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Analyses in Support of Risk-Informed Natural Gas Vehicle Maintenance Facility Codes and Standards: Phase II

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Abstract

Safety standards development for maintenance facilities of liquid and compressed natural gas fueled vehicles is required to ensure proper facility design and operating procedures. Standard development organizations are utilizing risk-informed concepts to develop natural gas vehicle (NGV) codes and standards so that maintenance facilities meet acceptable risk levels. The present report summarizes Phase II work for existing NGV repair facility code requirements and highlights inconsistencies that need quantitative analysis into their effectiveness. A Hazardous and Operability study was performed to identify key scenarios of interest using risk ranking. Detailed simulations and modeling were performed to estimate the location and behavior of natural gas releases based on these scenarios. Specific code conflicts were identified, and ineffective code requirements were highlighted and resolutions proposed. These include ventilation rate basis on area or volume, as well as a ceiling offset which seems ineffective at protecting against flammable gas concentrations.

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NOMENCLATURE

Abbreviation	Definition
ACH	Air Changes per Hour
AHJ	Authority Having Jurisdiction
CFD	Computational Fluid Dynamics
CNG	Compressed Natural Gas
CVEF	Clean Vehicle Energy Foundation
DOE	Department of Energy
FMM	Fuel Management Module
HAZOP	Hazardous and Operability Study
IBC	International Building Code
ICC	International Code Council
IFC	International Fire Code
IMC	International Mechanical Code
LFL	Lower Flammability Limit
LNG	Liquefied Natural Gas
NFPA	National Fire Protection Agency
NG	Natural Gas
NGV	Natural Gas Vehicle
NIST	National Institute of Science and Technology
OEM	Original Equipment Manufacturer
PRD	Pressure Relief Device
PRV	Pressure Relieve Valve
SDO	Standards Development Organization
SNL	Sandia National Laboratories
UFL	Upper Flammability Limit
UL	Underwriters Laboratories

1 INTRODUCTION

Natural gas vehicle (NGV) usage has increased in recent years, and this has increased the need for additional gaseous fuel compatible maintenance facilities across the country. The NGV industry has largely focused its efforts on development of vehicles and fueling infrastructure, while issues with maintenance facility design and operation have been left to fleet owners. Facility code requirements for liquefied natural gas (LNG) and/or compressed natural gas (CNG) applications were developed based on expert knowledge and field experience of the standards development organization (SDO) and did not include a risk analysis of the hazards. This report aims to review the hazards of NGVs in maintenance facilities based on a risk analysis and computational modeling to support the development of risk-informed and codes and standards.

This analysis was performed in two phases. The Phase I report [1] summarized code requirements for NGV repair facilities and gave background information on how some of those requirements came to be. A Hazard and Operability study (HAZOP) was performed, and preliminary results were given. Computational fluid dynamics (CFD) modeling was performed for critical scenarios identified by specific code issues and the initial HAZOP results. The Phase II report (this document) updates the code requirements, gives a more detailed analysis of the HAZOP results, and reports on additional CFD results on new scenarios identified by these new results. This report also details specific conflicting code requirements, and proposes ways in which these could be addressed.

1.1 Historical Code Development Process

Relevant codes for NGV maintenance facility operations have been developed over a number of years beginning in the late 1990s after a series of unintended releases from first generation pressure relief devices (PRDs) installed on CNG storage cylinders. The codes were initially written as prescriptive requirements based on assumed hazards determined from the cumulative expert knowledge and field experience of SDO code committee members. Code requirements for CNG and LNG vehicles have key distinctions based on historical user experience with the respective technologies.

The initial wave of PRD failures was either the result of models improperly selected for the design working pressure or design flaws. As a result of these incidents, the selected hazard for CNG systems was the unintended release and subsequent ignition of natural gas while the vehicle is in the repair garage. The code committees assumed that a conservative release amount was 150% of the total contents from the largest cylinder on the vehicle, with the extra 50% considered to be a safety factor. Since CNG cylinder PRDs are designed to only relieve during a fire, and not due to spurious in-cylinder pressure increases, PRD design standards were quickly revised.

For LNG vehicles, existing codes do not define a specific release scenario but instead assume two release types. The basic hazard is the possible ignition of gas released from the LNG tank relief valve due to pressure building as the contents warm over a period of time. Vacuum insulated LNG tanks are designed to have a ‘hold time’ of up to several days before the pressure builds to the relief setting. Typically, the LNG tank pressure would build at a rate of about 103 kPa (15 psi) per day giving a ‘hold-time’ of about seven days, which is a normal operating parameter of LNG tanks.

The codes also have requirements that address possible liquid-phase LNG spills in the maintenance facilities that can subsequently flash-boil; however, there are no reported incidents within the historical records.

Some of the existing code language was developed from ‘rule of thumb’ based on user experience, without risk-informed analysis of potential hazards as recommended by the Fire Protection Research Foundation [2]. A risk-informed process leverages insights obtained from qualitative HAZOP combined with more quantitative metrics to establish code requirements. For NGV maintenance facility operations these metrics include the results of deterministic analyses for select accident scenarios, leakage frequency events, and safety margins to account for uncertainties.

1.2 Objectives and Scope

This work has been separated into two activities: first, a HAZOP based on expert advice was developed, which included a comprehensive review of NGV onboard fuel system components and an analysis of recorded historical incidents. Second, this will work take advantage of validated computational modeling capabilities [3, 4] to evaluate credible release scenarios based on the HAZOP analysis.

This report first summarizes existing code requirements for NGV repair facilities to highlight inconsistencies from competing codes and identify code requirements that need quantitative analysis factored into their effectiveness. The HAZOP analysis is summarized in Section 3 and quantifies the most consequential potential hazardous scenarios. Scenario analysis based on the computational modeling results are discussed in Section 4. Section 5 highlights specific code issues identified in Section 2, and discusses possible resolution to these issues based on the HAZOP and modeling scenario analyses. Finally, a summary of all results along with conclusions based on the data are given in Section 6. These results are meant to inform code committees on the technical requirements for safe repair shop facility and design, with the goal for improved code harmonization and the implementation of scientifically defensible codes and standards.

2 EXISTING CODE REQUIREMENTS

In 2012, code requirements were thoroughly documented by the Clean Vehicle Energy Foundation (CVEF) [5]. This report updates code requirements to the latest editions. The dominant US and international codes that cover vehicle maintenance facilities are the International Code Council (ICC) 2018 codes for Fire (IFC), Mechanical (IMC), and Building (IBC) [6-8]. In addition, applicable National Fire Protection Association (NFPA) codes and standards are the Code for Motor Fuel Dispensing Facilities and Repair Garages (NFPA 30A, 2018 Ed.), the Vehicular Natural Gas Fuel Systems Code (NFPA 52, 2016 Ed.), and Standard for Parking Structures (NFPA 88A, 2015 Ed.) [9-11]. It is important to note that these codes are voluntarily adopted by jurisdictions on a case-by-case basis and enforced by the local Authority Having Jurisdiction (AHJ). Since the local AHJ can enforce additional requirements beyond the national codes, they should be consulted early as part of the initial evaluation.

The codes discussed below *apply only* to major repair facilities, with both NFPA 30A and the IFC exempting minor repair facilities from all code requirements specific to CNG and LNG. The codes require only that those facility areas designated as major repair areas to be subject to the additional NGV requirements.

- IFC 2311.8 exempts garages that do not work on the fuel system or use open flame or welding on the CNG-, LNG-, hydrogen- or other lighter-than-air-fueled motor vehicle from all additional requirements.
- NFPA 30A exempts garages that do not perform engine overhauls, painting, body and fender work, and any repairs requiring draining of the motor vehicle fuel tank from additional requirements. The maintenance work that can be done without any modifications to the facility include lubrication, inspection, engine tune-ups, replacement of parts, fluid changes, brake system repairs, tire rotation, and similar routine maintenance work, including associated floor space used for offices, parking, or showrooms.

2.1 Ventilation

IFC 2311.8.8 requires that repair garages for natural gas- or hydrogen-fueled vehicles use a mechanical ventilation system with a ventilation rate not less than 1 cfm per 12 ft^3 (0.00139 $m^3/s/m^3$ – depends on the volumetric size of the facility). However, NFPA 30A 7.3.6.7 requires a ventilation rate of 1 cfm/ft^2 (0.00508 $m^3/s/m^2$ - depends on the floor area of the facility) for fuel dispensing area. Mechanical ventilation must operate continuously except when it is either interlocked with a gas detection system for or electrically interlocked with the lighting circuit, as detailed below in Section 2.3. Depending on the height of the facility, these two requirements will most likely differ.

2.2 Pit Ventilation

Ventilation requirements for pits, below grade, and subfloor work areas are part of the basic requirements for liquid fuels where flammable vapors may accumulate. IFC 2311.4 states that for pits and below-grade work areas where Class I liquids are stored or used, ventilation is required at a minimum rate of 1.5 cfm/ft^2 (0.008 $m^3/s/m^2$) to prevent accumulation of flammable vapors.

NFPA 30A 7.4.5.4 states that pits and subfloor work areas have an exhaust ventilation at a rate of at least 1 cfm/ft^2 (0.00508 m^3/s/m^2) of floor areas at all times that the building is occupied or when vehicles are parked in or over these areas. Exhaust air needs to be taken from a point within 0.3 m (12 in.) of the floor. Neither code contains specific requirements to CNG or LNG.

2.3 Gas Detection

There is no requirement for gas detection in either major or minor repair garages where odorized CNG vehicles are maintained. However, both IFC 2311.8.9 and NFPA 30A 7.4.7 require approved gas detection systems for major repair garages servicing vehicles with non-odorized flammable gases. The other requirements under these codes for gas detection installation and operation are similar and may require the expertise of a gas detection design engineer for optimal performance. Both codes require the gas detection system to activate alarms when flammable gas concentrations reach 25% of the lower flammability limit (LFL). In NFPA 30A, a gas detection system must also deactivate heating systems and activate mechanical ventilation. Both codes require that gas detection be provided in pits, especially for LNG.

2.4 Ignition Sources

NFPA 30A 7.6.6 states that where major repairs are conducted on CNG or LNG-fueled vehicles, open flame heaters or heating equipment with exposed surfaces having a temperature in excess of 399°C (750°F) are not permitted in areas subject to ignitable concentrations of gas. The IFC does not have any specific requirements for CNG and LNG repair garages with respect to ignition sources except for liquid (heavier-than-air) fuels. IFC 2311.3 does require that ignition sources be restricted from the space within 0.46 m (18") from the floor. The liquid fuel ignition source requirement is likewise the standard requirement in IBC 406.2.9, IMC 304.3, and NFPA 70. Additionally, NFPA 30A 7.6.7 requires that heat-producing electrical appliances meet the requirements of Chapter 8 of that code. Electrical classification areas (included in Chapter 8 of NFPA 30A) are meant to reduce or eliminate sources of ignition that may result from electrical devices; however, they are treated somewhat differently than high temperature or open flame ignition sources and are discussed below.

2.5 Electrical Classification

Table 8.3.2 in NFPA 30A is used to delineate and classify areas for the purposes of installing electrical wiring and electrical utilization equipment where Class I liquids are stored, handled, or dispensed. The table states that for major repair garages where lighter-than-air-gas fueled vehicles are repaired or stored, the area within 0.46 m (18") of the ceiling is classified as Class 1, Division 2, Zone 2. This classification can be avoided if ventilation is at least 1 cfm/ft^2 (0.00508 m^3/s/m^2) of floor area with suction taken from a point within 0.46 m (18") of the highest point of the ceiling. NFPA 30A 8.2.1 similarly specifies the area within 0.46 m (18") of the ceiling of a CNG repair garage is a Class 1, Division 2 hazardous location; though this may be avoided with at least 4 air changes per hour (ACH). While NFPA 30A does not specify separate requirements for LNG, in practice LNG would generally be subject to the same requirements as heavier-than-air fuels in pits and as CNG in the 0.46 m (18") space below the ceiling.

2.6 Preparing a Vehicle for Repair

The only code requirement that addresses preparation of natural gas vehicles for maintenance is IFC 2311.8.1. It requires closing valves to isolate CNG cylinders and LNG tanks from the fuel system balance prior to maintenance to limit the potential fuel quantity that could be released due to damage or error during maintenance operations. It also requires that the NGV fuel system be tested for leaks if there is a concern that the fuel system has experienced any damage. If damage is suspected the vehicle may need to be de-fueled prior to any maintenance.

The most recent version of IFC (2018) section 2311.8 (repair garages for vehicles with lighter-than-air fuels) which adds two exceptions to additional requirements. The first exception is for vehicles that have fuel systems emptied and purged with nitrogen, as long as that procedure is documented. The second exception is for vehicles that have less than 250 psi at 70°F (1.72 MPa at 21.11°C) of natural gas, as long as work is not being performed on the fuel storage tanks nor open flame welding is not done on the vehicle. This low pressure (<250 psia = 1.72 MPa) release was not considered in the HAZOP, but is considered though CFD modeling in Appendix C.3.

2.7 Maintenance and Decommissioning of Vehicle Fuel Containers

Code requirements for vehicle fuel containers are part of the maintenance requirements for vehicle mounted fuel storage containers; hence, NFPA 52 [10] should be consulted for specific requirements. Additionally, CVEF has published the document Safety Advice for Defueling CNG Vehicles and Decommissioning and Disposal of CNG Cylinders [12], which includes requirements and best practices for record keeping, maintenance, and decommissioning of natural gas containers.

3 CONVENTIONAL NGV REPAIR FACILITY HAZOP

The purpose of a HAZOP is to identify and characterize potential hazards through a structured and systematic examination of a specific system [13, 14]. HAZOP studies are usually performed on discrete industrial processes, with defined inputs and outputs from each process step or system component. Hazard scenarios are then developed using a system of guidewords indicating relevant deviations from system design intents. For this HAZOP to be most useful, an application-specific method was used that combined aspects of a failure mode and effects analysis with a HAZOP study, which is described further in this chapter.

In this work, a HAZOP was performed on the operational activities that take place for both light- and heavy-duty NGV maintenance facilities. A detailed analysis of generic, system components was performed to identify hazards that could be encountered in representative facilities. Failure was defined as an unexpected or uncontrolled release of natural gas (liquid or gaseous), with specific hazards identified in order to characterize the associated consequences. Scenarios were then prioritized based on frequency and consequence to determine which should be evaluated further. Other hazards associated with vehicle maintenance activities (e.g., mechanical, electrical, ergonomic, and noise) were not considered as these hazards are not unique to NGV maintenance facilities. Spreadsheets that contain all identified hazard scenarios are included in Appendix A. The methodology for this HAZOP was initially detailed in the report for Phase I of this project [1], and are also included here for completeness. Phase I took place in 2013-2014, and Phase II started again in 2016.

3.1 HAZOP System Description

The HAZOP procedure involved an examination of each system component and identification of scenarios, conditions or failure modes that could lead to a release of natural gas. Typical LNG and CNG vehicle fuel systems that were analyzed are depicted in Figures 1 and 2, respectively. For each scenario identified, the component identified as the source of the release is recorded in the "Component" column of the HAZOP datasheets using the system and component number from these schematic diagrams. For example, releases of LNG from the storage tank are labeled LNG-4 and releases associated with the CNG manifold are labeled CNG-5.

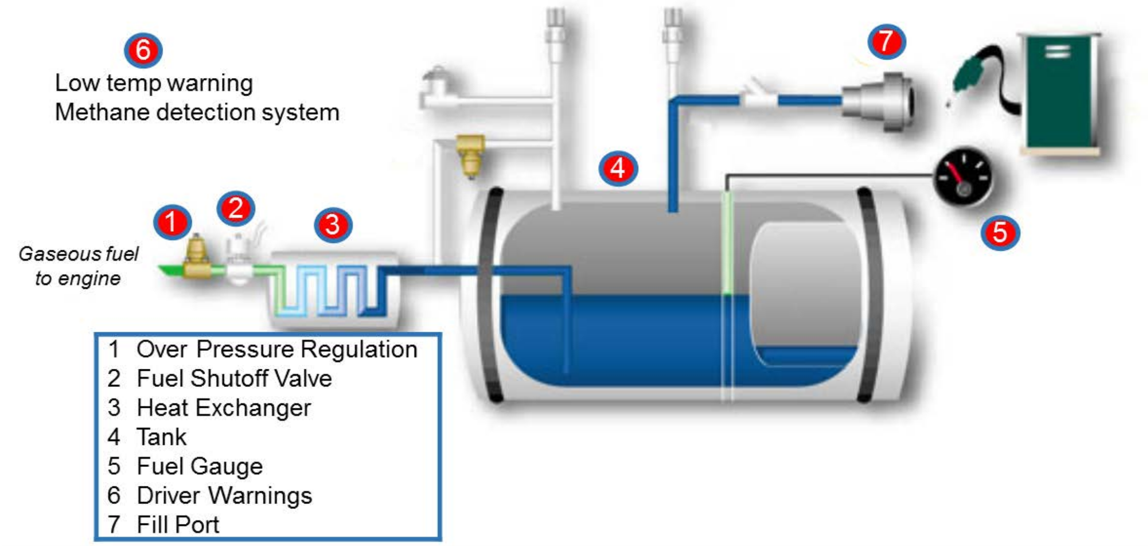

Figure 1. Typical large-duty LNG vehicle fuel system schematic, with major components highlighted (adapted from [15])

