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Early-Stage Quantitative Risk Assessment to Support Development of Codes and Standard Requirements for Indoor Fueling of Hydrogen Vehicles

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Abstract

Sandia National Laboratories is developing the technical basis for assessing the risk of hydrogen infrastructure for use in the development of relevant codes and standards. The development of codes and standards is an important step in ensuring the safe design and operation of the hydrogen fuel cell infrastructure. Codes and standards organizations are increasingly using risk-informed processes to establish code requirements.

Sandia has used Quantitative Risk Assessment (QRA) approaches to risk-inform safety codes and standards for hydrogen infrastructures. QRA has been applied successfully for decades in

many industries, including nuclear power, aviation, and offshore oil. However, the hydrogen industry is a relatively new application area for QRA, and several gaps must be filled before QRA can be widely applied to reduce conservatisms that influence the safety requirements for hydrogen installations.

This report documents an early-stage QRA for a generic, code-compliant indoor hydrogen fueling facility. The goals of conducting this activity were threefold: to provide initial insights into the safety of such facilities; to recommend risk-informed changes to indoor fueling requirements in safety codes and standards; and to evaluate the quality of existing models and data available for use in hydrogen installation QRA. The report provides several recommendations for code changes that will improve indoor fueling safety. Furthermore, the report provides insight into gaps in the QRA process that must be addressed to provide greater confidence in the QRA results.

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Nomenclature

AHJ Authority Holding Jurisdiction

AIR Average Individual Risk

ALARP As Low As Reasonably Practicable

ASME American Society of Mechanical Engineers

ASTM ASTM International (formerly American Society for Testing and Materials)

BLS U. S. Bureau of Labor Statistics

CFD Computational Fluid Dynamics

CGA Compressed Gas Association

CNG Compressed Natural Gas

DOE Department of Energy

EIGA European Industrial Gas Association

ESD Event Sequence Diagram

FAR Fatal Accident Rate

FMEA Failure Modes and Effects Analysis

FT Fault Tree

GH Gaseous Hydrogen

H_2 Hydrogen

HazOp Hazard and Operability Study

LNG Liquid Natural Gas

ICC International Code Council

IEA International Energy Agency

ISO International Organization for Standardization

NFPA National Fire Protection Association

PHA Preliminary Hazard Analysis

P&ID Piping and Instrumentation Diagram

PLL Potential Loss of Life

QRA Quantitative Risk Assessment

SIL Safety Integrity Level

SDO Standards Development Organizations

UL Underwriters Laboratories

VCE Vapor Cloud Explosion

1 Introduction

Hydrogen fueling stations in many countries including the United States are permitted by one or more authorities holding jurisdiction (AHJs) which generally include a local government entity. A critical step in the permitting process is the demonstration that the proposed fueling station meets the AHJ safety requirements. Currently, many AHJs rely on compliance with well-known codes and standards as one means to license a facility. Thus, the establishment of code requirements is critical to ensuring the safety of these facilities.

The U.S. Department of Energy (DOE) has launched an initiative to facilitate the permitting process for hydrogen fueling stations [2]. As part of this program, Sandia National Laboratories is developing the technical basis for assessing the safety of hydrogen-based systems for use in the development of relevant codes and standards. The focus of the current work is to develop a combined experimental and analytical approach for risk and consequence assessment of indoor fueling of hydrogen vehicles. This work is specifically intended to influence the *NFPA 2, Hydrogen Technologies Code* [3], Chapter 10 "GH_2 Vehicle Fueling Facilities."

1.1 Background

Codes and standards applicable to hydrogen facilities are currently developed by a variety of standards and code development organizations (SDOs) including the National Fire Protection Association (NFPA), American Society of Mechanical Engineers (ASME), Compressed Gas Association (CGA), Underwriters Laboratories (UL), International Organization for Standardization (ISO), and the International Code Council (ICC). The current codes and standards for hydrogen facilities specify that the facilities have certain safety features, use equipment made of material suitable for a hydrogen environment, and have specified separation distances. Codes and standards are typically adopted by governmental authorities, in which case they become regulations, and compliance with them is widely accepted as evidence of a safe design.

