electrical wiring purposes (Section. 3-1)	For CNG, the area within 18 in. of ceiling is Class 1, Div. 2 except where 4 ACH of ventilation is provided. Hydrogen determination may be different.
Permitted use of flame heaters or high temperature heating equipment (Section 3-2)	Permitted use in areas with hydrogen vehicles may be different than for CNG or LNG vehicles due to lower ignition energy requirements.
Building construction and design, including materials (Section 2)	No special provisions are required for CNG. Could also be true for hydrogen.
Required installation of fire alarms, sprinkler systems (Section 4)	No special provisions are required for CNG. Could be similar for hydrogen.
Storage and handling of gases (Section 3-5)	The handling of CNG references NFPA 52, the standard for CNG vehicle systems. Currently no similar standard exists for hydrogen vehicles. Determination for handling of hydrogen will require specific instructions or guidance from other documents.

It is difficult to determine from existing maintenance facility standards whether these types of buildings will require greater alterations for hydrogen vehicles than do parking facilities. On one hand, the risk difference between hydrogen and natural gas vehicle activities taking place at a maintenance facility is higher than the difference in hazards between parked hydrogen and CNG vehicles. On the other hand, NFPA 88B required few changes when provisions for CNG vehicles were added. It is possible that hydrogen vehicle maintenance will also add only minor changes.

7.2.2.5 Fuel Storage Requirements

NFPA 50A addresses hydrogen storage. Since gas storage is considered to be storage of much larger quantities of gas than would be found in individual vehicles, codes for storage do not directly apply to vehicles. As a result, NFPA 50A does not address requirements for parking or maintenance of hydrogen vehicles. Nevertheless, it is reasonable to assume that codes for parked vehicles would not be more restrictive than those for storage of hydrogen.

Table 7-9 provides a comparison of NFPA codes for CNG and hydrogen storage. Although the NFPA 50A codes are the least applicable to parking structures among those reviewed in this study, it is important to note the differences between CNG and hydrogen in Table 7-6. It is apparent that CNG tanks require the same or less distance to various other structures or locations. Similar caution may be required when converting other CNG codes to hydrogen distances.

Table 7-9 - Minimum required distances of CNG and hydrogen storage vessels from various buildings, property lines, or combustible materials (requirements for fueling stations).

Code	CNG	Code Reference	H_2	Code Reference
Public sidewalks and parked vehicles	10 feet	*NFPA52: 4-4*	15 feet	*NFPA50A: 3-2*
Place of public assembly	—	—	25-50 feet	*NFPA50A: 3-2*
Line of adjoining property that may be built on	10 feet	*NFPA52: 4-4*	5 feet	*NFPA50A: 3-2*
Distance to building with non-combustible walls adjacent	10 feet	*NFPA52: 4-4*	0-25 feet	*NFPA50A: 3-2*
Distance to building with other material wall	10 feet	*NFPA52: 4-4*	10-50 feet	*NFPA50A: 3-2*
Distance to flammable liquids above ground	20 feet	*NFPA52: 4-4*	10-50 feet	*NFPA50A: 3-2*
Flammable gas storage, either high or low pressure	3-5 feet	*CCR Title 8-531*	10-50 feet	*NFPA50A: 3-2*

California Code of Regulations Title 8, Subchapter 1, Article 7, Section 531 is generally in accordance with the NFPA 52.

7.3 Conclusions

Specific codes governing facilities for hydrogen fuel cell vehicles do not exist. However, codes reviewed in this study provide information on existing conventional fuel requirements that may affect parking structures, residential garages, and maintenance facilities that are intended to accommodate hydrogen vehicles.

For indoor or outdoor parking structures, the existing codes are likely to affect the issues listed in Table 7-10.