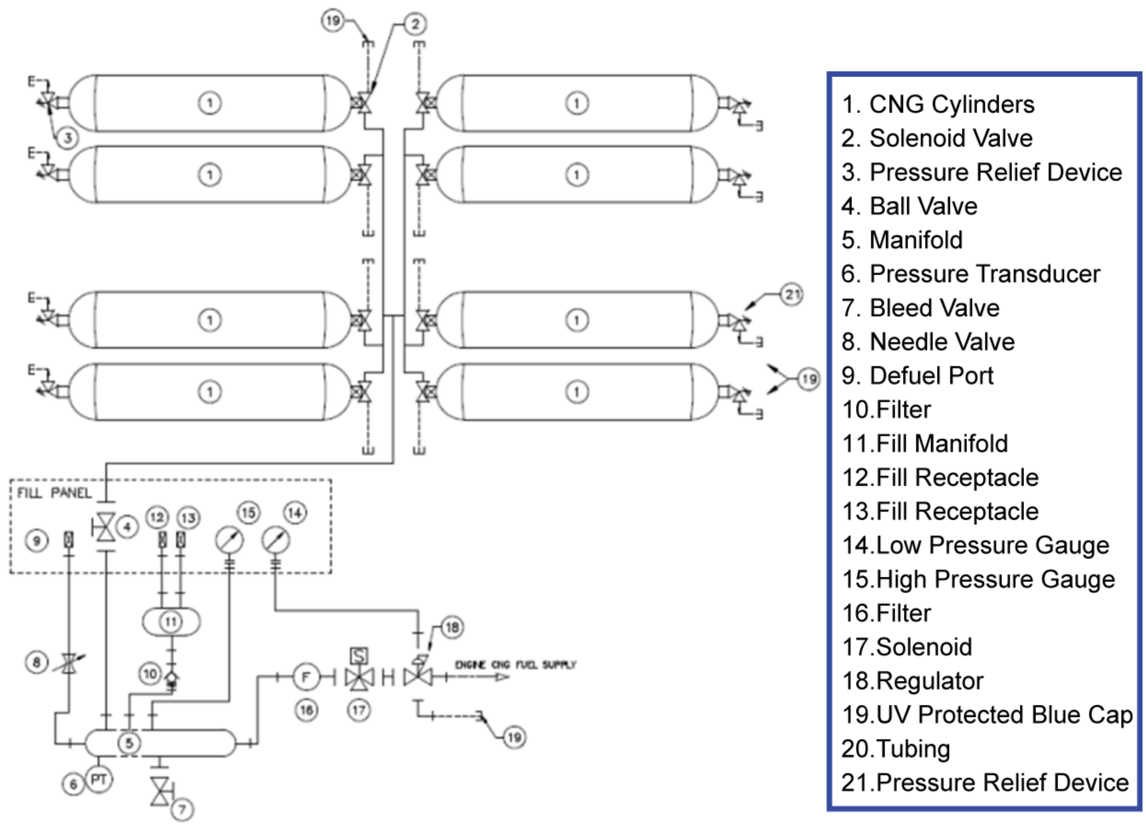

Figure 2. Typical large-duty CNG vehicle fuel system schematic with most major components (adapted from [15])

3.2 HAZOP Methodology

Table 1 lists typical activities associated with NGV maintenance. These activities were then categorized into Operation States based on where they are typically conducted (indoor or outdoor) and the fuel system state during the maintenance activities (see Table 2). Operation State 3 (dead vehicle storage) could occur either indoors or outdoors, so this operation state was broken up into two separate Operation States: “3in” and “3out”. Operation States 6 and 7 are differentiated based on the fuel system state; Operation State 6 represents fuel system services that require the entire fuel system to be evacuated and rendered inert (e.g., replacement of the solenoid valve on a CNG cylinder). However, Operation State 7 is characterized by repair activities that can be performed with the isolation valve closed between the bulk tanks and the remainder of the fuel system.

Table 1. Typical service and maintenance activities

Inspection of fuel storage and delivery piping, components (including PRD)
Inspection of fuel safety systems
Troubleshoot/testing
Exchange filters
Drain and replace fluids (non-fuel system)
Replace non fuel system component (brakes, tires, transmission, etc.)
Repair leaking fuel system
Replace fuel system components (e.g., tank, PRD, valve, plug, pressure gauge, economizer, fuel gauge cable)
Leak testing

The relevant Operation States for a Hazard Scenario are indicated in the datasheets, identified by the Operation State number from Table 2. The relevant Operation States assigned to each Hazard Scenario were based on the state of the fuel system. For example, if no natural gas is expected to be in the manifold (CNG-5) because the isolation valve (CNG-4) is expected to be closed, then a release from the manifold is not deemed feasible for this analysis. Situations where a release is possible due to human error or failure to close the isolation valve are dealt with both in the Hazard Scenarios associated with the isolation valve itself and in Hazard Scenario 37.

Table 2. Operation states of CNG- and LNG-fueled vehicles

			Operation State	**Fuel System State**
Outdoor	**Preparation for Service**	1	Defueling	Entire fuel system (FMM and tanks) being evacuated
		2	Cracking of fuel system (FMM only)	Tank valve off, FMM being evacuated
		3out	Dead vehicle storage	Fuel system charged but idle, key-off
Indoor		3in	Dead vehicle storage	Fuel system charged but idle, key-off
	Service	4	Engine operation/idling (during testing, fuel run down, inspection and troubleshooting activities)	Key-on operation
		5	Service on non-fuel systems	Tanks valve off, FMM evacuated (Run Down)
		6	Service on fuel system [Group 1]	Entire fuel system evacuated
		7	Service on fuel system [Group 2]	Tanks valve off, FMM Run Down then cracked
	Re-start	8	Fuel line refilling, connection of a small pony tank OR valve opening followed by restart	Fuel system recharging

Finally, potential Causes and Consequences for each Hazard Scenario are noted in the datasheets in the respective columns. Columns are also included in the datasheets where prevention features, detection methods, and mitigation features information can be recorded. These measures are used as the basis for identifying best practices and codes and standards improvements.

3.3 HAZOP Scenario Development

The HAZOP initially identified 41 Hazard Scenarios, although many were applicable to multiple Operation States [1]. For Phase II of the project, the 41 HAZOP scenarios were further evaluated to estimate both the frequency and the consequence of occurrence. The first step was to categorize consequence, frequency, and the ability for a situation to escalate into a larger consequence.

Consequences were ranked by whether the scenario would result in a minor release of natural gas (small amount), a major release (e.g., the entire contents of an LNG tank or multiple CNG cylinders), or in-between (e.g., one CNG cylinder). This ranking from 1-3 is shown in Table 3 below. The scenarios in which gas is released internally (within the system) were assigned a '0' and screened out of the analysis since gas is not released externally. Other scenarios were removed from consideration since they were the cause of another scenario, thus not having a unique consequence.

Table 3. HAZOP consequence classifications for release

Consequence Classifications for Release	
3	Major (all contents of tank) release of natural gas (for CNG multiple cylinders)
2	Moderate release of natural gas (for CNG one cylinder)
1	Minor release of natural gas

Frequency categories are listed in Table 4. A classification of '5' indicates that the scenario is expected to occur regularly during the lifetime of the facility. An example would be a LNG vehicle sitting for a period of time that exceeds the "hold time" and the pressure relief valve venting to reduce the pressure. Other scenarios may only be anticipated to occur several times in the life of the facility and are given a classification of '4'. A classification of '3' is an unlikely event that is not anticipated to occur during the lifetime of the facility. A classification of '2' is extremely unlikely and the event will probably not occur during the lifetime of the facility. Finally, a classification of '1' is an event that is beyond extremely unlikely to occur and has a frequency less than 10^{-6} per year.

Table 4. HAZOP frequency classifications for release

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

Finally, an escalation factor was identified, and recorded in Table 5. This factor accounts for the consequence escalation for the leak. For example, a leak that occurs when an employee is present would not escalate, as the employee could detect the leak and act to isolate it. Conversely, a leak that goes undetected because it occurs when the facility is not occupied could escalate into a higher consequence, given the larger amount of natural gas (NG) released.

Table 5. HAZOP escalation factor for release

Escalation Factor for Release	
Certain	Ignition is already present (+ faster release)
High	Faster release
Medium	Slow, large release
Low	Employee present

The HAZOP scenario datasheets listed the assigned consequence, probability, and escalation classes for each of the scenarios. Some scenarios were split into two, A and B, to further refine that scenario if the original scenario can have significantly different causes or consequences. The results of this team evaluation are shown in Appendix B.

Based on this risk ranking, several scenarios were selected for further evaluation and modeling. The scenarios that are expected to occur within the parameters of normal operations (probability class of 4 or 5) were selected for modeling so that best practices could be identified for these expected releases. Scenarios with the highest overall combinations of consequence, frequency, and potential for escalation were also selected for further evaluation. A simple risk metric was used to help identify scenarios, and this metric was the product of the probability and consequence class values. Additional scenarios besides the ones with high probability were selected if their risk metric was 6 or above and their escalation factor was “high”.

The HAZOP scenarios that were selected for further modeling included the four scenarios selected and modeled in Phase I as well as additional ones from the Phase II team evaluation. The key scenarios resulting from the risk ranking prioritization are shown in the Table 6 below.

Table 6. HAZOP results selected for further analysis – Phase II

HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences	Consequence Class	Probability Class	Risk Metric	Escalation
1	LNG-1 (Over pressure regulator)	3in, 4, 7, 8	External leakage from regulator body	Seal failure, mechanical defect, damage, etc.	Minor leakage of GNG	1	4	**4**	**L**
7	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Over pressure of tank and proper operation of relief valve	Excessive hold time, insulation failure	Minor release of GNG	1	5	**5**	**L**
12	LNG-5 (Pressure relief valve)	3in, 4, 5, 7, 8	Failure of PRV to reclose after proper venting, fails open	Mechanical Failure	Total volume of tank released	3	4	**12**	**H**
14	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Overpressure of Cylinder due to an External Fire	External fire AND successful operation of PRD	Potential catastrophic release of CNG	3	2	**6**	**H**
15	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Outlet or fitting on tank fails	Manufacturing defect or installation or maintenance error	Potential catastrophic release of CNG	2	3	**6**	**H**
19	CNG-3 (Pressure Relief Device)	3in, 4, 5, 7, 8	PRD fails open below activation pressure	Mechanical defect, material defect, installation error, maintenance error	Potential catastrophic release of CNG	2	4	**8**	**H**
35B	CNG-20 (Tubing)	8	Leakage from tubing	Mechanical damage, material failure, installation error	Potential release of CNG	3	4	**12**	**L**
37	Multiple	Multiple	Human error or disregard for maintenance procedures	Procedures violated (Gas train not emptied, tank not isolated)	Total volume of system released	3	3	**9**	**H**

4 SCENARIO ANALYSIS

To perform analyses of the identified HAZOP scenarios, a numerical modeling approach, previously validated for large-scale indoor hydrogen releases scenarios [3, 4], was adopted. The CFD solver, Fuego [16], was used to perform release simulations from a representative NGV inside the maintenance facility. Fuego is a Sandia National Laboratories (SNL) developed code designed to simulate turbulent reacting flow and heat transfer [16] on massively parallel computers, with a primary focus on heat transfer to objects in pool fires. The code was adapted for compressible flow and combustion, and is well suited for low Mach number flows. The discretization scheme used in Fuego is based on the control volume finite element method [17], where the partial differential equations of mass, momentum, and energy are integrated over unstructured control volumes. The turbulence model used was a standard two equation (k-ε) turbulence model [18] with transport equations solved for the mass fractions of each chemical species, except for nitrogen which was modeled as the balance. For the calculations reported here, the first order upwind scheme was used for the convective terms. Methane was used as a proxy for natural gas in all simulations. For releases that involved transient blow-downs, the isentropic expansion was modeled using the MassTran compressible network flow analysis code [19].

Time-histories of the flammable mass, volume, and extent—i.e., the maximum distance from the release point—are provided for each scenario. These plots are complemented by iso-contour images of the flammable boundary for each release at select time intervals to better illustrate the development of flammable clouds. Finally, maximum possible overpressures from an ignition event are calculated to help determine the harm posed for an unintended ignition event. The overpressure results will help identify scenarios where further mitigation efforts for release and ignition events are needed.

Table 7. CFD simulation description summary

Modeling Scenario	Scenario Description	Garage Details	Tank/Leak Volume	Tank Pressure	Orifice Diameter
A	LNG Blow-Off	Heavy Duty: 100’ x 50’ x 20’ (30.48 x 15.24 x 6.10 m)	1.7% of 700 L = 2.3 kg fuel	248 bar (24.8 MPa)	6.2 mm
B	CNG Fuel System Line Cracking	Heavy Duty: 100’ x 50’ x 20’ (30.48 x 15.24 x 6.10 m)	3.3 liters = 630 g of fuel	8.62 bar (0.86 MPa)	1.65 mm
C	Full blowdown of an CNG cylinder	Heavy Duty: 100’ x 50’ x 20’ (30.48 x 15.24 x 6.10 m)	700 liters	248 bar (24.8 MPa)	6.2 mm
D	CNG Fuel System Line Cracking	Light Duty: 60’ x 40’ x 20’ (18.29 x 12.19 x 6.10 m)	3.3 liters = 630 gm of fuel	248 bar (24.8 MPa)	1.65 mm
E	PRD failure for a CNG cylinder	Light Duty: 60’ x 40’ x 20’ (18.29 x 12.19 x 6.10 m)	370 liter	248 bar (24.8 MPa)	6.2 mm
F	Full blowdown of an LNG cylinder	Heavy Duty: 100’ x 50’ x 20’ (30.48 x 15.24 x 6.10 m)	405.5 liter	24 bar (2.4 MPa)	1.1 cm
G	Overpressure of CNG cylinder due to external fire	Model under development. External fire would cause release and ignition, leading to jet fire.			

Table 8. HAZOP scenarios and CFD description cross-reference

HAZOP Scenario Number		Heavy-Duty Facility Modeling Scenario (100’ x 50’ x 20’ = 30.48 x 15.24 x 6.10 m)		Light-Duty Facility Modeling Scenario (60’ x 40’ x 20’ = 18.29 x 12.19 x 6.10 m)	
1	External leakage from LNG regulator body	A/B	LNG blow-off	N/A	
7	Overpressure of LNG tank and proper operation of relief valve	A	LNG “Burping”/ “Weeping”	N/A	
12	Failure of LNG PRV to reclose after proper venting	F	Full blowdown of an LNG cylinder	N/A	
14	Overpressure of cylinder due to external fire	G	Analytical Jet Fire (In development)	G	Analytical Jet Fire (In development)
15	PRD Outlet or fitting on CNG cylinder fails	C	Full blowdown of a CNG cylinder	E	PRD failure for a CNG cylinder
19	CNG PRD fails open below activation pressure	C	Full blowdown of a CNG cylinder	E	PRD failure for a CNG cylinder
35B	Leakage from CNG tubing	B	CNG fuel system line cracking	D	CNG fuel system line cracking
37	Human error or disregard for maintenance procedures	All	Covered by other scenarios	All	Covered by other scenarios

4.1 Description of Maintenance Garages

Two sizes of maintenance garages are modeled. The first is a large facility representing what would be used for heavy duty vehicles and the second is a smaller facility that could be used for light duty vehicles.

The large maintenance garage was modeled as a pitched roof building (1:6 pitch) that was 30.5 m long (100’), 15.2 m wide (50’) and 6.1 m tall (20’), with the roof peak located at the center and 127 cm (50”) higher than the corresponding eaves (see schematic in Figure 3). Note that although the roof and main building are shown with different colors to emphasize the pitch, the enclosure was treated as a single volume. A roof layout both with and without horizontally orientated support beams was investigated to determine if the supports would cause the accumulation of flammable mixture in discrete pockets. For the condition with supports, 9 beams that were 15.2 cm wide (6”) and 107 cm tall (42”) were spaced 3.05 m apart (10’) and ran parallel to the roof pitch. The garage contained two vents that were used for air circulation; one near the floor along one of the smaller building side-walls, and a second placed on the opposite side wall near the roof. Each vent was 0.645 m tall (25”) and 3.42 m wide (131”). The NGV was modeled as a cuboid with a height and width of 2.44 m (8’) and a length of 7.31 m (24’). The vehicle was centered on the building floor with the major axis aligned to the building minor axis. There was no fluid flow through this volume.

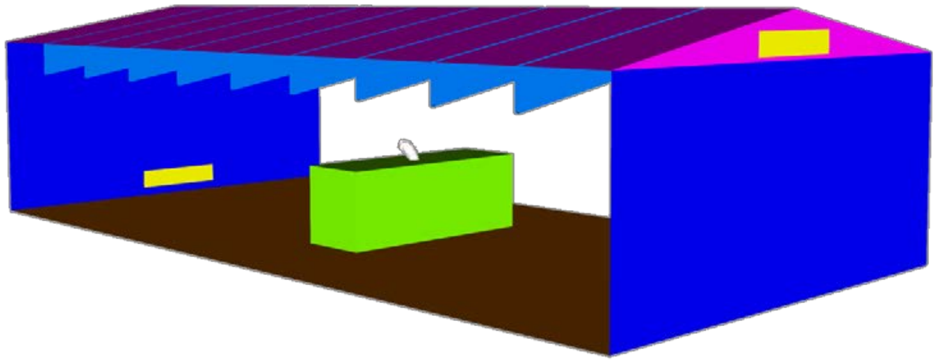

Figure 3. Schematic of the large maintenance facility for heavy duty NGV. 100' x 50' x 20' with inflow ventilation near the floor and outflow ventilation near the roof.

The smaller facility has a floor plan of 60' by 40' (18.3 m x 12.2 m) and 20' (6.10 m) high walls. It has a pitched roof with the peak 4.17' (1.27 m) higher than the walls. Inflow for the ventilation is modeled as having a 16' wide door opened 7.6" (0.19 m) from the floor. There is an output vent in the ceiling directly over the vehicle with the same area. The layout for this design is shown in Figure 4. The vehicle is modeled as a 18' x 7' x 6.5' (5.49 m x 2.13 m x 1.98 m) cube. No beams were tested for the smaller garage.