The safety basis for the current hydrogen codes and standards is not well documented and thus the safety of facilities complying with them may be questioned by some. For the most part, SDOs in the past have relied upon expert panels to establish necessary code requirements. The basis for the expert judgments is not documented but likely reflect a combination of good engineering practices to address the potential hazards associated with hydrogen, historical precedence based on requirements for other fuels such as Compressed Natural Gas (CNG), and anecdotal knowledge of past problems in hydrogen facilities. It is possible that some of the requirements are based on experimental or deterministic analyses of selected accidents that were felt to represent credible, but not worst case, accidents. It should be noted that this process appears to have worked to ensure safety in many industries primarily through the continuing process of adapting the applicable code requirements to address issues identified from an analysis of accidents.

Several of the SDOs are working to modify existing codes and standards and draft new ones related to the use of hydrogen as an automobile fuel and also for other electrical generation applications. NFPA has launched an effort to compile all requirements for hydrogen applications into one model code, NFPA 2. The Technical Committee for NFPA 2 is systematically reviewing all NFPA model codes and standards related to hydrogen as part of this compilation. In addition, the Technical Committee has created a number of task groups to assess the technical foundations of requirements in these codes and standards. One of these task groups is examining the technical basis for indoor fueling and is applying recent research on hydrogen behavior and Quantitative Risk Assessment (QRA) techniques as part of this examination.

There are many design and operational requirements that are used to ensure safe operation. A risk-informed process can help establish the baseline design and operational requirements for hydrogen fueling stations. In previous work, LaChance et al. [4] developed a framework for risk-informing the process of permitting hydrogen fueling stations; this includes establishing risk-informed hydrogen codes and standards. Using risk-informed codes and standards ensures that all permitted facilities have a basic design that ensures a minimum acceptable level of safety under intended operating conditions. A risk-informed process utilizes risk insights obtained from QRAs combined with other considerations to establish code requirements. The QRAs are used to identify and quantify scenarios for the unintended release of hydrogen, identify the significant risk contributors at different types of hydrogen facilities, and to identify potential accident prevention and mitigation strategies to reduce the risk to acceptable levels. Examples of other considerations used in this risk-informed process can include the results of deterministic analyses of selected accidents scenarios, the need for defense-in-depth for certain safety features (e.g., overpressure protection), the use of safety margins in the design of high-pressure components, and requirements identified from the actual occurrences at hydrogen facilities. A key component of this process is that both accident prevention and mitigation features are included in the code and standard requirements.

The challenge faced in permitting hydrogen fueling stations is to have a process that is relatively simple and fast but also ensures that the facilities are safe. To date, the experience in permitting hydrogen fueling stations is limited but growing. In many cases, the AHJs have applied the same approach used in the past to license other types of fueling stations – reliance upon conformance to applicable codes and standards. However, many of these hydrogen facilities are first-of-a-kind designs and consequently were subjected to more risk analysis in the permitting process.

The level of risk assessment that is currently performed for hydrogen fueling stations is variable ranging from purely qualitative assessments to comprehensive QRAs. Designers of these facilities often only use qualitative techniques such as Failure Modes and Effects Analysis (FMEAs) to help identify the potential hazards and required prevention and mitigation features. Others also use semi-quantitative risk matrices where different accidents are binned into quantitative frequency and consequence bins based on subjective judgments. If the associated risk of an accident is deemed high, a QRA of the accident scenario may be performed. Some AHJs require risk management plans that include emergency response procedures to address the high-risk scenarios. Since the use of hydrogen as an automobile fuel is a relatively new and unproven technology, it seems prudent to perform more comprehensive QRAs for the early facilities to provide confidence that they are indeed safe.