Table 7-10 - Issues/requirements relevant to hydrogen vehicle parking structures

Location/Type of Equipment	Electrical/Heating Classification	Ventilation	Sensors and Alarms
▪ No ventilation or classification required if avoid valves, flanges, other connectors that could leak (NFPA 497) ▪ No smoking (NFPA 52) ▪ Vehicle not considered ignition source (NFPA 52)	▪ Classification of locations unlikely for open structure (NFPA 497) ▪ Classification more likely in enclosed structures if inadequate ventilation (NFPA 497) ▪ Open flame heaters should be avoided near ceiling (NFPA 88A) ▪ No electrical equipment requirements for parking only (NFPA 88A)	▪ Mechanical continuous if enclosed (NFPA 88A) ▪ None required if open structure (NFPA 88A)	▪ Automatic sprinklers in below grade enclosed parking structures (NFPA 88A) ▪ Fire alarm if structure under building (NFPA 88A) ▪ Sensor based on gas detection activates alarm and visible indication of gas levels at dispensing facilities (NFPA 52)

Residential garages share some issues with parking structures, but because residential structures are likely to have very small amounts of gas on the premises, they have fewer requirements. In fact, NFPA 52 specifically exempts residential garages from many requirements. Therefore, the list of issues for residential garages is much shorter than for large facilities, as shown in Table 7-11. Ongoing studies of hydrogen leaks and dispersion in small spaces (such as garages) will help to determine if the short list of requirements for natural gas vehicles will carry over to hydrogen vehicles.

Table 7-11 - Issues/requirements relevant to hydrogen vehicles in residential garages

Location/Type of Equipment	Electrical/Heating Classification	Ventilation	Sensors and Alarms
▪ No ventilation or classification required if avoid valves, flanges, other connectors that could leak (NFPA 497) Vehicle not considered ignition source (NFPA 52)	▪ Classification seems unlikely based on exemption for natural gas fueling/parking (NFPA 52) ▪ No electrical equipment requirements for natural gas in residential fueling (NFPA 52)	▪ None required for natural gas fueling/parking (NFPA 52) Continuous ventilation if continuous emissions of hydrogen from EV batteries (NFPA 70)	▪ For natural gas fueling, sensor based gas detection to stop compressor (NFPA 52)

Requirements for maintenance facilities currently consider gaseous fuels, and will likely need adapting in several areas to deal with hydrogen. Specifically, current standards reference NFPA 52 in handling of fuels but no counterpart document exists for hydrogen. As the development of hydrogen vehicle fuel handling system design matures, solutions will be developed for some issues in Table 7-12.

Table 7-12 - Issues/requirements relevant to hydrogen vehicles in maintenance facilities

Location/Type of Equipment	Electrical/Heating Classification	Ventilation	Sensors and Alarms
▪ Determination of class and division dictates types of equipment (NFPA 497) ▪ Class 1, Div. 2 within 18 in. of ceiling unless 4 ACH of ventilation (NFPA 88B) ▪ Vehicle not considered ignition source (NFPA 52)	▪ Classification near ceiling possible based on natural gas standards (NFPA 88B) ▪ Permitted use of flame heaters or high temperature equipment may be restricted (NFPA 88B)	▪ Ventilation avoids classificatio n near ceiling for natural gas (NFPA 88B)	▪ No special alarms or sprinkler systems required for natural gas (NFPA 88B)

A flurry of activity by many equipment standards organizations and code developers undoubtedly will result in new guidance in the next year or two. This guidance may provide further insight into requirements for the types of buildings under discussion but they may or may not directly address the topics of this study.

One of the codes heavily referenced in this study, NFPA 52, is undergoing revision for 2004. Currently the NFPA 52 Committee is compiling many industry best practice documents and standards in order to determine how to incorporate hydrogen into a combined NFPA 52 (CNG) and NFPA 57 (LNG) Document that contains information for CNG, LNG, and hydrogen. Part of this work involves the review of hydrogen dynamics and the needs for high-pressure systems. The Sandia National Laboratory and the University of Miami are doing much of the required modeling in coordination with the US Department of Energy. In addition to this work in the US, development is ongoing in other parts of the world including Canada, Japan and Europe. There is already significant coordination among organizations in order to ensure that practices in different countries are recognized.