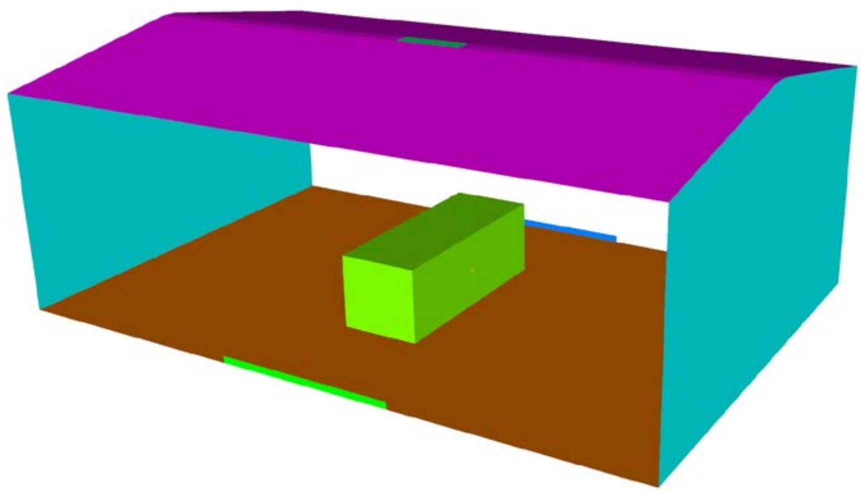

Figure 4. The smaller facility would be used for light duty vehicles. 60' x 40' x 20'. Inflow vents are located along the floor and the outflow vent is at the ceiling.

4.2 Simulation Boundary Conditions

The Fuego code solved the conservation equations in a time-dependent manner with gravity and buoyancy effects accounted for. A slip wall boundary condition with a constant ambient temperature (21°C) was used for all surfaces. The simulations were performed with and without mechanical ventilation to determine the impact on the development of flammable volumes in the garage. For the conditions with ventilation, a uniform air flow velocity of 2.0 m/s (6.56 ft/s) was forced through the floor vent into the enclosure, to produce 5 ACH for the enclosure. The upper enclosure exhaust vent was assigned an open boundary condition with a total pressure of 1 atm (101,325 Pa) and a temperature of 20°C. A relatively coarse grid was used with 195,000 node points. A grid study was completed for Scenario A and is discussed in Section 4.3.1.2. It was found that the coarse grid produce very similar results to the fine grid, so the coarse grid was used for the other scenarios as well. For the tank blow-down simulation with higher Reynolds number exit conditions, a fine grid was used that had 2.5 million grid points and spacing that was a least half of what was used for the original grid. For example, node spacing values around the leak and near the vents were 5 cm and 15 cm for the reference coarse grid, while these values were 2 cm and 6 cm respectively for the fine mesh. For all scenarios, initial turbulence was negligible ($k = 0.11\ cm^2/s$, $\varepsilon = 1.51\times10^{-4}\ cm^2/s^3$). For conditions with mechanical ventilation, air was forced into the enclosure at the prescribed 5 ACH flow rate for 720 seconds (large garage) or 300 seconds (small garage) prior to the start of the release to ensure the enclosure airflow was nominally steady.

4.3 CFD Scenario Results

The primary hazards associated with unintended natural gas releases are the maximum overpressure above ambient and the associated integrated pressure time-history or pressure impulse after the combustible gas mixes with air and ignites. Confinement, particularly with obstacles, can exacerbate overpressure and pressure impulse hazards for sufficiently small enclosures due to the volumetric expansion of gases [20], and can introduce new threats such as flying debris or building collapse [21]. Probit models for individual harm criteria are generally given a function of the expected maximum overpressure and the integrated pressure time-history or pressure impulse, along with any relevant structural details. Analytic methods to evaluate overpressure hazards from confined and vented deflagrations within enclosures generally only consider uniform air-fuel mixture compositions [20, 22-25], and not stratified environments with combustible clouds expected from the scenarios described.

Bauwens and Dorofeev [26] developed an analytic model that only considers the flammable mass quantities and enclosure volumes, without any regard to amount of mixing. Model results yielded good agreement with peak overpressure measurements from large-scale hydrogen release and deflagration experiments by Ekoto et al. [27]. Accordingly, the model was used here to estimate peak overpressure hazards based on the flammable mass prediction from the CFD simulations; pressure impulse was not considered. Note that the model assumes no instability enhancement of the flame front (e.g., acoustic) and that local blast waves were relatively minor; reasonable assumptions for leaks with small flammable volumes. Equation (1) describes how the adiabatic increase in pressure depends on the mass of hydrogen consumed:

$$\Delta p = p_0 \left\{ \left[\frac{V_T + V_{NG}}{V_T} \frac{V_T + V_{NG}/\chi_{stoich}(\sigma - 1)}{V_T} \right]^{\gamma} - 1 \right\} \tag{1}$$

where p_0 was the ambient pressure, V_T and V_{NG} were the total facility volume and expanded volume of pure methane following the release respectively, χ_{stoich} was the natural gas-air stoichiometric mole fraction, σ was the expansion ratio for stoichiometric natural gas-air combustion (7.561), and γ was the air specific heat ratio (1.4). Note that it was convenient to define V_{NG} as the ratio of total flammable natural gas mass—which was a ready output from the Fuego CFD simulations—to the known ambient density of pure natural gas. It was therefore important to accurately predict the flammable mixture across a range of characteristic leaks. The lower (LFL) and upper flammability limits (UFL) for methane mixed with air at atmospheric conditions is 5.0% and 15.0% methane volume fraction respectively [28], while mixtures outside of this range present no possibility for combustion. This overpressure correlation as developed only considers the sudden combustion of all flammable contents, which is unlikely to happen for a volume of flammable gas that is as large as seen in this case. The presence of ventilation, wall heat transfer, and the fact that the mixtures will continually lean out will mean that the actual overpressure will be much lower than is calculated. If the enclosure was perfectly sealed and there was no heat transfer out of the box, then the Δp calculated would be the same, assuming the flammable volume stayed constant throughout the entire burn. On the other hand, the flame front might become increasingly turbulent due to obstacles such as the beams, perturbing the flame-front making it even more turbulent, which would result in an increase in the turbulent flame speed. It is possible that the burn velocity could become fast enough that it could transition into a detonation, in which case the overpressures will be much greater. This is brought to the attention of the reader so that the assumptions in the calculation are clear, and it is known that the result should be taken as an estimate only.

Jeffries et al. [29, 30] shows the resulting consequences for a range of overpressures. These are show in Table 9 which will be referenced for the individual scenarios below. It is also important to note that the overpressure calculation should be linearly proportional to the facility volume. Hence, if the facility volume were to be halved, the expected overpressure from the volumetric expansion of hot gases would roughly double above the reported values, which could introduce potentially hazardous scenarios.

Table 9. Consequences of overpressures in an enclosed space [29, 30]

Overpressure (kPa)	Consequence
6.9	Injuries due to projected missiles
13.8	Fatality from projection against obstacles
13.8	Eardrum rupture
15-20	Unreinforced concrete wall collapse

4.3.1 Scenario A: Dormant LNG Blow-Off

4.3.1.1 Scenario A Description

A schematic of major LNG vehicle supply system components such as the tank, heat exchanger, fuel shutoff valve, and flow regulator are provided in Figure 1. These components are designed to limit natural gas content within the downstream fuel system. Instead, a more serious threat was deemed to be a fully fueled LNG vehicle that was left dormant in the NGV maintenance facility for a period longer than the LNG tank ‘hold time’ (~7 days). As a result, the pressure buildup would cause a pressure relief valve (PRV) to relieve and release a controlled amount of cool gas phase natural gas (~ -113°C) through a vertically orientated vent stack until the tank pressure fell below to the PRV seat pressure. Based on industry input, the release was expected to be about 1.7% of the cylinder contents before the PRV seats. Rather than rapidly discharging, the PRV was expected to ‘weep’ for several minutes with a nearly constant flow rate of around until the tank pressure reaches the seat pressure. Once reseated, the PRV likely would not relieve again for up to a day or more. Code requirements dictate the release points be from a 'safe location', which has typically been interpreted as a point that is above head height and roughly vertical. Relief vents are normally 3/8" stainless steel tubing with a plastic slip on cap to protect from rain water.

For the current scenario, saturated methane vapor was released through a vertically orientated 3/8” vent stack, whose exit was 2.44 m (8’) above the floor; note that the saturated vapor exit temperature (-113°C) and density (1.23 kg/m^3) at atmospheric pressure were taken from the online National Institute for Standards and Technology (NIST) calculator [31]. The fully fueled large tank had a volume of 700 liters, and the release of 1.7% of the cylinder contents corresponded with roughly 2.3 kg (5.1 lbs) of fuel. The nominal expected flow rate was 7.58 g/s (l.0 lbs/min), which resulted in a leak duration of 306 seconds. Due to gridding constraints, the leak area was modeled as a 10 cm^2 (1.55 in^2) square hole with an exit velocity of 61.5 cm/s (2.02 ft/s). Although the leak greatly exceeded tubing area, the plastic rain cap would result in a much larger effective leakage area; thus the 10 cm^2 exit area was deemed reasonable.

4.3.1.2 Scenario A Results

The first scenario involved a PRV release of cool natural gas through a vent stack for a fully fueled LNG vehicle that was left dormant in a maintenance facility beyond the prescribed hold-time. Natural gas mole fraction contours are illustrated in Figure 5 from the maintenance facility central plane for conditions with mechanical ventilation 280 seconds after the start of the release for facility layouts with and without roof supports. Mole fraction maps are provided in Appendix C.1 for additional details. Velocity maps from the maintenance facility central plane for the conditions with and without roof supports in illustrate the influence of the strong inlet flows needed to sustain the 5 ACH ventilation rate. When ventilation currents reached the vehicle side, they were deflected upward and formed a low-pressure recirculation region that was capable of bending a vertical natural gas plume toward the vent inlet. For the facility layout with roof supports, there was no substantial shape change in the flammable region.

For both scenarios, flammable natural gas was confined to a small region near the source; areas shaded in blue are too lean to combust. To illustrate this point more clearly, the time-history of the total mass, volume, and extent of flammable natural gas within the enclosure (i.e., mixture between the LFL and UFL) for each scenario is plotted in Figure 6. For the facility configuration without beams, the flammable volume and mass initially spiked to a peak value ~10 seconds after the release before assuming a nominally constant value, whereas for the facility with flammable beams the values were nominally steady throughout the release duration. Interestingly, the condition with support beams had a lower flammable mass and volume for most of the release as vertical structures induced by the support beams were able to more rapidly mix air into the release plume. Over time it appears that both the flammable mass and volume steadily increased as the cloud within the center of the maintenance facility steadily grew, although the release duration was too short for this to become a significant hazard. The maximum flammable mass within the facility at any point was 20 g, which corresponded to a max possible overpressure potential of 90 Pa from Equation (1). According to probit models from [29] the lowest potential overpressure harm threshold is the threat of broken glass (see Table 9), which has a lower limit of 1 kPa. Hence, no substantial hazard is expected from this scenario.

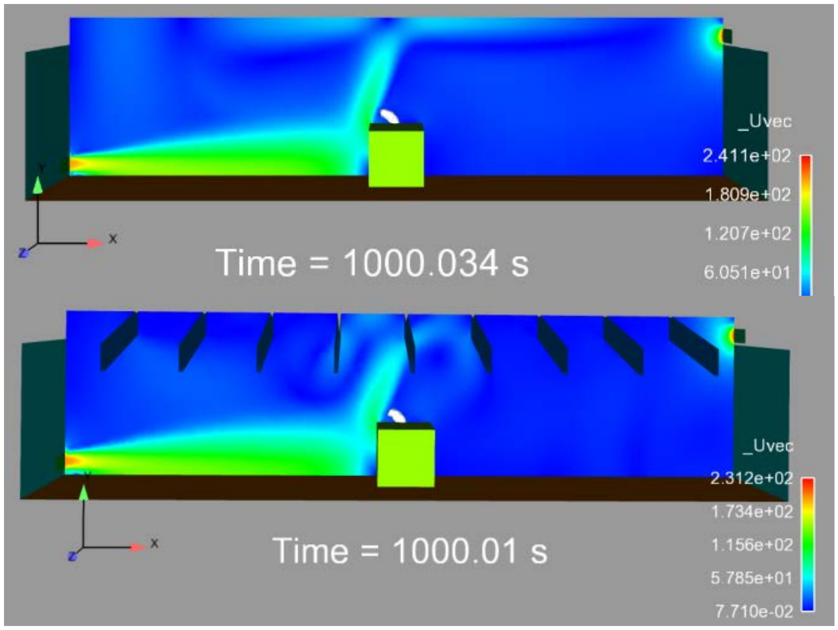

Figure 5. Natural gas mole fraction contours at 280 seconds into the release for facility layouts without (top) and with (bottom) roof supports for the LNG blow-off scenario. Velocity maps are also shown along the facility centerline to illustrate the impact of room currents on flow dispersion.

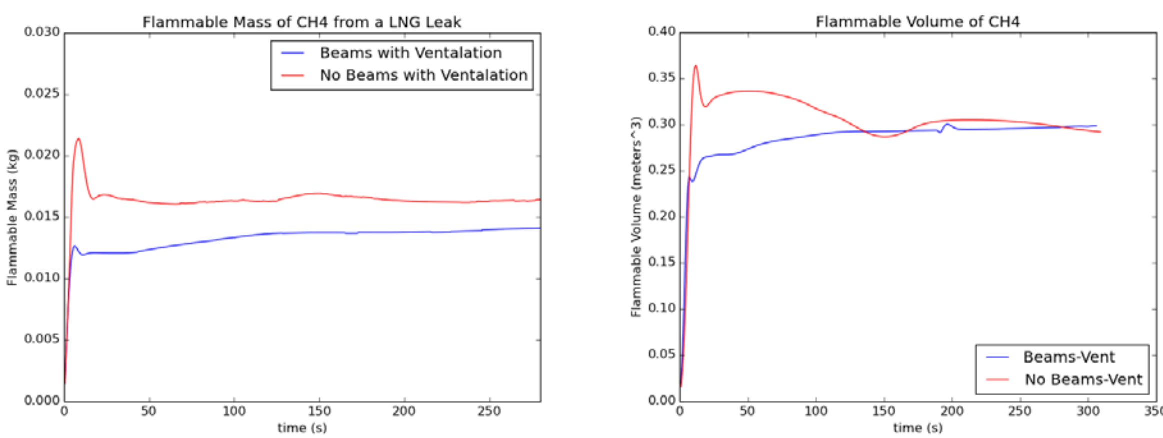

Figure 6. Time-history of the natural gas flammable mass and volume for LNG blow-off scenario with ventilation (left) and without ventilation (right).

To ensure the simulation results were not from an artifact of the coarse grid geometry, a grid-convergence study was performed for the scenario with roof supports that was believed to be more sensitive to grid sizing. The fine grid described earlier was used to repeat the simulation and the flammable mass time-history from both simulations, and as can be seen in Figure 7 produced near identical results to the simulation with the coarse grid out to just past 200 seconds into the release. From these results, it is clear that these simulation outputs are independent of grid sizing.

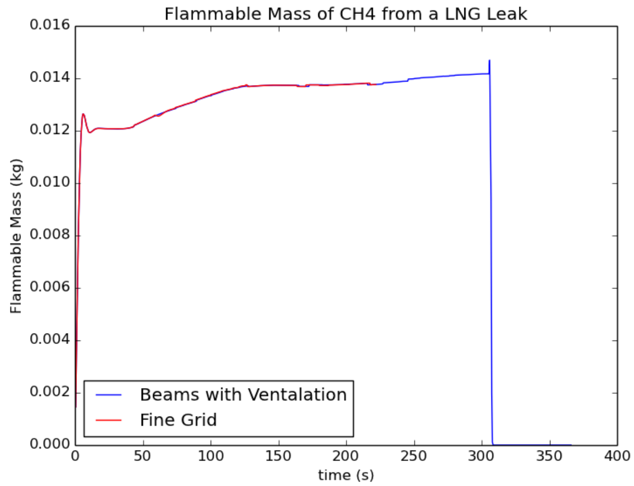

Figure 7. Grid convergence test with coarse (195,000 nodes) and fine (2.5 million nodes) grids for the LNG blow-off scenario with roof rafters

4.3.2 Scenario B: CNG and LNG Fuel System Line Cracking in a Large Garage

4.3.2.1 Scenario B Description

From the HAZOP, there were concerns that a natural gas release may occur during the purge of a vehicle fuel system as part of regular operational maintenance. Current NGV fuel systems are equipped with fail-closed solenoid valves located either at the tank or fuel supply manifold. The solenoid valves can only be actuated open when the engine is running, which effectively isolates onboard storage from the fuel system when the engine is off—there is no recorded instance of the valves failing open. For the identified scenarios, it was assumed that maintenance is to be performed on a CNG or LNG fueled vehicle where cylinder or manifold valves were used to isolate the fuel storage from the remainder of the fuel system where the work will be performed. However, room temperature (21°C) residual natural gas downstream of the onboard storage isolation (and heat exchanger for LNG vehicles) remains in the fuel system. Prior to the start of maintenance, a technician purges the remaining natural gas by cracking a ½” tube fitting on the fuel system at the control panel in the engine compartment—both are assumed to be on the vehicle side at a height of 1.0 meters from the floor.

For LNG vehicles, original equipment manufacturer (OEM) specifications indicate downstream line and filter volumes are around 1 to 2 liters with a maximum pressure of 8.62 bar (0.862 MPa = 125 psia). Accordingly, for this scenario the fuel system storage volume was set to 1.8 liters (110 in^3) with an overall natural gas storage mass of 10.4 g. Following LaChance et al. [32], the release area was assumed to be 3% of the overall tube area, which corresponded to a 3.8 mm^2 hole size. For CNG vehicles, the fuel system volumes are roughly double those for LNG vehicle, and the storage pressure can equal the tank pressure. Hence, the CNG line cracking scenario was identical except that the storage volume was increased to 3.3 liters (201 in^3) and the storage pressure was increased to 248 bar (24.8 MPa = 3,600 psia), which corresponded to an overall natural gas fuel system mass of 630 g. Note that for both scenarios it was presumed that the shutoff valve was engaged, which prevented the contents downstream of the storage isolation to escape once the line was cracked. Transient blow-downs were modeled as an isentropic expansion using MassTran [19]. Once again, gridding constraints limited the leak area to a 10 cm^2 (1.55 in^2) square hole, but was considered reasonable since the released gas was expected to first accumulate in the control panel or engine compartment before escaping into the maintenance facility.

4.3.2.2 Scenario B Results

For the second scenario, the impact of a fuel system ½” line cracked prior to the start of maintenance operations for CNG fueled vehicles was analyzed—since the total fuel within LNG fuel systems is much lower than for CNG vehicles, the CNG release was modeled since it is the bounding case. Moreover, only the facility layout without roof supports was considered since the plume from the side-release was not expected to be influenced by the centrally located circulation region above the vehicle. The transient blow-down was modeled via MassTran, with the release rate time-history provided in Figure 8.