Once the safety basis for hydrogen fueling facilities has been established through analysis that leads to the development of risk-informed codes and standards, risk analysis of individual fueling stations may not be required. At this point in time, the AHJs can be assured that a facility designed, constructed, and operated according to code requirements should meet accepted risk criteria (assuming risk criteria are utilized in the code development process) and thus will not require additional risk analysis. In particular, standard designs that meet the code requirements should require very little deliberation by the AHJs. However, risk assessment may be required to evaluate major deviations from code and standard requirements or from standard designs.

1.2 Objectives

The Fire Protection Research Foundation provided guidance for NFPA Technical Committees to use risk concepts in their decision making process [5]. The NFPA 2, Chapter 10 working group would like to develop a QRA approach that can be used to ensure that the code requirements are demonstrably linked to safety improvements and to ensure that code requirements are not unnecessarily burdensome. NFPA 2, Chapter 10 is primarily intended to ensure the safety of vehicle fueling facilities.

Sandia was asked to conduct an early-stage QRA on a generic, code-compliant indoor fueling system, with the following objectives:

Objective 1: Provide screening-level assessment of the fatality risk for a generic, code-compliant indoor fueling system. A risk-informed approach had previously been used to establish the separation distances for bulk gaseous hydrogen storage areas [6, 7]. The goal of the current work was to extend this approach in a way that could be used to inform codes and standards for indoor fueling, and to provide an initial assessment of fatality risks for a generic system.

Objective 2: Provide science-based and risk-based recommendations to improve NFPA 2, Chapter 10 as possible. The goal of Sandia's work was to provide insights that resulted from the early-stage QRA. Furthermore, Sandia was also asked to conduct experiments that could provide insight on the minimum room volume for indoor fueling facilities. The 2010 version of NFPA 2 included Table 10.3.3.2.2.2, which expresses a minimum room volume for indoor fueling activities, based on the maximum fuel quantity per dispensing event (Table 1). The table was based on NPFA 52, Table 9.4.3.2.1, which was developed for Liquid Natural Gas (LNG) and CNG systems [8]. The minimum room volumes in this table were determined from calculations to ensure a maximum 1% homogenous mixture of hydrogen in air; this value represents 25% of the lower flammability limit (LFL) of hydrogen in air. However, homogeneity is not immediately obtained after a gas release, so the amount of gas that produces a 1% homogenous air/hydrogen mixture may still be reactive.

Objective 3: Identify required improvements to the QRA that will provide more detailed insights than screening-level analysis. NPFA 2 describes key design and operational requirements that are intended to ensure safe operation. The design requirements include leak detection and isolation capability, ventilation, emergency manual shutoff switches, pressure relief devices and associated vent lines, process monitoring and safety interlocks, and fail safe design requirements (e.g., closure of isolation valves on loss of power). Operational requirements can include normal operating procedures, maintenance and surveillance procedures, limiting conditions of operation,

Maximum Fuel Quantity per Dispensing Event		Minimum Room Volume	
lb	kg	ft^3	m^3
Up to 1.8	Up to 0.8	40,000	1,000
1.8 to 3.7	>0.8 to 1.7	70,000	2,000
3.7 to 5.5	>1.7 to 2.5	100,000	3,000
5.5 to 7.3	>2.5 to 3.3	140,000	4,000
7.3 to 9.3	>3.3 to 4.2	180,000	5,000

Table 1. NFPA 2 Table 10.3.3.2.2.2, which specifies the minimum permissible room volume for indoor fueling activities as a function of maximum quantity of fuel dispensed per event.

and emergency procedures for major accidents. The screening-level QRA approach used to satisfy Objective 1 is not detailed enough to address all of the design requirements in Section 10 of NFPA 2. The goal of Sandia's work was to identify gaps in QRA that must be filled to provide more specific insights.