7.4 Hydrogen Specific Codes and Standards Adopted by the International Code Council (ICC)

In December 2002, the International Code Council (ICC) adopted the United States Department of Energy (DOE) sponsored hydrogen codes and standards in the areas of building, fire, fuel gas, mechanical, and residential. The final code language was officially issued in March, 2003.

Supported by DOE's several years of research and development in the area of hydrogen utilization, the adopted codes were primarily based on adding hydrogen specific language to existing NFPA and National Electric Codes (NEC). The adopted codes could be used as a starting point to guide designers and builders in addressing hydrogen issues in facilities. Although a majority of the work

in this study was completed prior to the ICC code adoption, a listing and analysis of the adopted ICC codes and their potential impact on the outcome of this study is included in this section.

Following the NFPA and National Electric Code (NEC) format, the ICC adopted codes focus on ensuring the safe handling of hydrogen in facilities within the context of the NFPA and NEC. The ICC language was careful not to alter any safety requirements that already existed in the NFPA and NEC.

7.4.1 Building Codes

The newly adopted ICC Building Codes did not add any significant language to hydrogen references in the earlier ICC Building Codes.

Earlier ICC codes defined hydrogen as an organic peroxide compound in Chapter 3 Section 302 "Classification". Section 406.6.5 "Gas Detection System in Repair Garages" of the old ICC also requires the use of a gas detection system in repair garages for vehicles fueled by non-odorized gases such as hydrogen and LNG. Section 406.6.6.1 "System Design" further specifies that the flammable gas detection system must be designed to activate when the level of flammable gas exceeds 25 percent of the lower explosive limit. Activation of the gas detection system must result in all of the following:

1) Initiations of distinct audible and visual alarm signals in the repair garage
2) Deactivation of all heating systems located in the repair garage, and
3) Activation of the mechanical ventilation system, where the system is interlocked with gas detection.

Section 406.6.6.3 "Failure of the Gas Detection System" requires that failure of the gas detection system must result in deactivation of the heating system, activation of the mechanical system when the system in interlocked with the gas detection system, and cause a trouble signal to sound in an approved location. Subsection 608.5 "Stationary Lead-Acid Battery Systems - Ventilation" requires that the ventilation system must be designed to limit the maximum concentration of hydrogen to 1.0 percent of the total volume of the room, or that continuous ventilation be provided at a rate of not less than 1 cubic foot per minute per square foot (1cfm/ft^2) [(0.0051 m^3/(s . m^2)] of floor area of the room.

Such requirements in the earlier ICC codes are similar to existing NFPA codes related to hydrogen as discussed in Section 7.1 of this report. The requirements are somewhat general and leave much interpretation to the designer or builder. For example, the gas detection system design and failure requirements specify that hydrogen detectors must be used in maintenance facilities for hydrogen fueled vehicles. However, the codes are mute as to the quantity and locations of such detectors. In addition, the requirement to deactivate the heating system and to activate a mechanical ventilation system upon activation of the detectors does not address facilities during warm seasons when no heating is required and when the mechanical ventilation system would be operating anyway.

7.4.2 Fire Code

Reinforcing NFPA's requirements for hydrogen gas emitted from Valve-Regulated Lead-Acid (VRLA) batteries in facilities discussed in Section 7.2.2.3 of this report, the newly adopted ICC Fire Code added a new Section 609.

This Section specifically addresses venting, controlling of thermal runaway, safety systems, room design and construction, neutralization of a release of electrolyte, room ventilation, cabinet ventilation, warning signs, seismic protection, and smoke detection. While these requirements do

not specifically address hydrogen-fueled vehicle facilities, they highlight the handling of hydrogen released from batteries used in providing uninterruptible power supply (UPS) systems in facilities such as banks, hospitals, and computer rooms. Such requirements may guide the development of facility codes to safely accommodate hydrogen releases from hydrogen-fueled vehicles in facilities similar to the scenarios examined in this study.