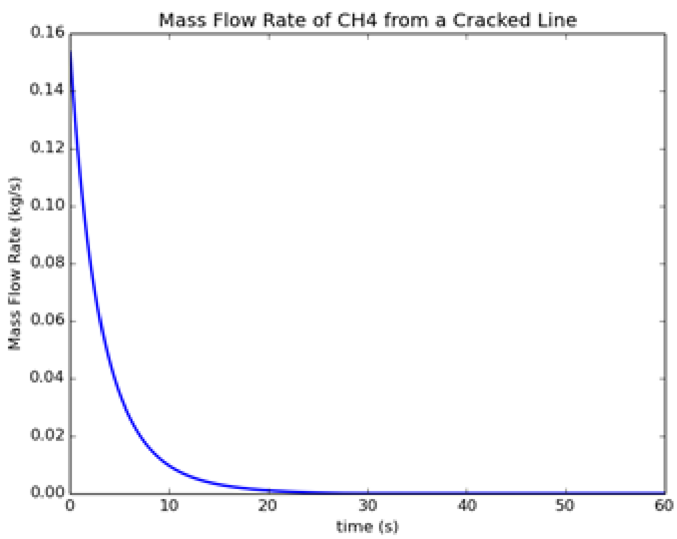

Figure 8. Mass flow rate time-history plot for the CNG line cracking scenario calculated from MassTran

Center plane LFL iso-contour maps for the facility without support beams are provided at select times in Figure 9. Complementary time-history plots of the total enclosure flammable mass, volumes, and extents are included in Figure 10. For the first few seconds into the release, the plume near the vehicle was where flammable mass was highest (up to 100 g) due to a combination of high initial mass flow rates and limited mixing. For this release, the peak flammable mass, volumes, and extents were small, which limited the peak possible overpressure to 0.43 kPa; well below the lowest harm threshold. Moreover, the duration of flammable mixture within the enclosure was very short, with all flammable regions gone by 23 seconds into the release (see Appendix C.2 for further details).

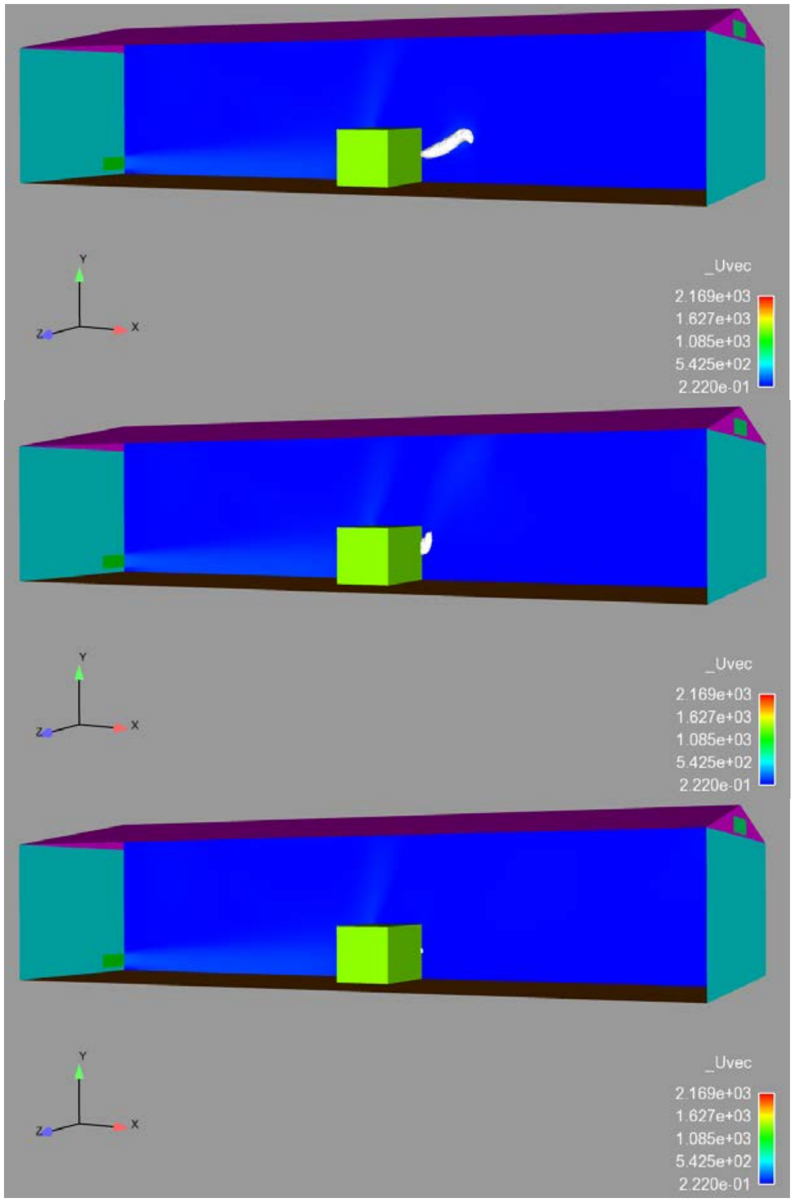

Figure 9. Natural gas LFL iso-contours at 2.5 (top), 10 (center), and 30.0 (bottom) seconds into the release for the CNG line cracking scenario without roof supports

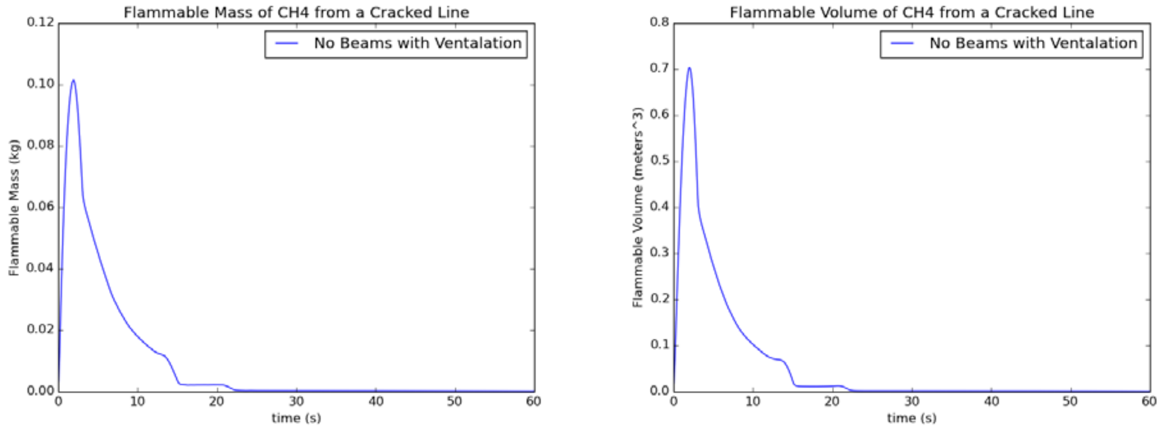

Figure 10. Time-history plots of total natural gas flammable mass (left) and volume (right) for CNG line cracking scenario without roof supports

4.3.3 Scenario C: Mechanical Failure of a PRD in a Large Garage

4.3.3.1 Scenario C Description

In the event a CNG cylinder becomes engulfed in a flame, onboard storage cylinders are protected against excessive pressure buildup by a thermally triggered PRD designed to fully open without the possibility for reseat in the event of activation. Accordingly, inadvertent actuation due to some mechanical failure would result in a rapid and uncontrollable decompression of all cylinder contents. Advances such as the use of dual activated valves have been implemented to reduce the likelihood of unintended release, although there remains some nominal risk due to the potential for human error. The SDOs view such a release as a bounding event for hazard potential. For this scenario, the entire contents of a 700 L, fully pressurized (248 bar = 24.8 MPa) CNG cylinder at room temperature (21°C) was released into the large NGV maintenance facility. Note that the tank volume was 50% greater than normal to simulate a worst case scenario. For convenience, the specified release point was identical to the LNG blow-off scenario. The PRD orifice diameter was set to 6.2 mm (0.24”) based on the flow rate specifications of typical commercially available PRDs. At the start of the release, the valve was assumed to fully open and remain that way for the duration. Once again gridding constraints limited the initial leak to 10 cm^2, and MassTran was used to model the transient blow-down.

4.3.3.2 Scenario C Results

The transient blow-down was modeled via MassTran, with the blow-down curve plotted in Figure 11. Note that higher flow rates and longer release durations meant these simulations were far more computationally expensive. Accordingly, only a single configuration could be evaluated within the current project scope. To ensure the worst-case-scenario, the facility layout with roof supports and active mechanical ventilation was selected since vertical flow structures above the plume were thought to aid in the accumulation of flammable mixture near the release point. The fine mesh was used to ensure convergence of all conservation equations for the higher Reynolds number flow from the larger release.

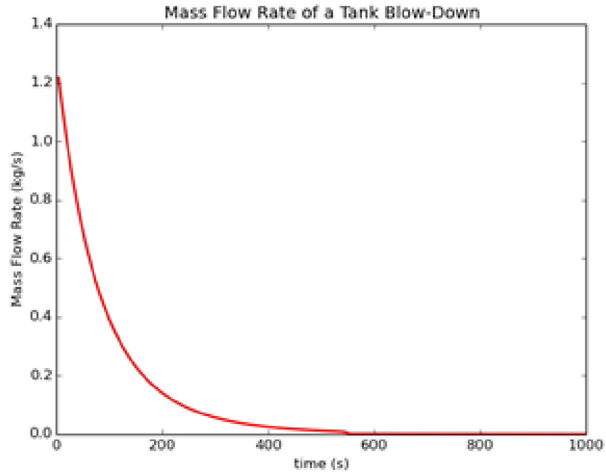

Figure 11. Mass flow rate time-history for the CNG tank blow-down scenario calculated from MassTran

Within the first second after the release for this scenario, a flammable mass already exists between the top of the vehicle and the ceiling of the garage (see Figure 12). The region with flammable gas concentrations then spread outward across the ceiling and filled a region up to approximately 80” (2.03 m) thick at the point of maximum flammable mass (~220 seconds after start of leak), as seen in Figure 12. As can be seen in Figure 11, the entire blowdown lasts approximately 10 minutes, and most of the mass has emptied the tank in less than 5 minutes. The flammable mass dissipates from the ceiling within 15 minutes of the start of the blowdown, as shown in Figure 13. Flammable volumes in the figures are in units of cm^3.

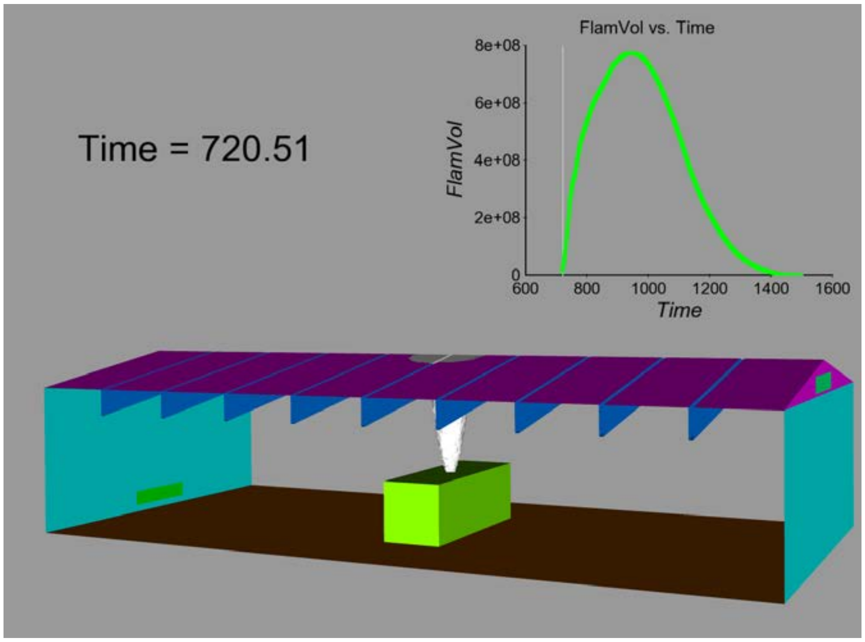

Figure 12. Flammable volume (white contour) and time history of CNG tank blowdown for first second of release

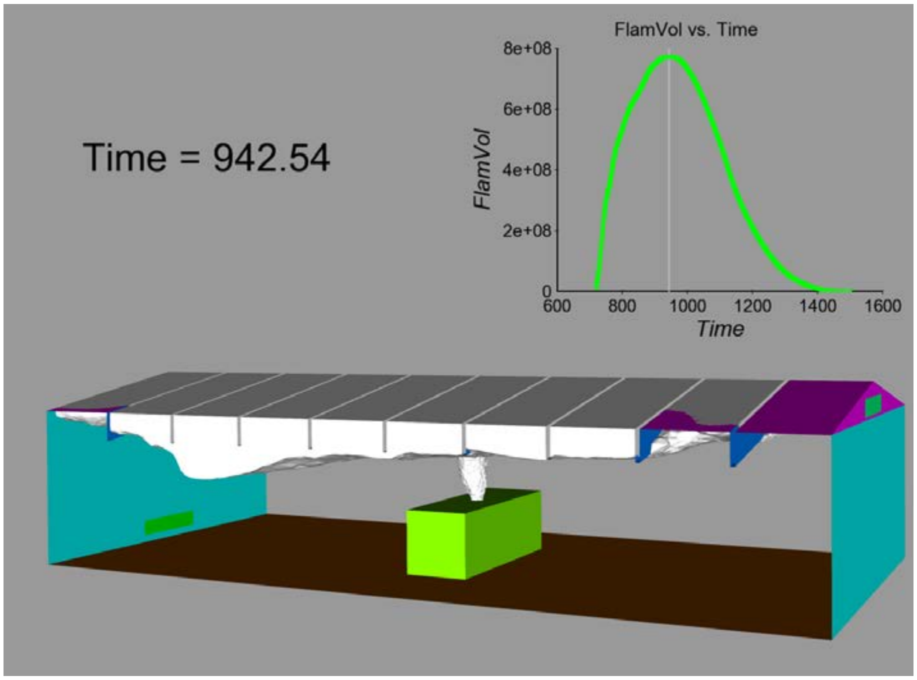

Figure 13. Maximum flammable volume is reached ~220 seconds after the start of the leak for CNG tank blowdown

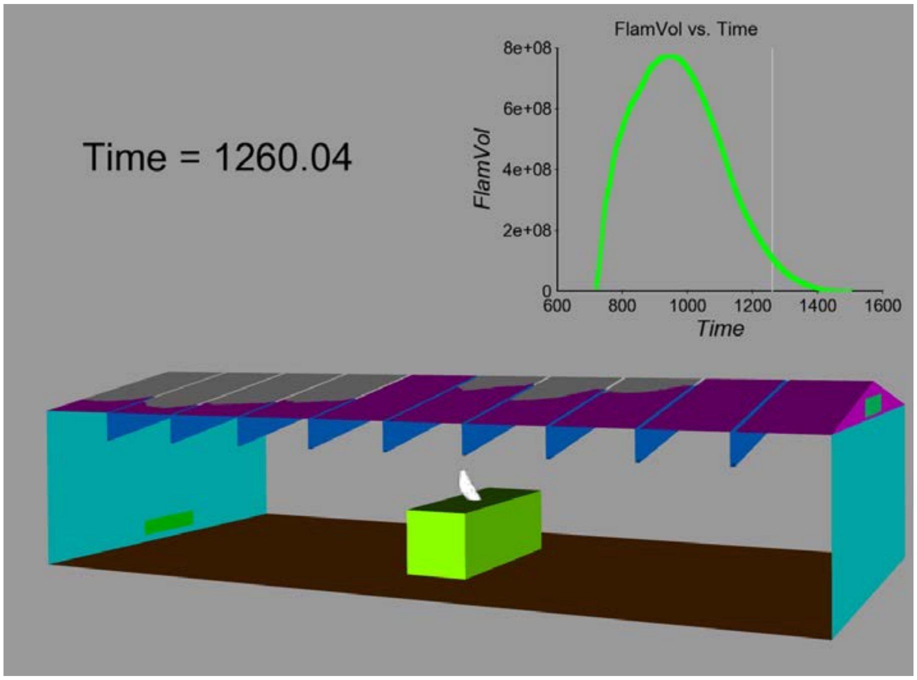

Figure 14. Flammable volume 680 seconds after the start of CNG blowdown

During this simulation, the maximum flammable volume of 772.7 m^3 occurred at 222.5 seconds from the start of the leak blowdown (942.5 seconds into the simulation). The volume of the garage is 3,122 m^3, and the stoichiometric consumed methane volume is 590 m^3. These conditions are used with Equation (1) to produce a change in pressure, or overpressure, of about 220 kPa. As stated above, as long as there is not enough turbulence to produce a detonation, this is most likely an overestimation of the actual overpressure that would occur for this scenario in this garage. According to [29, 30], this is large enough to collapse unreinforced concrete walls (see Table 9). Even if the calculated overpressure were as much as 50% off, it would still have this same consequence. Note that most of the flammable volume exists in the plume, which does extend below the 0.46 m threshold for protection from electrical ignition sources stipulated in NFPA 30A.

4.3.4 Scenario D: CNG Fuel System Line Cracking in a Small Garage

4.3.4.1 Scenario D Description

The setup of this scenario is very similar to Scenario B. The same velocity profile for the tank blowdown that is shown in Figure 8, but the release occurs in the smaller facility. Again, the simulation was done both with and without ventilation. To achieve the desired 5 ACH in the case with ventilation, a velocity of 200 cm/s is imposed on the vent opening near the floor of the garage. The vent in the ceiling was given an open boundary condition so the air flows out freely.

4.3.4.2 Scenario D Results

The figures below show the comparison of the results for crack in the tubing of the system for a vehicle in the small garage both without (Figure 15) and with (Figure 16) ventilation. The shapes of the two cases are compared in Table 10. Along with the maximum height of the plume, the distance to the top of the ceiling and the distance from the top of the plume to the height of the juncture between the walls and the pitched roof is noted. For this configuration of ventilation that produces flow from the floor to the roof, the plume of flammable mass is actually pushed higher.