1.3 Scope

The purpose of this research was to assess the safety of hydrogen indoor fueling systems in a way that could be used to inform codes and standards, such as Chapter 10 of NFPA 2. The analysis includes risks from all indoor components of the hydrogen dispensing systems. The analysis does not include risks from hydrogen storage, processing, or use outside of the building. However, exterior components (e.g., shutdown valves) intended to mitigate indoor fueling risks are included in the analysis. We are only addressing risks that occur during fueling, not the risks associated with operation of the hydrogen fuel cell vehicle[1].

The primary consequence of interest is loss of human life among building occupants; occupants includes the forklift operators and other warehouse personnel. It is assumed that there are no members of the public inside the facility. This QRA was not intended to address environmental risk or asset risk, although future work should address these types of consequences. Furthermore, to maintain consistency with previous work, this QRA does not consider injuries since there is very little available data that can be used to help quantify injuries.

[1] Analysis of the risks associated with operation of hydrogen fuel cell vehicles will be the topic of future work.

2 Methodology

Quantitative Risk Assessment (QRA) is a structured approach to analyzing and managing the risks presented by a complex engineering system. Risk analysis is used to identify and quantify risks and uncertainties associated with a specific industrial system, and risk management uses risk analysis results to support decision making. QRA builds a bridge between scientific knowledge (e.g., experiments, theoretical models), industry practices, and decision makers (e.g., codes and standards organizations). QRA has a long history of supporting safety analyses in the nuclear power, oil and gas, and aviation and aerospace industries.

QRA provides a basis for making decisions about the objectives outlined in Section 1.2. Sandia used stakeholder participation to establish a common understanding of the safety level of hydrogen indoor fueling. Sandia also performed computational fluid dynamics (CFD) simulations to characterize releases of hydrogen from fuel cell vehicles and to study the behavior of the released hydrogen under different conditions. Sandia developed targeted experiments to validate the CFD models. The results of the experiments and CFD simulations were used to provide input to the QRA.

2.1 Quantitative Risk Assessment Overview

Broadly defined, *risk* is the potential for undesired outcomes (consequences) to occur as the result of an activity that is subject to hazards; it is implicit in this definition that there is uncertainty about which outcomes will occur and how likely these outcomes are. *Risk analysis* is a process that identifies and prioritizes contributors to different consequences, and *risk assessment* uses this process to provide decision support to help manage the likelihood and mitigate the effects of undesirable consequences. Quantitative risk assessment uses models to predict the probability of different consequences; the models and the probability information provide a framework for reasoning about different decision options, based on the background information encoded in the models.

Risk is characterized by a set of hazard exposure scenarios (i), the consequences (c_i) associated with each scenario, and the probability of occurrence (p_i) of these consequences. One commonly used expression for calculating risk is:

$$Risk = \sum_i (p_i \times c_i) \tag{1}$$

In QRA, the consequences are expressed in terms of an observable quantity, such as expected number of fatalities or an expected repair cost in a specific period of time. The probability term expresses the analysts uncertainty about predicted consequences (which encompasses the frequency of different scenarios and the range of possible consequences for each scenario). The QRA process generally includes the following steps:

- **Analysis scoping** – Defining the purpose and scope of the analysis, and setting criteria for unacceptable levels of risk.

- **System description** – Describing the system and site in sufficient detail to reach the analysis goals established in the scoping phase.
- **Cause analysis** – Identifying the hazards that may degrade the targets of interest, identifying and modeling the hazard scenarios (including the initiating events, the mitigating features and the root causes) and quantifying the probability of each scenario in the model using appropriate background information, including data and distributions.
- **Consequence analysis** – Identifying the consequences in terms of physical effects (loads) of each scenario, identifying the responses of the facilities, personnel, environment, assets, etc. when exposed to the loads, and building models and assessing the probability of different consequences using appropriate background information, including data and distributions.
- **Risk analysis** – Integrating the cause and consequence models and using them to assess the probability of the consequences, performing sensitivity studies to address assumptions and model uncertainties, and documenting the results of the analysis.
- **Risk management** – Communicating analysis results to stakeholders, engaging stakeholders to decide which risks are significant and to employ strategies to minimize risks, and continually updating risk models as new information becomes available.