The newly adopted ICC Fire Code also added Section 2209 "Hydrogen Motor Fuel-Dispensing and Generation Facilities". In 20 subsections, Section 2209 details definitions of equipment, locations on property, dispensing into motor vehicle at self-service hydrogen motor fuel-dispensing facilities, and safety precautions.

While Section 2209 details specific requirements including fueling/defueling infrastructure design and construction, it does not directly address parking only or non-fueling conditions similar to the scenarios examined in this study. The results of this study along with Section 2209 could be used as guidance to develop requirements that deal with parking only conditions and to further refine Section 2209 requirements. (See Appendix for Section 2209 of the ICC Fire Code)
In addition to Section 2209, the ICC Fire Code also added subsection 2211.8 "Defueling of Hydrogen from Motor Vehicle Fuel Storage" to Section 2211 "Repair Garages" .

In Chapter 35 "Flammable Gases", the ICC Fire Code excluded hydrogen from being considered a flammable gas under NFPA 50A when dispensed from an approved fuel-dispensing station into a motor vehicle. This exclusion makes hydrogen equal to other vehicle fuels and removes it from restrictions imposed by the NFPA 50A which deals with flammable gas at consumer sites.

It should be noted that prior to modifications for hydrogen reference, the ICC Fire Code included hydrogen references in Section 2211 "Repair Garages". In particular, subsection 2211.7 "Repair Garages for vehicles Fueled by Lighter than Air Fuels". This subsection expands slightly the requirements listed under ICC Building Code Section 406.6.6 but exempt repair garages where no work is performed on the fuel system of the vehicle.

7.4.3 Fuel Gas Code

Recognizing hydrogen as fuel for non-vehicle applications such as home heating, the ICC Fuel Code added Chapter 7 "Gaseous Hydrogen Systems" which regulates the design and construction of systems and facilities using hydrogen as fuel for non-vehicle applications. In Chapter 1 "Administration", the ICC Fuel Gas Code made a point of excluding hydrogen systems on-board vehicles from being covered under this code.

Chapter 7 covers hydrogen systems such as generation, refueling, and operations. Elements such as piping, compressors, and pressure regulators are discussed. The Chapter also refers to other sections of the ICC code for mechanical system ventilation and gas detection of hydrogen. Because of the depth of coverage, Chapter 7 is expected to influence future development of related codes governing hydrogen when used as vehicle fuel especially in fueling and defueling systems.

7.4.4 Mechanical Code

The Mechanical Code added a definition of a Hydrogen Generating Appliance in Chapter 1, and further discussed using such appliances in generating and refueling operations in Section 304.4 along with ventilation requirements.

In Chapter 5, the Mechanical Code reiterates Fire Code requirements for handling hydrogen emitted from Valve-Regulated Lead-Acid (VRLA) batteries. The significance of this reiteration is the fact that hydrogen has been added to this Code, which sets the stage for future refinement and modifications.

A shortcoming of the existing (prior to adoption in 2003) Mechanical Code lies in Section 502.16 and its subsection 502.16.2. Section 502.16 "Repair Garages for Natural gas- and Hydrogen-fueled Vehicles" states that the mechanical ventilation system in these facilities shall be governed by Section 502.16.2 and 502.16.2. Examining Section 502.16.2 indicates that the Code referenced compressed natural gas (CNG) but neglected hydrogen. It is not clear if hydrogen was omitted intentionally. However, the 2003 ICC code did not add consideration of hydrogen to that subsection.

7.4.5 Residential Code

While the Residential Code added several references to hydrogen, it did so by replicating other codes that specify hydrogen systems such as Fire, Fuel, Building, and Mechanical Codes. Such replication sets the stage for future modifications.