Table 10. Comparison of effect of ventilation on flammable mass dimensions for fuel line crack in small garage

	Maximum Height	Distance to Ceiling	Distance to top of Walls
No Ventilation	215” (5.46 m)	75” (1.91 m)	25” (0.64 m)
With Ventilation	222” (5.64 m)	68” (1.73 m)	18” (0.46 m)

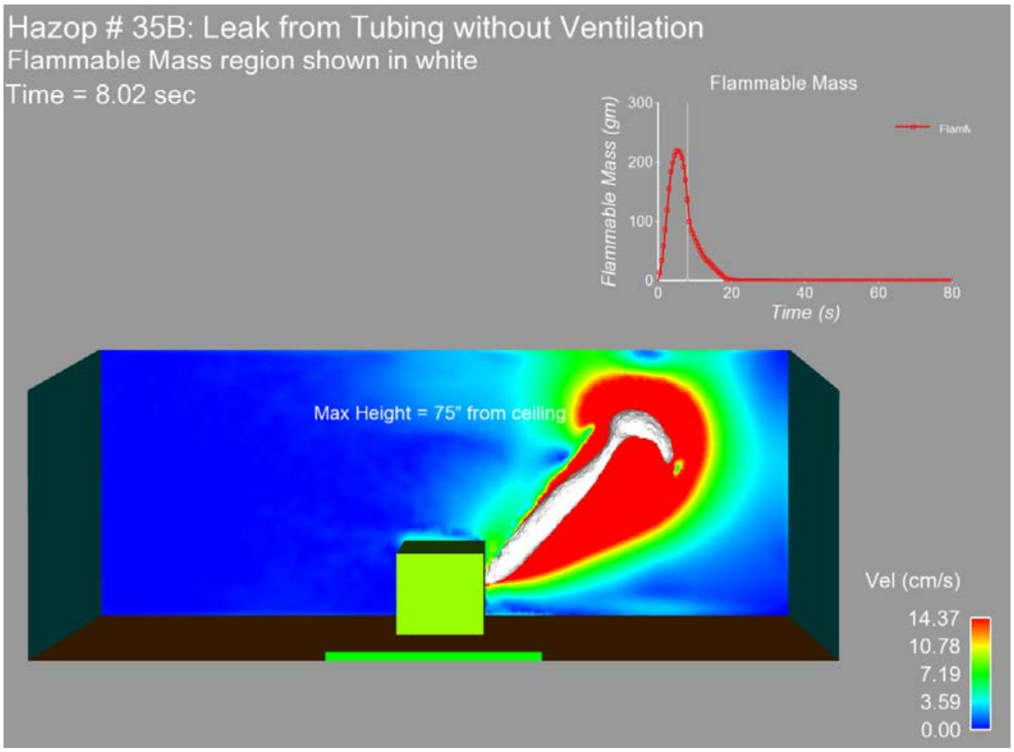

Figure 15. Leak from a crack in the line in a small garage without ventilation

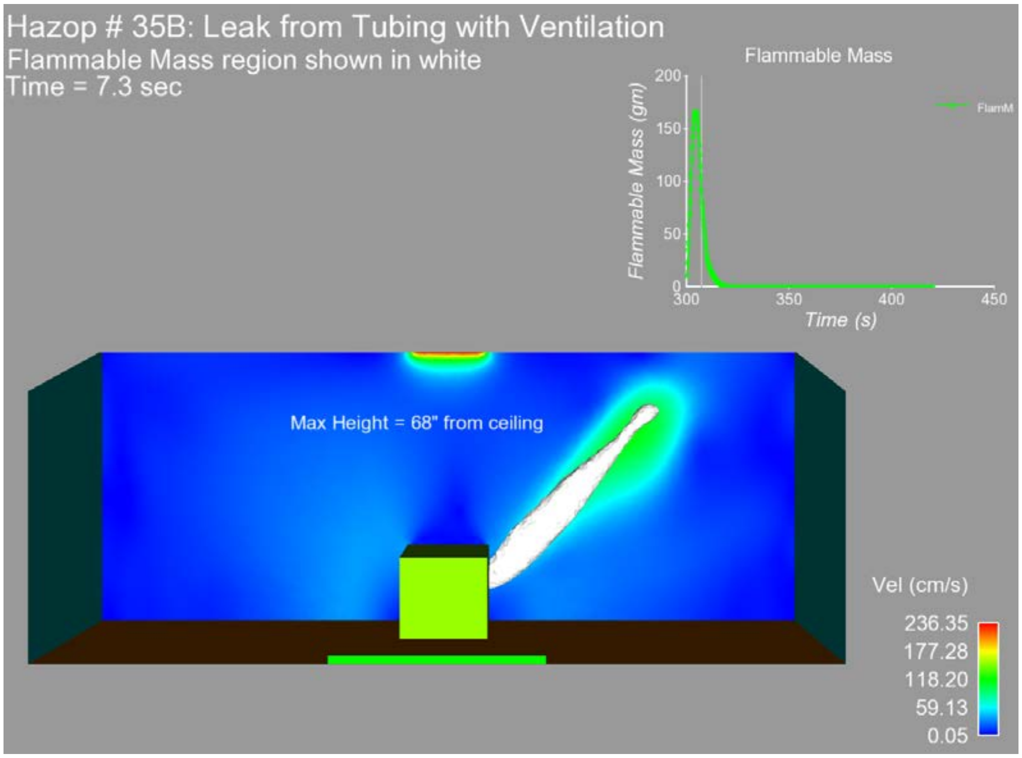

Figure 16. Leak in from a crack in the line in a small garage with ventilation

The flammable mass and flammable volume that occurs over time in this simulation are shown in Figure 17. The ventilation reduces the amount of flammable mass from a maximum of 0.22 kg to 0.17 kg. Using Equation (1), the calculated maximum overpressure if those plumes were to ignite is reduced from 2 kPa to 1.5 kPa. Both of these are under the 6.9 kPa overpressure from Table 9 that would cause injuries.

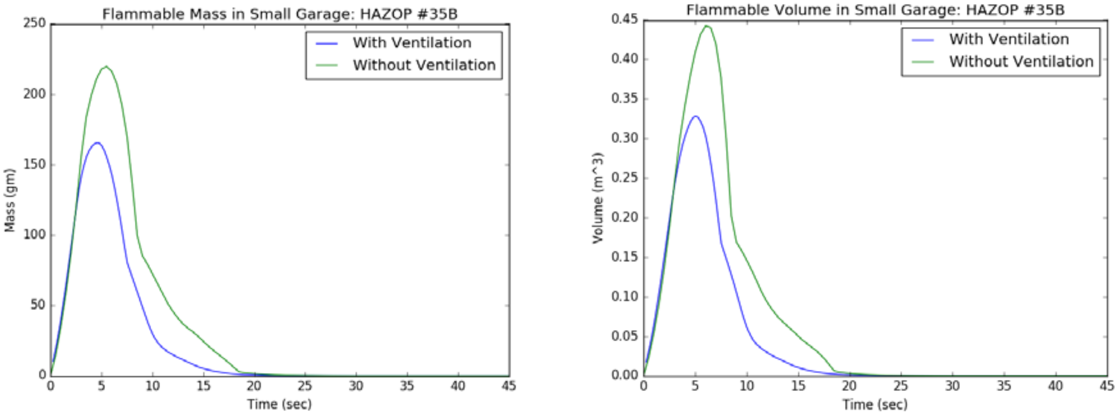

Figure 17. Flammable mass (left) and volume (right) for the release of natural gas from crack in the line of a system for a vehicle in a small garage

4.3.5 Scenario E: Mechanical Failure of a PRD in a Small Garage

4.3.5.1 Scenario E Description

The setup of this scenario is very similar to Scenario C. The same velocity profile for the tank blowdown that is shown in Figure 11, but the release occurs in the smaller facility, making this a very conservative estimate of a release. For this scenario the gas was released horizontally, to see the effects of leak orientation. This simulation was done only with ventilation. To achieve the desired 5 ACH in the case with ventilation, a velocity of 200 cm/s is imposed on the vent opening near the floor of the garage. The vent in the ceiling was given an open boundary condition so the air flows out freely.

4.3.5.2 Scenario E Results

Figure 18 shows the results for a full tank blowdown in the small garage with ventilation. A full tank blowdown inside of a smaller facility can result in a cloud of flammable mass that reaches floor to ceiling, especially if the release direction is to the side.

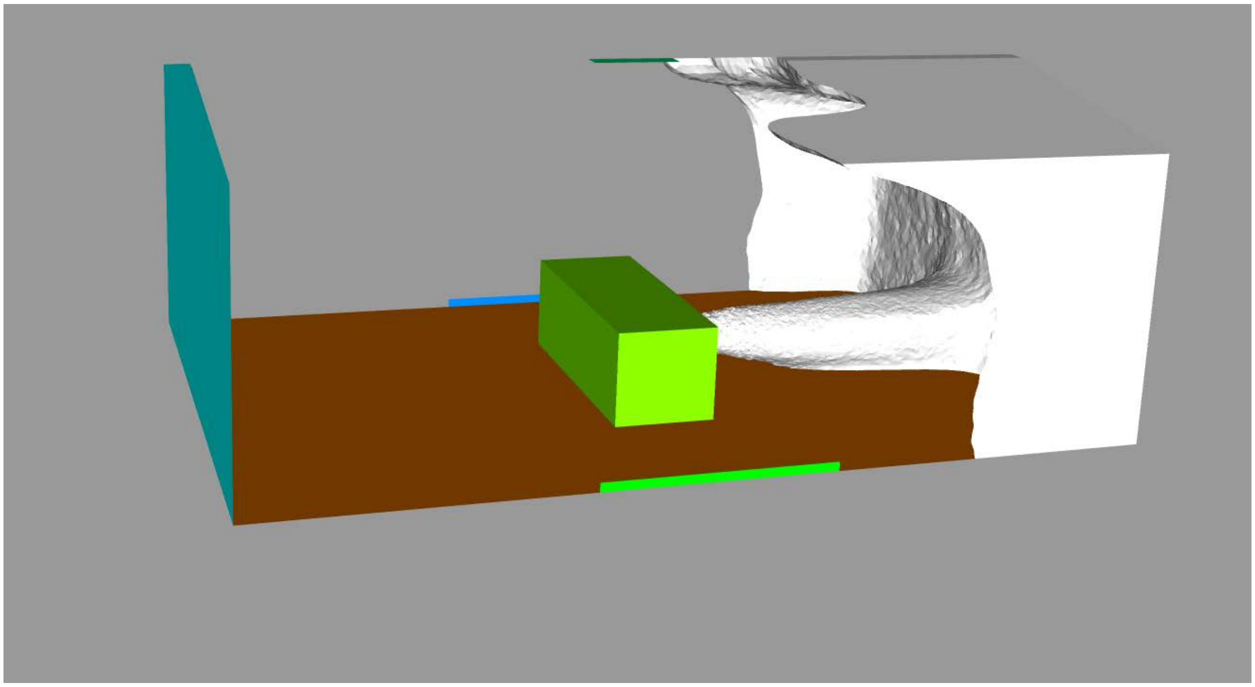

Figure 18. Full tank blowdown inside of a smaller facility can result in a cloud of flammable mass that reaches floor to ceiling

4.3.6 Scenario F. Failure of an LNG PRV to Reclose After Proper Venting

4.3.6.1 Scenario F Description

The final scenario is of a release from a 119 gallon (450.46 L) liquefied natural gas (LNG) tank. Since LNG is used mostly on larger vehicles, the release was modeled in the large garage without ventilation. The temperature inside the tank was assumed to be -152°C and the pressure started at 350 psig (2.51 MPa absolute), which is the release point of the secondary relief valve. The orifice was assumed to have a diameter of 0.44” (0.011 m). The quality of the tank is 55%.

This hazard scenario is a failure of a pressure release valve (PRV) to re-close after proper venting. This is a mechanical failure and results in the total volume of the tank released. This scenario was modeled with the assumption that the leak originates from the saturated vapor region of the tank. The mixture in the tank was modeled quasi-steady and it was assumed that the mixture was in thermodynamic equilibrium and in a saturated state. This assumption is only valid if the rate of vaporization is much faster than the mass loss at the leak and will have to be verified, otherwise a two-temperature model would be required.

4.3.6.2 Scenario F Results

The velocity of the hydrogen being released from vapor side of the tank is shown in Figure 19. This was calculated using a modified MassTran that can take into account two phase vessels. The temperature of the released gas was assumed to be the same as the tank: -153°C.

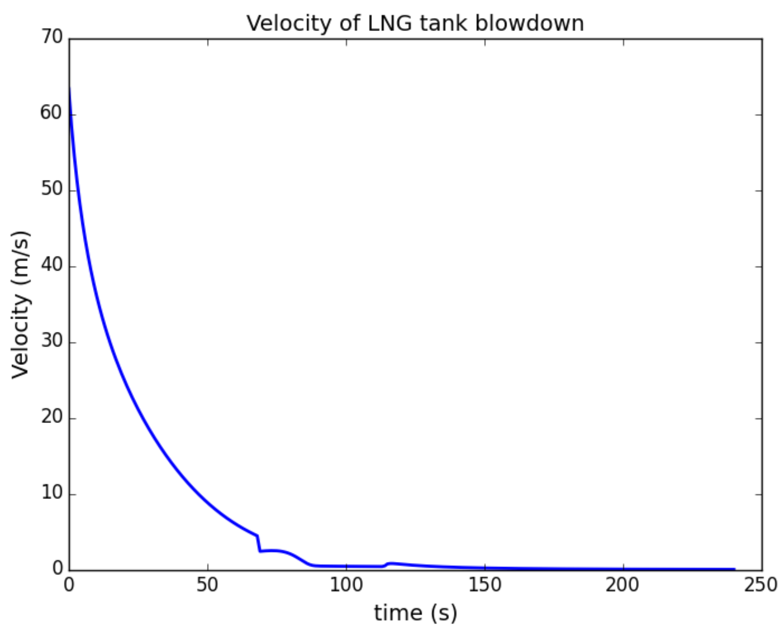

Figure 19. Velocity of saturated vapor leaving the LNG tank when valve fails open

The results from Fuego show that the momentum of the released methane would cause a plume of flammable mass (shown in white) to reach the ceiling if the valve opening were pointed upwards.

This can be seen in the top panel of Figure 20. However, in the later times of the blowdown when the velocity is less, the cold methane is actually denser than air, so it will sink to the floor of the garage until ventilation has dispersed the gas. Near the end of the release when the mass flow rate is the smallest, the cloud of flammable mass becomes buoyant. This matches the scenarios when only small amounts of methane are released from a LNG system.

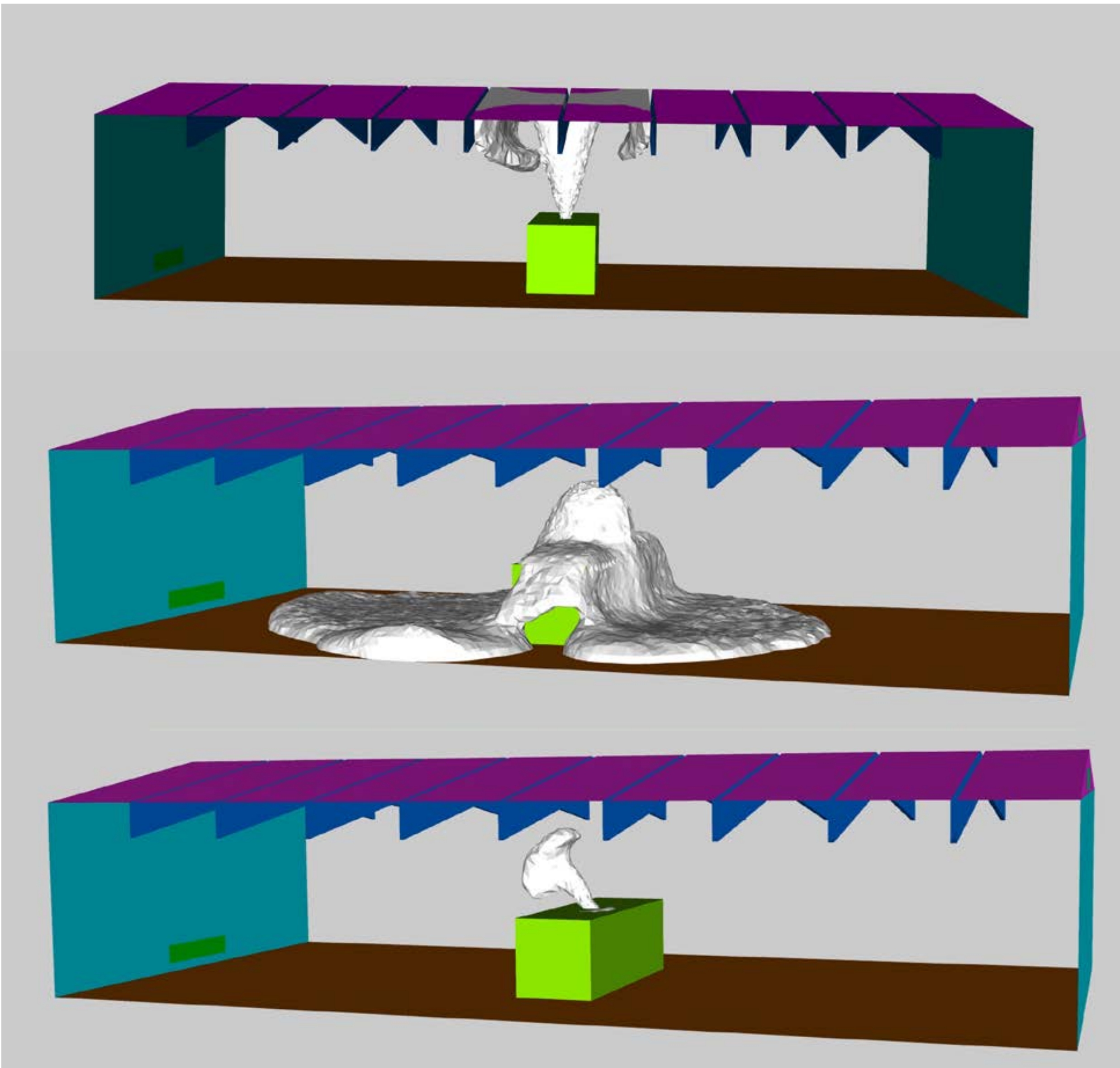

Figure 20. Flammable mass released from LNG tank at 8 seconds (top), 40 seconds (middle), and 190 seconds (bottom) after the start of the release from an open valve.