The remainder of this chapter discusses the methodology for conducting QRA for hydrogen systems. For additional information on how to conduct QRA, the reader is referred to the references [9, 10, 11].

2.2 Unacceptable risk threshold

The purpose of QRA is to provide insight that supports decision making about a system [2]. One way that QRA can support decisions is to establish that the risk from an industrial system is *As Low As Reasonably Practicable* (ALARP). The ALARP approach balances the fatality risk with the reasonableness of risk reduction activities and the personal or societal benefit of the technology. Embedded in the ALARP approach is the understanding that there is no zero risk situation, but that there is an unacceptably high level of risk. The threshold for unacceptable risk varies based on activity.

For the indoor fueling QRA, we use two different thresholds for unacceptable risk. The two thresholds allows us to compare the indoor fueling risk to the risks posed by other activities. The first threshold is a maximum Average Individual Risk (AIR) value, which is used to compare indoor fueling risk to the level of risk posed by gasoline stations and the level of publicly accepted risk in many industrialized nations. The second threshold is a maximum Fatal Accident Rate (FAR), which we use to compare the indoor fueling risk to the level of risk posed by operating an industrial vehicle. AIR and FAR are defined further in Section 2.6.

For indoor hydrogen applications the unacceptable level of risk is an AIR greater than 1×10^{-4}/yr for a worker or a fatality rate greater than 1×10^{-5}/yr for a member of the public; these risk acceptance criteria were established by the International Energy Agency (IEA) and were used in

[2] The QRA can provide insight for the decision making, but it is not a decision-making system.

previous work [7]. NFPA 2 selected a fatality risk guideline of 2×10^{-5}/yr for members of the public for use in the separation distance work documented in [7]. This value is consistent with the risk at existing gasoline stations, is in general agreement with criteria being utilized in several countries, and is approximately twice the value recommended by European Industrial Gas Association (EIGA) for hydrogen facilities. Furthermore, it represents a low fraction (less than 10%) of the risk currently experienced by the public to all causes (approx. 3×10^{-4}/yr) and is roughly equal to the risk imposed by other fires. In most QRA applications, the acceptable risk levels for the public are generally set one to two orders of magnitude lower than the level for workers.

The second unacceptable level of risk for indoor hydrogen fueling is an FAR greater than 0.3. The U.S. Bureau of Labor Statistics (BLS) publishes annual data about fatality rates in their annual Census of Fatal Occupational Industries [12]. Based on 2010 data, the FAR for the BLS category "industrial truck and tractor operators" is 3.0 and the FAR for "laborers and freight, stock, and material movers, hand" is 3.1. We set the FAR threshold for indoor fueling to represent 10% of the FAR for workers who used industrial vehicles in 2010.

The 1×10^{-4}/yr AIR value and the 0.3 FAR value must be used as guidelines rather than a hard criterion due to the uncertainty in the risk evaluations. State-of-knowledge, or epistemic, uncertainties in modeling hydrogen accidents in a QRA preclude a definitive decision based solely on the numerical results of a QRA. Thus, in the context of risk-informed decision making, the guidelines should not be interpreted as being overly prescriptive. These thresholds are intended to provide an indication, in numerical terms, of what is considered unacceptable. Once it is determined that a risk is below the unacceptable threshold, the best practice is to continue to allocate resources to further reduce the risk (i.e., continuously target improvements to the major remaining risk drivers) in a cost-beneficial way.

2.3 System description methodology

The dispenser and facility designs were developed from careful review of the requirements in the 2010 version of NFPA 2. The designs use only the components required by current code requirements. Operational parameters were selected based on current industrial practice. The resulting descriptions were vetted by industry experts from the NFPA 2 fueling working group.