7.4.6 Summary

While the depth of coverage of the ICC adoption of hydrogen related codes and standards is less than comprehensive, the mere introduction of some detailed specifications can be considered a major stepping stone in the development of comprehensive hydrogen codes and standards.

Two ICC codes, Fire and Fuel Gas, added detailed specifications of hydrogen systems. Other codes such as Residential, Mechanical, and Building added minor sections that deal with hydrogen systems, and also replicated the Fire and Fuel Gas hydrogen related sections.

Analysis of the ICC hydrogen-related codes clearly indicates the high level of effort that the United States Department of Energy (DOE) has provided in introducing hydrogen-related codes and standards. The depth of specifications indicates that DOE has assisted in the preparation of such codes based on comprehensive technical analysis of hydrogen applications and was able to present them in a format acceptable to several code officials.

The reviewed ICC codes, however, do not address parking facility scenarios similar to the ones examined in this study. The outcome of this study could, therefore, provide significant data that DOE, and others, could use to further refine the ICC during its next modification cycle. On the other hand, this study should be expanded to examine the effectiveness of recently adopted codes on real-life scenarios such as fueling and defueling of vehicles in garages.

8. Environmental, Safety, and Other Considerations

This study focused on the flammability hazards of hydrogen leaks in parking and maintenance facilities. Since hydrogen is categorized as a flammable gas, this should be the primary consideration.

Ignitability and sources of ignition, as well as the inclusion of other equipment and activities around the vehicle being modeled, were not considered. The structures that were modeled were assumed to be "bare-wall" facilities. Furthermore, the vehicle was assumed to be equipped with a safety system that was designed to operate in a certain prescribed manner. The vehicle design was not taken into consideration.

Some environmental concerns are related to the fact that in very large releases, hydrogen may displace the oxygen in the air surrounding a vapor cloud. Human exposure to a large hydrogen concentration cloud could experience dizziness, unconsciousness, and/or suffocation. Through the various modeling exercises in this study, there was no indication that such a large concentration of hydrogen could exist in any of the facilities due to the assumptions made and the limitations of the study. Comparison between the volume of possible hydrogen that could be released, including vehicle's entire fuel tank, and the volume of any facility also indicated that the possibility of a large concentration of hydrogen cloud to exist in any facility is very small.

9. Study Limitations and Recommended Expansion Opportunities

External limitations include the status of hydrogen fuel cell vehicle technology development and market penetration.

Because HFCV technology is still in development, final vehicle configurations are not known. Therefore, the study was based on existing technology development. For example, while several vehicle manufacturers indicated that the HFCV existing and planned on-board safety systems include hydrogen detectors that are able to detect and initiate isolation of the leaking hydrogen source, the final quantity and specifications of such detectors is not known or may not be eventually used. Similarly, while fuel cell system design and construction will likely comply with Society of Automotive Engineer (SAE) J2578 and 2579 which provide guidance for safe design and construction, SAE standards were not in their final form at the time of this writing. Although it is not anticipated that either vehicle manufacturers or SAE standards will reduce safety considerations on the vehicles, the final market product that will use the facilities could not be confirmed. Depending on technology development, such limitations may not significantly alter the results of this study.

Because HFCVs have not been in operation for extended periods of time, their limited historical and performance data was another external limitation that impacted the assumptions made in this study. For example, one reason for eliminating the possibilities of a hydrogen leak caused by pressure relief device (PRD) release was the available data on PRD releases which indicated low possibilities. Over time, with greater fleet experience, this conclusion could change.

An internal limitation that impacted the study was its scope, which limited the study to only four facility types and assumed no fuelling or de-fuelling of vehicles. In addition, the limited scope resulted in less than desirable CFD modeling to determine the effectiveness of potential facility modifications.