5 CODE ISSUES AND SUGGESTED RESOLUTIONS

There are several issues, points of confusion, and conflicts within various national and international codes that apply to natural gas vehicle repair garages. These are summarized in Table 11, and will be discussed in the following sections. Specific issues in different codes will be identified for each topic area, and suggested ways to resolve these issues will be presented.

Table 11. Code issue matrix

Subject	Applicable Standard					Issue	Potential Resolution	HAZOP Scenario	Modeling Scenario
	Org	Code	Year	Section	Requirement				
Ventilation	ICC	IFC	2018	2311.8.8	Ventilation for NG/H_2 repair garages 1 cfm/12 ft^3 (0.00139 $m^3/s/m^3$)	Different ventilation rates IFC not explicit about fueling system	Propose to harmonize	1, 15, 35B	A, B, C, D, E
	NFPA	30A	2018	7.3.6.7	Ventilation of 1 cfm/ft^2 (0.00508 $m^3/s/m^2$) for NG/H_2 fuel dispensing area only				
Ventilation in Pits	ICC	IFC	2018	2311.4.3	Where Class I liquids are stored/used, minimum 1.5 cfm/ft^2 (0.008 $m^3/s/m^2$)	Different rates, nothing specific to CNG but other liquid fuel codes should be sufficient	Propose to harmonize after modeling	1, 7, 12	A, B, F
	NFPA	30A	2018	7.4.5.4	When building is occupied or vehicles present, 1 cfm/ft^2 (0.00508 $m^3/s/m^2$) from <12" of floor				
Gas Detection	ICC	IFC	2018	2311.8.9 & 916.8	Detection system must activate when gas level exceeds 25% of LFL.	No issue	No action	1, 7, 12, 15, 35B	A, B, C, D, E, F
	NFPA	30A	2018	7.4.7	For nonodorized gas, must have approved gas detection system	No issue	No action	N/A	N/A
				7.4.7.1	Calibrated to fuel type, activate when level exceeds 25% of LFL, must be in pits for LNG/CNG	No issue	No action	1, 7, 12, 15, 35B	A, B, C, D, E, F
				7.4.7.2	Activation leads to audible/visual alarms, deactivation of heating, activation of mechanical ventilation	Lower ignition energy for H2, not necessary to shut down all heating for NG	Propose change to gas-specific temperatures	None	None
				7.4.7.3	Failure of gas detection system results in deactivation of heating systems and activation of mechanical ventilation and cause a signal in approved location			None	None
				7.4.7.4	Must be monitored as per NFPA 72	No issue	No action	N/A	N/A
Sources of Ignition	NFPA	30A	2018	7.6.6	Major repairs on lighter-than-air fueled vehicles, open flame heaters or surfaces 400C not allowed with flammable concentrations of gas	Only way to determine area where ignitable concentration of gas may be present is using CFD or similar, need a way that is easier but still safe	Need better path forward	1, 7, 12, 15, 19, 35B, 37	A, B, C, D, E, F
	ICC	IFC	2018	2311.3	No ignition sources within 18" (0.46 m) of floor for liquid fuel	Liquid fuel requirements likely do not apply to CNG, H2 gas requirements might	No action	1, 7, 12, 37	A, B, F
	ICC	IBC	2018	406.2.9					
	ICC	IMC	2018	304.3					
	NFPA	70	2017	(various)					

Subject	Applicable Standard					Issue	Potential Resolution	HAZOP Scenario	Modeling Scenario
	Org	**Code**	**Year**	**Section**	**Requirement**				
Electrical Classification	NFPA	30A	2018	8.2.1	Set area within 18" (0.46 m) of ceiling in major repair garages as Class 1, Div. 2 hazardous location	Based on 150% of CNG releases	Issues with 18" (0.46 m) basis. Modeling does not support these. A path forward needs to be reached	1, 7, 12, 14, 15, 19, 35B, 37	A, B, C, D, E, F
				Table 8.3.2	Major repair garages with lighter than air gases, area is Class 1 Division 2 within 18" (0.46 m) of ceiling unless ventilation 1 ft^3/min/ft^2 taken from a point within 18" (0.46 m) of highest point on ceiling	No specifics on LNG, CNG requirements may be too high		1, 7, 12, 15, 19, 35B, 37	All
Preparation of Vehicles for Maintenance	ICC	IFC	2018	2311.8.1	Close valves to isolate CNG/LNG to reduce amount that could be lost, leak test fuel system if any damage is expected	No issue	No action	35B, 37	B, C, D
			2018	2311.8	Newly adopted exception for vehicles with fuel systems emptied and purged with N_2 and for fuel systems with <250 psi (1.72 MPa) of gaseous fuel	250 psi (1.72 MPa) of natural gas still gives flammable concentration	Need better path forward		
Maintenance and Decommissioning of Containers	NFPA	52	2016	(various)	Specifics on construction and maintenance requirements	No issue	No action	37	None

5.1 Ventilation

There are two conflicts between the IFC and NFPA 30A: ventilation rates and areas. IFC requires that a ventilation rate not less than 1 cfm per 12 ft^3 (0.00139 $m^3/s/m^3$), while NFPA 30A requires a ventilation rate of 1 cfm/ft^2 (0.00508 $m^3/s/m^2$). This difference in basis (garage volume vs. floor area) will lead to one code or the other being more conservative, depending on the ceiling height. Figure 21 shows that for ceiling heights that are less than 12 feet (3.66 m), NFPA 30A is more conservative (higher ventilation rate), whereas for ceiling heights >12 feet (3.66 m), the IFC is more conservative.

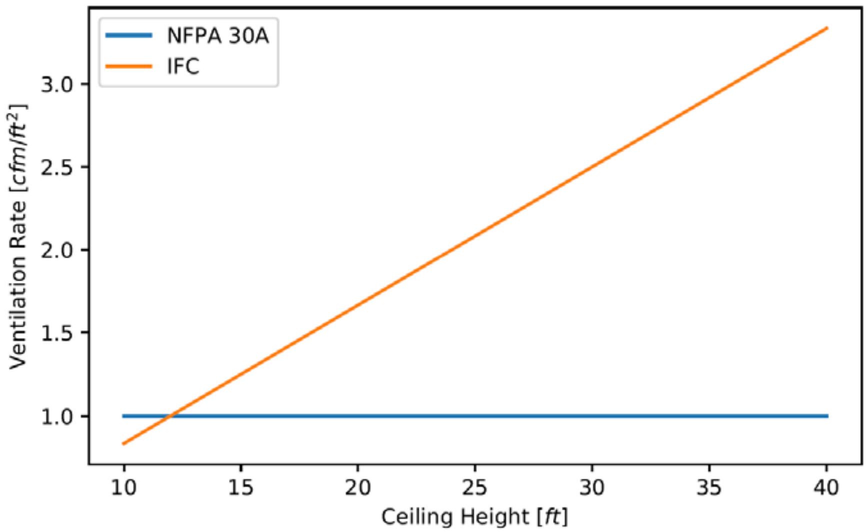

Figure 21. Comparison of repair garage ventilation rates from IFC and NFPA 30A

The two codes should be harmonized, preferably by both relying on a justified ventilation rate. Enforcing ventilation rates based on floor area is much easier to do, but ignores the height of the ceiling. Measuring garage volume is more difficult; ceilings may not be flat at a single height. However, determining the ventilation rate from the volume of the space to be ventilated could provide a more useful approach. Ideally, to maximize ventilation effectiveness, ventilation rates would be based specifically on each specific container of flammable gas, including amount of gas and geometry of the vehicle/container; however, this is unrealistic and unreasonable to do for each and every possible case. Thus, more general examination of ventilation rates would help to ensure that the volume-based ventilation rate chosen provides a good balance of protection and inconvenience. While ventilation changes showed an effect of lowering the flammable mass in the results above, a wider study is needed to draw definite conclusions.

5.2 Pit Ventilation

The IFC requires a minimum rate of 1.5 cfm/ft^2 (0.008 $m^3/s/m^2$) to prevent accumulation of flammable vapors in pits, whereas NFPA 30A requires a rate of at least 1 cfm/ft^2 (0.00508 $m^3/s/m^2$). Until the codes are harmonized, the local AHJ must specify the applicable rate for each facility. While the probability of a LNG liquid release may be low, the cold vapor release may initially be heavier than air and persist in a subgrade area before eventually warming up and rising due to buoyancy. The existing ventilation requirement for liquid fuels should be adequate for the addition of LNG to major repair facilities with approval of the local AHJ. Note that pit requirements were not considered for the present analysis, but the potential for accumulation of cool LNG within a pit is something that should be considered for future work. Fluid dynamics modeling of LNG releases in pits will improve the understanding and inform what ventilation rate will be most useful.

5.3 Gas Detection

Both IFC and NFPA 30A require gas detection systems for major repair garages that activate audible and visual alarms. NFPA 30A requires that the gas detection system deactivate heating systems and activate mechanical ventilation. However, deactivating heating systems that do not have an open flame and have lower temperature surfaces may not be necessary for all flammable gases. While both are lighter-than-air flammable gases, natural gas (methane) and hydrogen have several important differences in various flammability and ignition metrics [33], which are summarized in Table 12.

Table 12. Ignition and flammability properties of hydrogen and methane in air (from [33])

	Hydrogen	Methane
Lower Flammability Limit (vol%)	4.0	5
Upper Flammability Limit (vol%)	75	15
Auto-Ignition Temperature (°C)	520	640
Minimum Ignition Energy (mJ)	0.017	0.3

The first difference of note is the extremely wide range of concentrations of hydrogen that are flammable, compared to methane. This contributes to more opportunities for ignition; Schefer et al. found that methane had much lower probabilities of ignition and over a much shorter distance from a leak than hydrogen [34]. Second, the auto-ignition temperature is the temperature at which a gas/air mixture will spontaneously ignite at ambient pressure. The 120°C difference in these temperatures mean that an external surface temperature of 500°C on a heating source is very close to igniting a hydrogen mixture, but is well below this autoignition temperature for methane. Third, the minimum ignition energy is the smallest amount of energy in a spark or other source of ignition that is needed to ignite a flammable mixture of gas and air. The minimum ignition energy for hydrogen is over one order of magnitude less than for methane. This indicates that a hydrogen flammable mixture is much more sensitive to low-energy ignition sources than methane. Adjusting codes to differ heating system shutdown requirements based on the specific gas used does add complexity to compliance, but should prevent unnecessary burdens on NGV repair garages, while ensuring that additional safety precautions remain in place where warranted.

5.4 Ignition Sources

Code requirements for ignition sources tend to focus on more traditional liquid (heavier-than-air) fuels, limiting ignition sources from the space 0.46 m (18”) from the floor. Floor-level requirements are likely not applicable to CNG due to the lighter-than-air nature of the gas, causing a leak to rise away from the floor. NFPA 30A requires that open flame heaters or high temperature heating equipment be kept away from areas subject to ignitable concentrations of gas.

At the moment, the only way to quantify where these flammable mixtures exist is to perform CFD modeling of credible CNG and LNG releases within representative facility geometries. There is a need to develop and validate reduced order methods that are expedient and accessible to a wide range of users, but still provide a sufficient level of accuracy.

5.5 Electrical Classification

Electrical classification areas are treated somewhat differently than ignition sources discussed above and so have additional requirements. NFPA 30A classifies the area within 0.45 m (18”) of the ceiling is classified as Class 1, Division 2 for electrical devices. When considering what constitutes a credible release, it has been noted that existing CNG code requirements were based on the release of 150% of the contents of the largest cylinder in the repair facility in response to a series of PRD failures in the 1990s . The PRDs have been through several design revisions since then and the last few cases of premature release were over ten years ago, so these assumptions should be revisited.

The area within 18” (0.46 m) of the ceiling does not cover the areas in which ignitable concentrations of gas can be present for a release of natural gas. As modeling results for multiple scenarios in Section 4.3 show, there is often a significant plume of ignitable gas between the leak and the ceiling, which is not covered by this near-ceiling requirement. Accumulation of natural gas in the ceiling can result in ignitable concentrations of natural gas that extend from the ceiling to well below 18” (0.46 m), as shown in Section 4.3.3.2. Even accumulation on a wall from a release to the side can result in flammable masses that extend from floor to ceiling (see Section 4.3.5.2). Flammable volumes can be confined to small areas near the point of release (Scenario A, Section 4.3.1.2), larger areas away from the point of release but for short time scales (Scenario B, Section 4.3.2.2 and Scenario D, Section 4.3.4.2), or near complete coverage of the ceiling (Scenario C, Section 4.3.3.2), wall (Scenario E, Section 4.3.5.2), or floor (Scenario F, Section 4.3.6.2) of the garage. This also includes a low-pressure release case which results in a flammable volume from the point of release to the ceiling (Appendix C.3). It is not immediately obvious how best to account for these differences. However, current requirements appear less than effective for establishing electrical device requirements, and a better path forward must be developed.

6 SUMMARY, CONCLUSIONS, AND FUTURE WORK

Existing code language has been developed from expert knowledge and field experience, but it is recognized by SDOs that risk-informed approaches that identify high-risk scenarios along with dominant causal factors and that quantify the effectiveness of accident prevention/mitigation strategies are needed. The scope of work has been split into two phases with the current report summarizing the results from Phase II. This work involved a highlight of specific code issues, a HAZOP to identify critical hazards from operational activities, and an analysis of potential consequences for credible hazards.

A HAZOP was performed using representative CNG and LNG system diagrams and common maintenance facility activities. This resulted in 41 Hazard Scenarios, which were correlated with 9 different Operation States. Each of these Scenarios was then classified according to consequence of the release, frequency of the release, and an escalation factor, which related to whether or not the release could be mitigated. This classification resulted in identification of 8 critical scenarios out of the original 41 based on scenarios expected to occur and those determined to be high risk based on consequence, frequency and escalation. The critical scenarios ranged from relatively small releases of natural gas from a relief valve, to large scale releases of the entire contents of a CNG cylinder or LNG storage tank. This allowed for specific causes of critical hazardous releases to be identified.

Computational fluid dynamics calculations were performed for five different scenarios (and an additional low-pressure leak scenario), which included two different garage sizes for heavy- and light-duty vehicles. The scenarios considered releases from both gaseous and liquid tanks, and ranged from small releases from fuel lines or venting to large scale full blowdowns of the entire fuel system. The effect of ventilation was considered with and without roof supports. Based on various leak sizes of methane from a simulated vehicle, the flammable volume was calculated at different times through the simulation. This flammable mass was then estimated to an overpressure hazard should it ignite. In general, flammable volumes extended from the point of release for short distances for small leaks, but for larger leaks could completely cover the ceiling, wall, or floor of the repair garage. The specific covered areas for each release depended on the orientation of the leak, amount of fuel released, and conditions (e.g., temperature) of the released fuel.

Conflicts between the NFPA and ICC codes and code requirements that could be improved were identified. Ventilation rate differences between IFC and NFPA 30A were identified and quantified for various ceiling heights; it was noted that ventilation rates should account for this celling height. In addition to differing requirements in the basis (volume or area) of the required rate, differences in the required ventilation rate itself were also noted; many AHJs require the most conservative code requirement to be used, but these codes should be harmonized based on a technical basis for the ventilation rates. Differences in flammability and ignition characteristics for natural gas and hydrogen were highlighted, and it is suggested that code requirements account for this difference in the shutting down of heating systems. The 18” (0.46 m) from ceiling electrical classification requirement was shown by modeling to be ineffective at protecting against flammable concentrations of natural gas. There still exists a need to develop a better way to address this issue of limiting sources of ignition.

There is a significant need for better understanding of how various alternative fuels behave in order to mitigate flammability and other hazards associated with these fuels. Natural gas is lighter than air when in the gaseous phase near ambient temperatures, but liquefied natural gas releases show flammable concentrations near the ground before it is warmed by the surrounding air. This difference has already resulted in some code differences between CNG and LNG hazards, but these codes should be better informed by how these fuels behave. This includes developing a better understanding of gaseous releases that tend to rise to near the ceiling; a better way of mitigating these flammable masses is needed. This improved understanding can also be combined with previous experience and expertise at SNL with other non-maintenance facilities relating to hydrogen vehicle infrastructure. For example, risk-informed design for CNG and LNG fueling stations could be implemented. Furthermore, similar analyses can be developed for other alternative fuels, such as propane and hydrogen.

6.1 Future Opportunities and Synergy with Hydrogen Programs:

The overlap between hydrogen fuel cell vehicles and NGV in physical characteristics of the fuel, experimental capabilities, modeling tools, and expertise at SNL creates significant amount of added value to alternate fuel energy projects in both the DOE and external entities. Listed below are examples and opportunities of how VTO and other sponsors benefit simultaneously from model development and validation leading to a deeper understanding of alternative fuel behaviors that will improve safety codes and standards (SCS).

1. Improving the fundamental science of alternative fuel release behavior and applying science to predict risks and potential for harm during design and safety assessments:

   Previous Example: Extracted and adapted HyRAM physics models to natural gas and propane to predict leak rates and plume characteristics.

   Future Opportunity: Expanding risk analysis to natural gas and propane and adding these fuels to the "HyRAM" package.

2. Experiments and modeling of liquefied cryogenic flows releases for SCS improvement and supporting novel applications of alternative liquid fuels with increased energy density.

   Previous Example: Laboratory releases of liquid hydrogen (LH_2) and LNG on the same experimental platform for model validation.

   Future Opportunities:

   - Modify currently planned large scale release experiments of LH_2 to validate models for alternative liquid fuels.

   - Multi-phase flow modeling developed for LH_2 can be adapted for LNG and other alternative fuels.