Many experts noted that it is common for hydrogen dispenser designs to exceed the code requirements with regard to layers of safety. For example, the incorporation of automatic leak monitoring function incorporated into dispenser control logic is common and provides an additional layer of protection with little increased equipment cost. These additional measures are not considered in the current analysis, because the goal of this analysis is to evaluate the level of safety provided by NFPA 2.

2.4 Cause analysis methodology

The goal of cause analysis is to provide insight into the causes of hazardous exposures and the likelihood of those causes. This involves documenting the hazards relevant to the system, creating detailed models that describe the scenarios that occur after a release of hydrogen, and quantifying these models using probability information.

2.4.1 Exposure scenarios

A hazard is the potential for harm. In practical terms, a hazard often is associated with a condition or activity that, if left uncontrolled, can result in an injury or illness. When a person might be harmed by a hazard they are "exposed" to the hazard, this is called an *exposure*. Relating this back to the risk equation, Equation 1, the risk associated with each possible exposure is quantified by multiplying the probability of the exposure scenario by the severity of the hazard (i.e., the consequence) for that scenario.

Hazard are identified using qualitative hazard analysis tools such as FMEA (Failure Modes and Effects Analysis), HazOp (Hazard and Operability Study), PHA (Preliminary Hazard Analysis) What-if and Fault Tree Analysis (DOE accepted methods for hydrogen activities are listed in [13], Appendix 1). The qualitative approaches generally provide means for subjectively ranking hazards.

Once the hazards are identified, the exposure scenarios and their root causes are developed by exploring several sources of information:

- Results from qualitative analysis (FMEA, HazOp, etc) conducted as part of the hazard identification
- Release and accident scenarios from hydrogen fueling (if available) or from similar facilities (CNG and gasoline fueling industries)
- Historical data from hydrogen fueling (if available) or from similar facilities (CNG and gasoline fueling industries)
- Generic data on component leakage and failure rates from other industries
- Engineering and system safety analyses, including system-level failure information and failure information for individual components of the dispenser and vehicle

Exposure scenarios are documented graphically in Event Sequences Diagrams (ESDs) and root causes are documented in Fault Trees (FTs). ESDs and FTs also provide the form of the quantitative expression that deterministically relates the occurrence of low-level events (e.g., component failures) to higher-level events (e.g., system failures). The occurrence of the events in the ESDs and FTs are modeled probabilistically.

The ESD model documents the various scenarios that result after a hydrogen release. In an ESD, each pivotal event has two possible paths: the upper branch represents "yes" or "true" and the lower branch represents "no" or "false." The probability of the upper branch is $P(event)$ and the probability of the lower branch is $P(\overline{event}) = 1 - P(event)$. Each possible end state is represented by a diamond. The probability of the end state is the sum of the probability of the paths leading to the end state. The path probability is the product of the probability at each branch point.

The FT model documents the root causes of a hydrogen release. FTs contain a detailed description of how root causes combine to produce a top event. In a FT, logic gates (AND, OR) are used to document how root causes combine.

2.4.2 Scenario quantification

Supporting analyses and data are required to quantify the ESDs and the FTs. Specifically, failure data is required to quantify the accident scenarios. The data required includes component leakage frequencies and hydrogen ignition probabilities. Component leakage frequencies have been historically gathered by the chemical processing, compressed gas, nuclear power plant, and offshore petroleum industries; however, there has been little consistency across the disciplines and studies performed. In many of these industries, industry data has been used to develop models that allow component leakage frequencies for process components to be predicted from the leak diameter.