The study has identified some recommended expansion opportunities that could use the results of this study as a base to build upon and benefit the HFCV industry. The recommended opportunities focused on expanding the scope of this study to include:

1. Conduct additional CFD modeling to determine effectiveness of potential facility modifications using various leak scenarios including fueling/de-fueling operation. Consider home refueling systems. Also, investigate the possible ramifications of other equipment, including additional vehicles, in and around the facility. Potential ignition sources in or near the vehicles may also need to be considered.
2. Hydrogen Fuel Cell Bus Depot (parking, maintenance, and dispatch): Conduct a similar study of an actual bus depot (i.e. VTA, AC Transit, and/or Sunline).
3. Fueling Station: Conduct a similar study of an actual public fueling station
4. Conduct Failure Mode Effects Analysis (FMEA) or fault-tree analyses of a particular facility and/or system.
5. Liquid Hydrogen vehicles: Conduct a similar study using a liquid hydrogen vehicle.
6. Delta Climate: Conduct the study of the facilities under different climate conditions.

10. Conclusions

A set of elementary hydrogen fuel cell vehicle designs, environmental conditions, and parking structure facilities were chosen as an investigation theater for initiating the evolving vehicle/facilities safety considerations.

The approach for beginning the definition of the parameters and the effects of their interactions on a simple scale involved the use of CFD to help envision certain environmental factors. CFD modeling results revealed that in all four cases chosen, the hydrogen cloud at the LFL concentration did not extend beyond two feet immediately surrounding the vehicle. In the case of the parking and maintenance facilities, the confinement of the gas cloud was attributed to typical airflow rates at ground level due to natural or mechanical ventilation. This airflow resulted in diluting the leaking hydrogen cloud to less than flammable concentration levels. In situations with low ventilation rates, the CFD model results showed the cloud spreading to the wheel wells where it could be detected if the vehicle were equipped with functional hydrogen sensors.

The authors concluded that no modifications were required to accommodate HFCVs for the vehicle configuration identified in this study. These results depend on vehicle safety systems limiting the leak rate to 20 CFM when the fuel cell engine is on. Hydrogen sensors could detect leaks in situations with low ventilation. Carmakers could also employ other strategies to limit the potential hazard when vehicles are parked.

This conclusion is based on the results of modeling hydrogen leaks from hydrogen fuel cell vehicles in four generic facility types utilizing the assumptions made in this report. The modeling identified the most likely behavior of the leaking hydrogen in the facilities. Except for the immediate surrounding area of a vehicle (within two feet) the modeling results indicated that hydrogen concentrations did not reach the low flammability limit of 4.1% anywhere in the facilities.

Hydrogen leak scenarios used in the models were based on analysis of available and assumed data and on ‘practical’ applications of vehicles and facilities. Because existing conventional facilities appear able to safely accommodate HFCVs without any modifications, a cost benefit analysis of high cost modifications that once were perceived necessary and/or effective indicates that the benefits from such modifications are negligible in terms of reducing the risk associated with leaking hydrogen.

The study’s results were based on existing and assumed practical parameters. Changes to such parameters may impact the results of the study and therefore, users should tailor this study to accommodate their specific applications. Some limitations that may have impacted the results of this study include the hydrogen fuel cell vehicle development, existing codes and standards, more realistic, but complicated, conditions surrounding the vehicles, and market penetration status.

Automakers will need to consider other risk scenarios when developing safety systems for vehicles. The reliability of hydrogen sensors onboard the vehicle, their locations, impact of severe weather, their functional reliability and calibration, and system response dependability for dealing with exterior eventualities such as are extant between different parking situations will need to be considered. In the absence of robust safety systems that shut off the flow of hydrogen in the event of a leak, automakers might consider strategies that limit the flow of hydrogen when the vehicle is not moving. This approach may be especially effective in residential garages where airflow is normally limited. Alternatively, more extensive evaluations of potential ignition sources in residential garages must be given serious consideration before any recommended safety precaution protocol can be prescribed.