- Design and execute validation experiments for multi-phase flow modeling of LH_2 and alternative fuels.

3. Vehicle Tunnel Safety Study

   Previous Example: DOE FCTO project which characterized the risks and consequences of traffic incidents involving hydrogen fuel cell vehicles in tunnels

   Future Opportunity: Conduct simulations with NGV vehicles or busses to assess risk in tunnels

4. Risk Analysis and Modeling in Repair Garages

   Previous Example: Risk analysis and simulations of release events in repair facilities performed as a part of this project

   Future Opportunity: Consider multi-fuel maintenance facilities.

5. Release Scenarios for Maritime Applications

   Previous Example: Risk analyses and safety assessments for a hydrogen fuel cell ferry boat and refrigeration units (DOT/MARAD project).

   Future Opportunity: Assess the maritime use of CNG/LNG.

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APPENDIX A: HAZOP DATA SHEETS – PHASE I

HAZOP Analysis: Indoor LNG and CNG Maintenance Activities in Major Repair Facilities

						Prevention Features			Mitigation Features	
HAZOP Number	**Component**	**Operation State**	**Hazard Scenario**	**Causes**	**Consequences**	**Design**	**Administrative**	**Detection Method**	**Design**	**Administrative**
1	LNG-1 (Overpressure regulator)	3in, 4, 7, 8	Leakage from regulator body	Seal failure, mechanical defect, damage, etc.	Minor leakage of GNG					
2	LNG-1 (Overpressure regulator)	3in, 4, 7, 8	Inadequate regulation of gas flow	Regulator failure	Overpressure of downstream components and potential GNG release					
3	LNG-1 (Overpressure regulator)	3in, 4, 7, 8	Inprocess leakage	Mechanical defect, damage, etc.	Potential minor release of GNG					
4	LNG-2 (Fuel Shutoff Valve	3in, 4, 5, 7	Valve fails to shut completely, or leaks	Failure of seals,spurious operation	Potential catastrophic release of GNG					
5	LNG-3 (Heat exchanger)	3in, 4, 5, 7	Leakage from heat exchanger	Leaks of LNG or GNG due to defective materials, corrosion, thermal fatigue, pressure rupture, etc.	Release of LNG or GNG					
6	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Overpressure of tank and failure of relief valve to open	Valve failure, insulation failure, excessive hold time	Rupture of tank and catastrophic release of LNG					
7	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Overpressure of tank and proper operation of relief valve	Excessive hold time, insulation failure	Minor release of GNG					
8	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Outlet or fitting on tank fails	Manufacturing defect or installation error	Potential catastrophic release of LNG					
9	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Leak of LNG into the interstitial space between inner and outer tanks	Internal corrosion of tank, fatigue failure	Insulation failure, warming, overpressurization of the outer tank and potential catastrophic release					

						Prevention Features			Mitigation Features	
HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences	Design	Administrative	Detection Method	Design	Administrative
10	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Damage to outer tank resulting in compromising the insulative capacity	Mechanical damage, accident	Accelerated warming of the tank, overpressurization of the outer tank and potential catastrophic release					
11	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Damage to the outer tank due to leakage from the inner tank to the interstitial space	Embrittlement and cracking due to cryogenic properties of the material	Potential catastrophic release of LNG					
12	LNG-5 (Pressure relief Valve)	3in, 4, 5, 7, 8	Release of GNG through PRV	Failure of PRV to reclose after proper venting	Total volume of tank released					
13	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Overpressurization of Cylinder	External fire AND failure of PRD to operate	Potential catastrophic release of CNG					
14	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Overpressurization of Cylinder	External fire AND successful operation of PRD	Potential catastrophic release of CNG					
15	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Outlet or fitting on tank fails	Manufacturing defect or installation or maintenance error	Potential catastrophic release of CNG					
16	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	CNG tank rupture	Mechanical damage, tool or equipment impingement	Potential catastrophic release of CNG					
17	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Leakage from the cylinder	Accident, vandalism, crack propagation, fatigue failure	Potential catastrophic release of CNG					
18	CNG-2 (Cylinder Solenoid Valve)	3in, 4, 5, 7, 8	Leakage of CNG through body of solenoid	Mechanical damage, material failure	Minor release of CNG					
19	CNG-3 (Pressure Relief Device)	3in, 4, 5, 7, 8	Failure of PRD to hold pressures below activation pressure	Mechanical defect, material defect, installation error, maintenance error	Potential catastrophic release of CNG	Use improved PRD design		Gas detection system	Improved PRD is more reliable	Prioritize parking of dead vehicles outdoors

						Prevention Features			Mitigation Features	
HAZOP Number	**Component**	**Operation State**	**Hazard Scenario**	**Causes**	**Consequences**	**Design**	**Administrative**	**Detection Method**	**Design**	**Administrative**
20	CNG-3 (Pressure Relief Device)	3in, 4, 5, 7, 8	PRD leak of CNG	Mechanical defect, material defect, installation error, maintenance error	Minor release of CNG					
21	CNG-4 (Ball Valve)	3in, 4, 5, 7, 8	Valve leaks	Failure of valve seat, material defect	Potential catastrophic release of GNG					
22	CNG-4 (Ball Valve)	5, 7	Inprocess leak through valve	Failure of valve seat, human error, material defect	Potential release of CNG					
23	CNG-5 (Manifold)	3in, 4, 8	Leakage from manifold	Material defect, mechanical damage, installation error	Minor release of CNG					
24	CNG-6 (Pressure Transducer)	3in, 4, 8	Leakages from transducer	Material defect, mechanical damage, installation error	Minor release of CNG					
25	CNG-7 (Bleed Valve)	3in, 4, 8	Leakages of CNG through bleed valve	Failure of bleed valve to reseat following purge of residual pressure	Potential release of CNG					
26	CNG-8 (Needle Valve)	3in, 4, 8	Leakage from needle valve	Failure of valve to reseat properly, mechanical damage, material defect	Potential release of CNG					
27	CNG-9 (Defuel Port)	1	No credible scenario for indoor operation states							
28	CNG-10 (Fuel Port Filter)	8	Leakage from filter housing or fitting	Installation error, material damage	Potential release of CNG					
29	CNG-11 (Fill Manifold)	8	Leakage from manifold	Material defect, mechanical damage, installation error	Minor release of CNG					
30	CNG-12 and CNG-13 (Fill Receptacles)	8	Leakage from receptacles during refueling	Misalignment of nozzle, mechanical damaged seal on fill port	Potential release of CNG					
31	CNG-14 and CNG-15 (Pressure Gauges)	3in, 4, 8	Leakage from gauges or fittings	Installation error, material damage	Potential release of CNG					
32	CNG-16 (Inline Fuel Filter)	3in, 4, 8	Leakage from filter housing or fitting	Installation error, material damage	Potential release of CNG					

						Prevention Features			Mitigation Features	
HAZOP Number	**Component**	**Operation State**	**Hazard Scenario**	**Causes**	**Consequences**	**Design**	**Administrative**	**Detection Method**	**Design**	**Administrative**
33	CNG-17 (Fuel Line Solenoid Valve)	3in, 4, 8	Leakage of CNG through body of solenoid	Mechanical damage, material failure	Minor release of CNG					
34	CNG-18 (Regulator)	4, 8	Overpressurization of engine fuel line	Failure of regulator to properly restrict downstream pressure to the engine	Potential damage to downstream piping or component, leading to release of CNG					
35	CNG-20 (Tubing)	3in, 4, 5, 7, 8	Leakage from tubing	Mechanical damage, material failure, installation error	Potential release of CNG					
36	Multiple	3in, 4, 5, 7, 8	Release of NG from any fuel component after re-opening of the ball valve	Mechanical damage to fuel system lines during other system maintenance, Improper installation or re-assembly	Potential for release of total volume of gas					
37	Multiple	Multiple	Release of LNG or GNG	Procedures violated (Gas train not emptied, tank not isolated)	Total volume of system released		Procedure to perform run down prior to service	Gas indicator alarm		Personnel training
38	Multiple	6	Release of NG from any component when removed	Failure of personnel to properly defuel or vent gas	Release of total volume of tank					
39	Multiple	6	Release of NG from any component when removed	Failure of system to vent completely due to blockage or constriction due to debris or contaminants in the system	Release of a portion of the tank contents					
40	Multiple	6	Release of NG from any component when removed	Faulty signal from electronic control unit or sending unit indicates inaccurate fuel level	Release of total volume of tank					
41	Multiple	6	Release of NG from any component when removed	Faulty signal from high or low pressure gauge falsely indicates system has been vented	Release of total volume of tank					

APPENDIX B: HAZOP SCENARIO RISK RANKINGS DATA SHEETS

The HAZOP scenarios data sheets had consequence, probability and escalation classes evaluated and determined for each of the scenarios by the team during Phase II.

HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences	Consequence Class	Probability Class	Risk Metric	Escalation
1	LNG-1 (Overpressure regulator)	3in, 4, 7, 8	External leakage from regulator body	Seal failure, mechanical defect, damage, etc.	Minor leakage of GNG	1	4	**4**	**L**
2	LNG-1 (Overpressure regulator)	3in, 4, 7, 8	Inadequate regulation of gas flow	Regulator fails high	Overpressure of downstream components and potential GNG release	0		**0**	
3	LNG-1 (Overpressure regulator)	3in, 4, 7, 8	In-process leakage	Mechanical defect, damage, etc.	Potential minor release of GNG	0		**0**	
4A	LNG-2 (Fuel Shutoff Valve)	3in, 4, 5	Valve fails to shut completely, or leaks external or in-process	Failure of seals, spurious operation	Potential catastrophic release of GNG	0		**0**	
4B	LNG-2 (Fuel Shutoff Valve)	7	Valve fails to shut completely, or leaks external or in-process	Failure of seals, spurious operation	Catastrophic release of GNG	3	2	**6**	**M**
5	LNG-3 (Heat exchanger)	3in, 4, 5, 7	External leakage from heat exchanger	Leaks of LNG or GNG due to defective materials, corrosion, thermal fatigue, pressure rupture, etc.	Catastrophic release of LNG or GNG	1	3	**3**	**L**
6	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Overpressure of tank and failure of relief valve to open	Valve failure, insulation failure, excessive hold time	Rupture of tank and catastrophic release of LNG	3	1	**3**	**H**
6A	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Overpressure of tank and failure of relief valve to open	External fire	Rupture of tank and catastrophic release of LNG	3	1	**3**	**C**
7	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Overpressure of tank and proper operation of relief valve	Excessive hold time, insulation failure	Minor release of GNG	1	5	**5**	**L**
8	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Outlet or fitting on tank fails	Manufacturing defect or installation error	Potential catastrophic release of LNG	3	2	**6**	**M**
9	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Leak of LNG into the interstitial space between inner and outer tanks	Internal corrosion of tank, fatigue failure	Insulation failure, warming, overpressurization of the outer tank and potential catastrophic release	To be Deleted			

HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences	Consequence Class	Probability Class	Risk Metric	Escalation
10	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Damage to outer tank resulting in compromising the insulative capacity	Mechanical damage, accident	Accelerated warming of the tank, overpressurization of the outer tank and potential catastrophic release	To be Deleted			
11	LNG-4 (LNG tank)	3in, 4, 5, 7, 8	Damage to the outer tank due to leakage from the inner tank to the interstitial space	Embrittlement and cracking due to cryogenic properties of the material	Potential catastrophic release of LNG	3	1	**3**	**M**
12	LNG-5 (Pressure relief valve)	3in, 4, 5, 7, 8	Failure of PRV to reclose after proper venting, fails open	Mechanical Failure	Total volume of tank released	3	4	**12**	**H**
	LNG-7 (Fill Port)	8	Release of GNG through fill port	Failure of check valve	Total volume of tank released	3	2	**6**	**M**
13	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Overpressurization of Cylinder	External fire AND failure of PRD to operate	Potential catastrophic release of CNG	3	1	**3**	**C**
14	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Overpressure of Cylinder due to an External Fire	External fire AND successful operation of PRD	Potential catastrophic release of CNG	3	2	**6**	**H**
15	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Outlet or fitting on tank fails	Manufacturing defect or installation or maintenance error	Potential catastrophic release of CNG	2	3	**6**	**H**
16	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	CNG tank puncture	Mechanical damage, tool or equipment impingement	Potential catastrophic release of CNG	2	1	**2**	**C**
17	CNG-1 (Cylinders)	3in, 4, 5, 7, 8	Leakage from a cylinder	Accident, vandalism, crack propagation, fatigue failure	Potential catastrophic release of CNG	2	2	**4**	**M**
18	CNG-2 (Cylinder Solenoid Valve)	3in, 4, 5, 7, 8	External leakage of CNG through body of solenoid or joint	Mechanical damage, material failure, installation error	Minor release of CNG	2	3	**6**	**M**
19	CNG-3 (Pressure Relief Device)	3in, 4, 5, 7, 8	PRD fails open below activation pressure	Mechanical defect, material defect, installation error, maintenance error	Potential catastrophic release of CNG	2	4	**8**	**H**
20	CNG-3 (Pressure Relief Device)	3in, 4, 5, 7, 8	External leakage through PRD of CNG	Mechanical defect, material defect, installation error, maintenance error	Minor release of CNG	2	3	**6**	**M**
21	CNG-4 (Ball Valve)	3in, 4, 8	External valve leak	Failure of valve seat, material defect	Potential catastrophic release of GNG	3	2	**6**	**L**
22	CNG-4 (Ball Valve)	5, 7	Inprocess leak through valve	Failure of valve seat, human error, material defect	Potential release of CNG	0		**0**	
23	CNG-5 (Manifold)	3in, 4, 8	External leakage from manifold	Material defect, mechanical damage, installation error	Minor release of CNG	1	2	**2**	**M**

HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences	Consequence Class	Probability Class	Risk Metric	Escalation
24	CNG-6 (Pressure Transducer)	3in, 4, 8	External Leakage from transducer	Material defect, mechanical damage, installation error	Minor release of CNG	1	2	**2**	**M**
25	CNG-7 (Bleed Valve)	3in, 4, 8	External leakage of CNG through bleed valve	Failure of bleed valve to reseat following purge of residual pressure	Potential release of CNG	1	2	**2**	**L**
26	CNG-8 (Needle Valve)	3in, 4, 8	External or internal leakage from needle valve	Failure of valve to reseat properly, mechanical damage, material defect	Potential release of CNG	1	2	**2**	**M**
27	CNG-9 (Defuel Port)	1	No feasible scenario for indoor operation states						
28	CNG-10 (Fuel Port Filter)	8	Leakage from filter housing or fitting	Installation error, material damage	Potential release of CNG	1	2	**2**	**L**
29	CNG-11 (Fill Manifold)	8	Leakage from manifold	Material defect, mechanical damage, installation error	Minor release of CNG	1	2	**2**	**L**
30	CNG-12 and CNG-13 (Fill Receptacles)	8	Leakage from receptacles during refueling	Misalignment of nozzle, mechanical damaged seal on fill port	Potential release of CNG	1	2	**2**	**L**
31	CNG-14 and CNG-15 (Pressure Gauges)	3in, 4, 8	Leakage from gauges or fittings	Installation error, material damage	Potential release of CNG	1	2	**2**	**L**
32	CNG-16 (Inline Fuel Filter)	3in, 4, 8	Leakage from filter housing or fitting	Installation error, material damage	Potential release of CNG	1	2	**2**	**L**
33A	CNG-17 (Fuel Line Solenoid Valve)	3in, 4, 8	Leakage of CNG through body of solenoid	Mechanical damage, material failure	Minor release of CNG	1	2	**2**	**L**
33B	CNG-17 (Fuel Line Solenoid Valve)	3in, 4, 8	Failure to close solenoid	Mechanical damage, material failure	Minor release of CNG	0		**0**	
34	CNG-18 (Regulator)	4	Failure of regulator to properly restrict downstream pressure to the engine	Mechanical damage, material failure	Potential damage to downstream piping or component, leading to release of CNG	0		**0**	
35A	CNG-20 (Tubing)	4	Leakage from tubing	Mechanical damage, material failure, installation error	Potential release of CNG	3	2	**6**	**L**
35B	CNG-20 (Tubing)	8	Leakage from tubing	Mechanical damage, material failure, installation error	Potential release of CNG	3	4	**12**	**L**

HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences	Consequence Class	Probability Class	Risk Metric	Escalation
36	Multiple	3in, 4, 5, 7, 8	Human error during maintenance	Mechanical damage to fuel system lines during other system maintenance, Improper installation or re-assembly	Potential for release of total volume of gas	1	3	**3**	**L**
37	Multiple	Multiple	Human error or disregard for maintenance procedures	Procedures violated (Gas train not emptied, tank not isolated)	Total volume of system released	3	3	**9**	**H**
38	Multiple	6	NG present after attempted evacuation of fuel system	Failure of personnel to properly defuel or vent gas, failure of system to vent completely due to blockage or constriction due to debris or contaminants in the system or faulty signal from electronic control unit or sending unit indicates inaccurate fuel level or faulty signal from high or low pressure gauge falsely indicates system has been vented	Release of total volume of tank	1	3	**3**	**M**

APPENDIX C: SUPPLEMENTAL CFD SIMULATION DATA

In this Appendix, supplemental CFD simulation data that could not easily fit into the body of the text is included.

C.1. Supplemental CFD Data for Scenario A

For the LNG blow-off scenario (Scenario A, Section 4.3.1), concentration maps are provided in Figure 22 and Figure 23 for the conditions with and without roof supports respectively. From these images, it can be observed that ventilation induced low pressure regions led to substantial distortion of the release plume near the release where flammable concentrations were highest. For the scenario without roof supports, the plume impinged on the ceiling and formed a wall jet that spread along the ceiling. The spread direction was biased towards the exit vent due to the room currents from the ventilation system.