For example, in the offshore oil industry, the component leak frequencies (LF) have been modeled as a power function of the fractional leak area (FLA):

$$LF = a_1 \times (FLA)^{a_2} \tag{2}$$

The power function relationship can be simplified by taking the logarithm of both sides, which allows us to use linear regression to estimate the parameters a_1 and a_2 (log-log regression).

$$ln(LF) = ln(a_1) + a_2 \times ln(FLA) \tag{3}$$

Data on hydrogen systems is extremely limited, so it is not possible to estimate a_1 and a_2 in from hydrogen-specific data. However, sources from commercial operations may be used as a baseline for a frequency analysis. SAND2009-0874 [7] documents a Bayesian approach for predicting the frequency of leaks from hydrogen components using the power function relationship in Equation 3. This approach generated leak frequency distributions for each leak size, for each component in the analysis. The parameters of these distributions are summarized in Appendix B. These leak frequencies are used in model quantification in this report.

2.5 Consequence analysis methodology

The goal of the consequence analysis is to determine the physical effects of hydrogen releases, to determine what type of consequences result from those effect, and to provide a quantitative measure for the consequences.

2.5.1 Physical effects of gaseous hydrogen releases

Physical effects of hazardous material releases are well documented in literature. The primary physical effects relevant to ignited gaseous hydrogen releases are fire effects (impinging flames, temperature, heat flux) and explosion effects such as pressure and impulse waves [14]. Overpressurization in hydrogen vessels also presents a hazard, but current models to predict the fragmentation behavior of hydrogen vessels are not sufficiently predictive for use in QRA [14].

When a high-pressure leak of hydrogen is immediately ignited near the source, the result is a classic turbulent-jet flame. Houf [15] developed a methodology for predicting flame length, flame width, and the heat flux at an axial position x and a radiation position r, given knowledge of the jet exit conditions. This work is documented at length in [7], and a corresponding Matlab scripts and functions can be found in Appendix C.

Indoor hydrogen releases have a the potential to cause deflagrations or detonations, because hydrogen can accumulate if it is not immediately ignited. If the accumulated hydrogen is ignited, the resulting deflagration or detonation will have both thermal and pressure effects. Overpressures created from hydrogen combustion can vary significantly based on the scenario. The least significant is a flash fire where the hydrogen is consumed rapidly as it is released thus preventing the formation of a large volume of gas. Flash fires result in very small overpressures. Vapor cloud explosions (VCEs) involve a large release of hydrogen that mixes with air to form a large flammable cloud before ignition occurs. The overpressure effects produced by a VCE can vary greatly and are determined by the speed of flame propagation. In most VCEs, a deflagration occurs where the flame front is subsonic and the resulting behavior is similar to a flash fire. A detonation event involves a supersonic flame front and results in significant overpressures and impulse effects. The presence of turbulence in the hydrogen release, unburned gases, or externally produced due to the presence of objects can potentially result in a transition from a deflagration to a detonation event.

Simple engineering models for predicting deflagration and detonation effects are not fully developed for hydrogen gas. However, the DOE is funding research efforts to develop hydrogen dispersion and flammability models by 2015 [16]; current progress can be found in the references [15, 17]. Until these models are fully developed and validated, the pressure and impulse effects of hydrogen deflagrations and detonations must be established using computational fluid dynamics (CFD) simulations and experimental activities. Previous work at Sandia developed a set of indoor hydrogen release simulations [1] and experiments [18, 19, 1] to predict the effects of delayed hydrogen ignitions. These experiments and simulations were based on generic forklift specifications, guidance in NFPA 2, and a leak sized based on industry recommendations. A release scenario was defined where the entire contents (0.8kg) of a 35 MPa hydrogen tank onboard a fuel-cell forklift was released and ignited at different times inside a 1/2.8 scale model of a 1000m^3 fueling room. The hydrogen was released through a 6.35mm opening meant to simulate a medium sized leak or thermally activated pressure relief device onboard the enclosure containing the forklift hydrogen storage tank. The hydrogen was then allowed to exit through a grill on the side of the forklift and enter the surrounding warehouse. The warehouse sizing, ventilation, and amount of hydrogen on board were based on the parameters outlined in the NFPA 2 draft. NFPA 2 requires a minimum ceiling height of 7.62m (25ft) and a minimum room volume specified in Table 1.