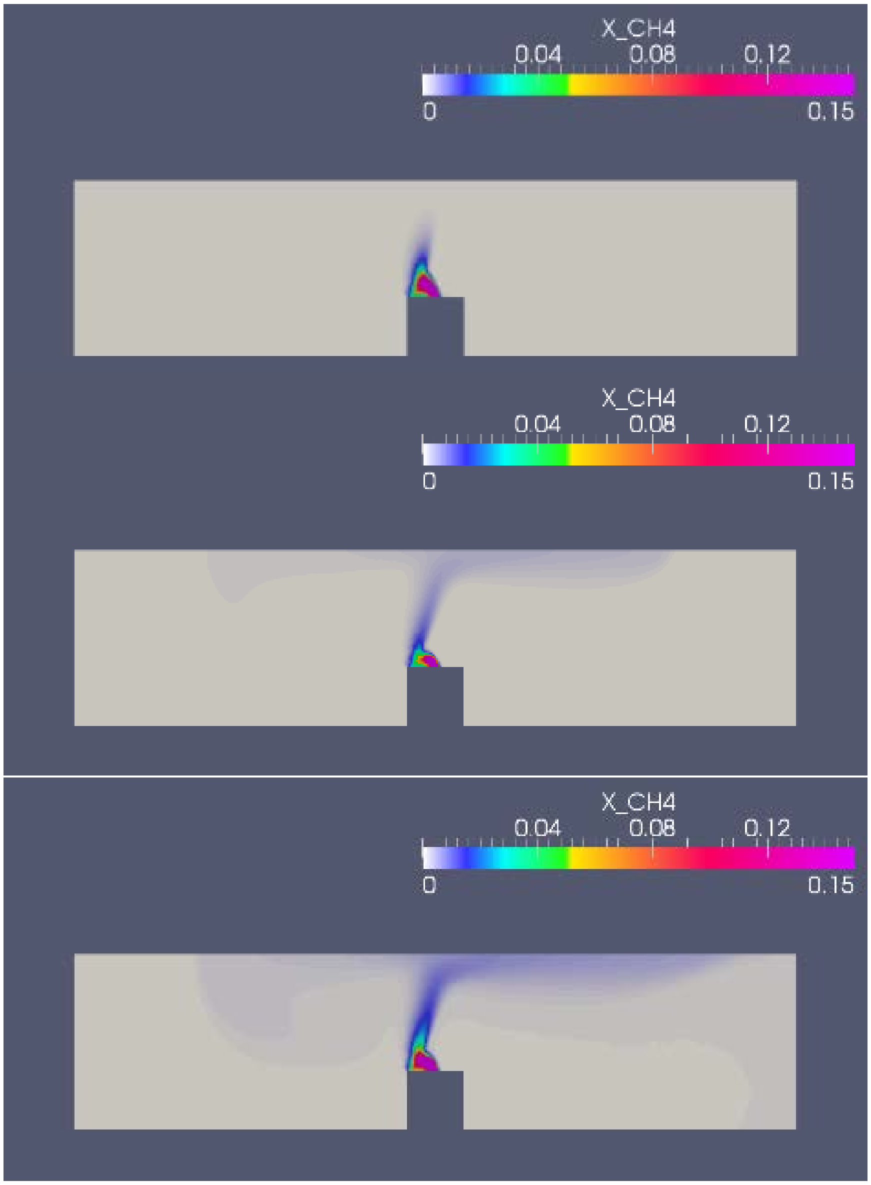

Figure 22: NGV maintenance facility natural gas mole fraction contours at 10, 60, and 306 seconds into the release for the facility layouts without roof supports for the LNG blow-off scenario.

For the facility layout that included roof supports, recirculation vortices formed by the interaction between the room currents and the beams resulted in a localized accumulation region of lean natural gas near the release plume. Over time, the concentration of plume became richer as very little natural gas was able to escape through the exit vent. However, as was seen in Figure 6, the impact on flammable concentrations within the enclosure was negligible since the accumulation rates were slow relative the release duration. It was thought that the accumulation region could have a bigger impact for longer duration releases, which is why this facility configuration was selected for the CNG tank blow-down scenario.

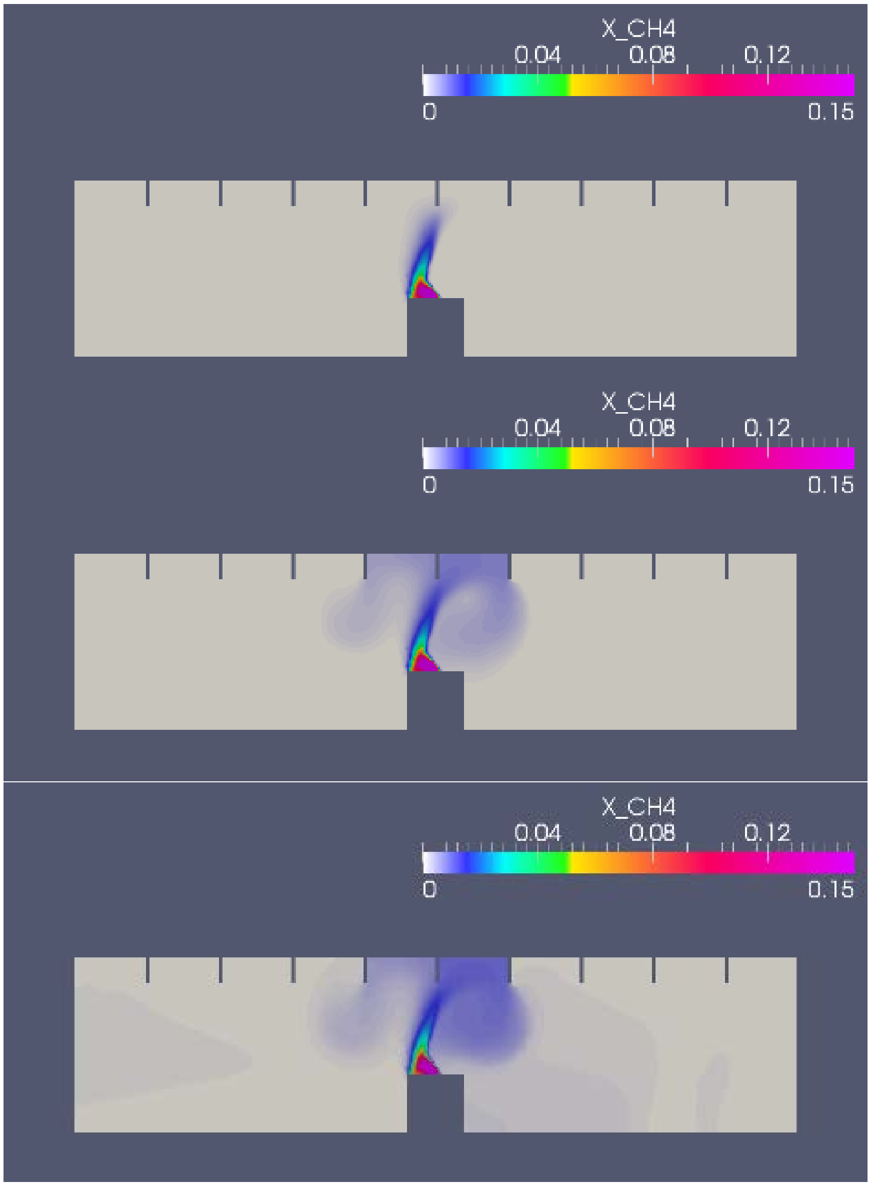

Figure 23: NGV maintenance facility natural gas mole fraction contours at 10, 60, and 306 seconds into the release for the facility layouts with roof supports for the LNG blow-off scenario.

C.2. Natural Gas Concentration Maps for Scenario B

Natural gas concentration maps from the maintenance facility center plane at 2.5 and 30.5 seconds into the release for the NGV facility configuration without support beams are provided in Figure 24. These correspond to Scenario B (see Section 4.3.2). Despite flammable concentrations initially concentrated near the release, the rapid decay in mass flow rates coupled with strong diffusion that quickly mixed the plume with ambient air led to very short durations for flammable mixtures in the facility.

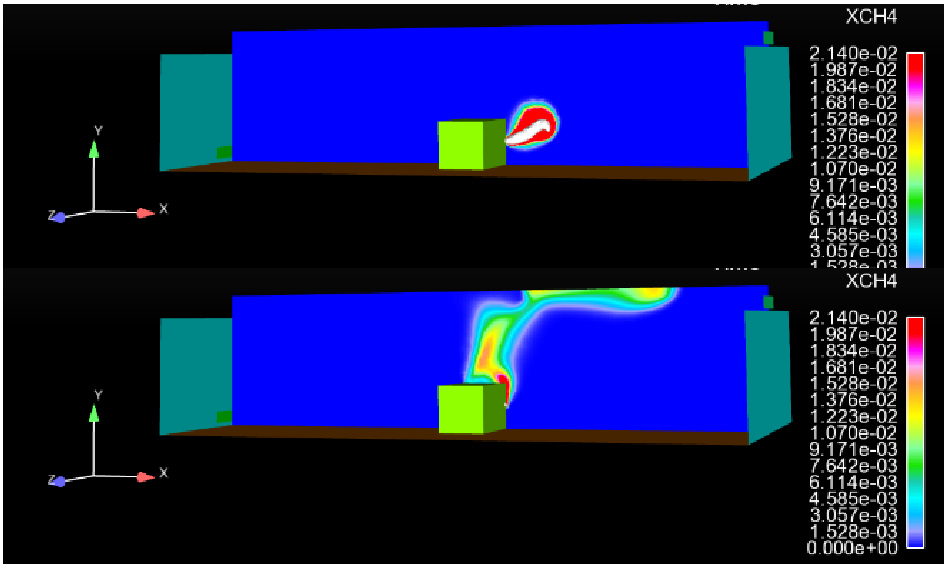

Figure 24: Maintenance facility natural gas mole fraction contours at 2.5 (top) and 30.5 (bottom) seconds into the release for the layouts without roof supports for the CNG line cracking scenario.

C.3. Low Pressure CNG Release

One scenario was modeled that was not identified in the HAZOP study, but is still of interest due to the recently adopted IFC wording addressing reducing CNG cylinder pressure down to 250 psi (1.72 MPa) that would allow CNG vehicles into the unmodified building. Results show that the leak is similar to previous scenarios of gas leaks from the lines of vehicles that held comparable amounts of fuel as the depressurized tank.

The tank volume was set to be 123 gal (466 L) and the release was simulated at room temperature (23°C). The leak was assumed to have a diameter of 0.24 inches (6.1 mm). The velocity calculated by MassTran is shown in Figure 25, which shows that the flow is choked for about 150 seconds. Due to the same modeling constraints explained in Chapter 4, the mass flow rate, shown in Figure 26, was conserved but released through a larger diameter (4.44 inches = 0.11 m).

Ventilation in the small garage was run for 300 seconds before the release was started. As can be seen in Figure 27, a plume of flammable mass does reach the ceiling for a short period of time.

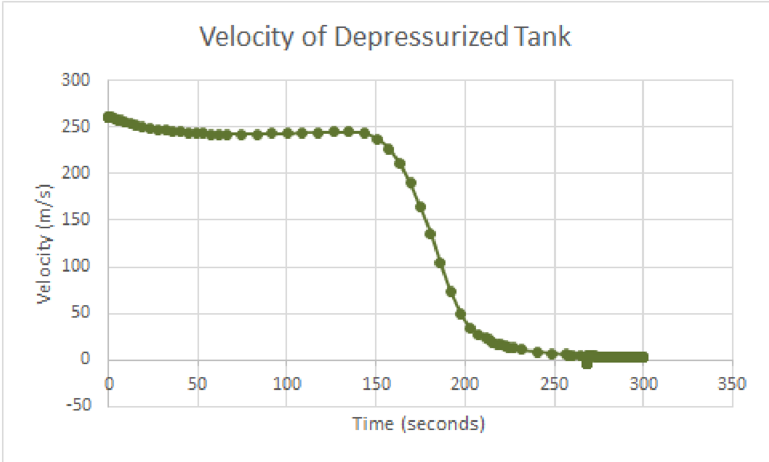

Figure 25. Velocity of leak from 123 gallon (466 L) tank depressurized to 250 psi (1.72 MPa)

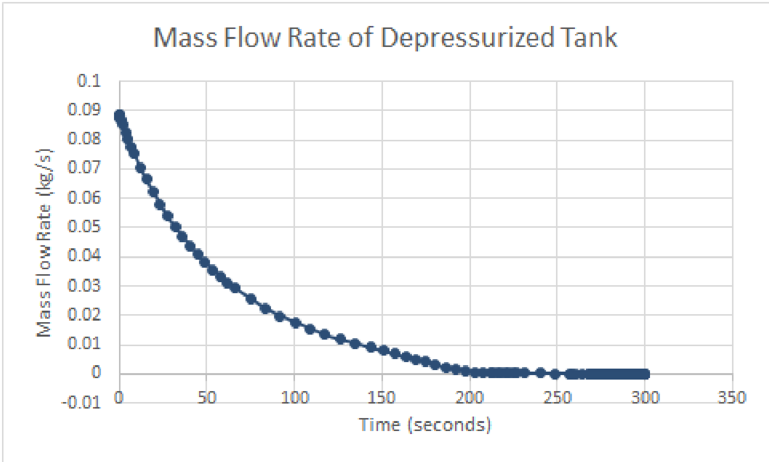

Figure 26. Mass flow rate of leak for depressurized tank

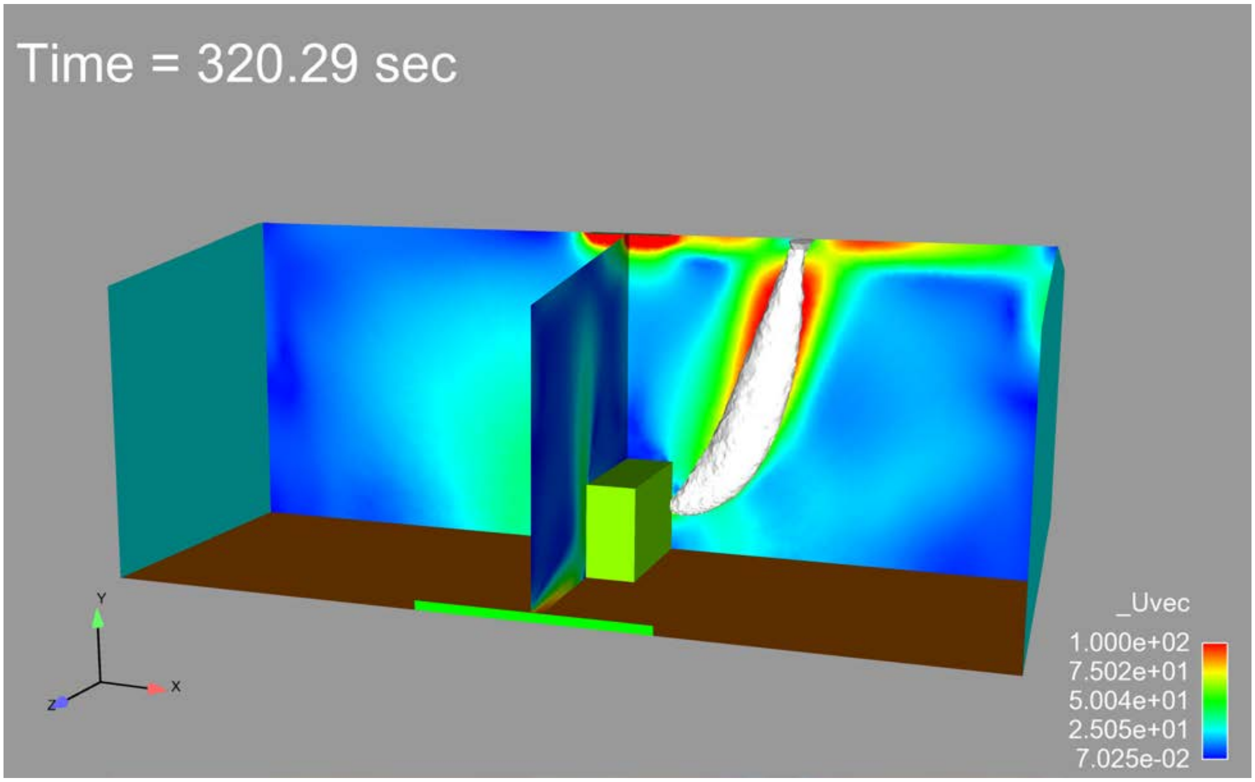

Figure 27. Flammable mass (white contour) at the time (20.29 sec after the start of the release) of maximum flammable mass in the garage

Since a larger orifice is used for the CFD model, a separate plume model was used to calculate the release through the correct size orifice. For this calculation, the gas inside the tank is assumed to be at room temperature (23°C), at a pressure of 250 psi (1.72 MPa), and have an orifice diameter of 0.24 inches (6.1 mm). The resulting plume is shown in Figure 28, which shows a flammable concentration of methane >2 m (>6.6 feet) from the release.

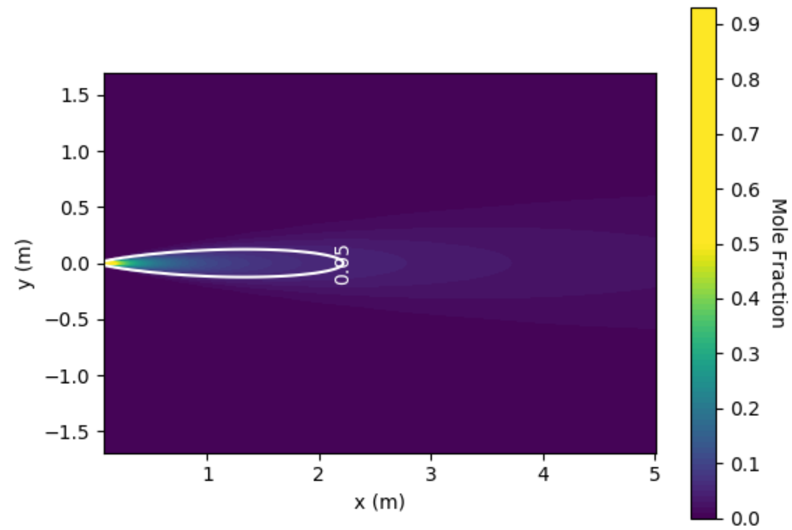

Figure 28. Mole fraction of low pressure CNG release with white contour shown at 5%, the flammability limit of methane

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