CFD simulations of hydrogen releases from the fuel-cell powered forklift inside the warehouse were performed using the Sandia developed FUEGO CFD model [20]. Concentrations taken from FUEGO simulations were then used in a FLACS [21] model of the fueling room to simulate the overpressure generated by ignition of the hydrogen cloud at different ignition delay times. The FUEGO/FLACS simulations were performed at both full scale ($1000 m^3$) and the scale of the experiments (1/2.8 scale). The scaled simulations were compared with data taken in the scaled fueling room experiments for the purposes of validating the modeling approach. The validated model was then used to perform additional full-scale release simulations to provide information for risk-informed hydrogen codes and standards development.

2.5.2 Fatality estimation

Fatalities from hydrogen releases can result from thermal exposures and from overpressure effects. For the hydrogen fueling industry, there is no statistical information available relating hydrogen release events to fatalities. However, it is possible to estimate the number of fatalities from a given accident based on existing fatality models.

Probit models are used to establish the probability of injury or fatality for a given exposure. The probit model is a linear combination of predictors that model the inverse cumulative distribution function associated with the normal distribution [3]. The probability of a fatality is predicted from Equation 4, which evaluates the normal cumulative distribution function at the value established by the probit model(Y). Different probit models for thermal and overpressure effects are discussed below.

$$P(fatality) = F(Y|\mu, \sigma) = \Phi(Y - 5) \tag{4}$$

For thermal radiation, the harm level is a function of both the heat flux intensity and the duration of exposure. Harm from radiant heat fluxes is often expressed in terms of a thermal dose unit which combines the heat flux intensity and exposure time by the following equation:

$$Thermal\ Dose\ Unit = V = I^{(4/3)\times t} \tag{5}$$

where I is the radiant heat flux in W/m^2 and t is the exposure duration in seconds.

Table 2 lists available probit models that can be used to determine the probability of a fatality from a given thermal dose, V. The probability of a fatality is evaluated by inserting the probit model from Table 2 into Equation 4. The available probit models and Equation 4 have been implemented in the Matlab scripts in Appendix C.6. Figure 1 shows a comparison of the four thermal fatality probit models. The HSE [22] recommended values for “Dangerous Dose” (defined as resulting in death to 1% of the exposed population) and LD50 (the lethal dose for 50% of the exposed population) are also shown on the figure for comparison. LaChance et al. [23] recommend using both the Eisenberg and the Tsao & Perry probit models for hydrogen-related applications.

[3] Today, probit model are associated with the standard normal distribution, $\mu = 0$ and $\sigma = 1$. However, historically, probit analysis was based on normal distributions with $\mu = 5$ to avoid negative values. We have retained this $\mu = 5$ value to be consistent with the probit models in fatality literature.

Table 2. Probit models for that are used in Equation 4 to calculate fatality probability as a function of thermal dose (V).

Reference	Fatality Model	Notes
Eisenberg [24]	$Y = -38.48 + 2.56 \times ln(V)$	Based on population data from nuclear blasts at Hiroshima and Nagasaki (ultra-violet radiation)
Tsao & Perry [25]	$Y = -36.38 + 2.56 \times ln(V)$	Eisenberg model, modified to account for infrared radiation
TNO [26]	$Y = -37.23 + 2.56 \times ln(V)$	Tsao and Perry model modified to account for clothing
Lees [27]	$Y = -29.02 + 1.99 \times ln(0.5V)$	Accounts for clothing, based on porcine skin experiments using ultraviolent source to determine skin damages. Uses burn mortality information.

Structures and equipment can also be damaged by exposure to radiant heat flux. Some typical heat flux values and exposure times for damage to structures and components were provided by LaChance et al. [23]. However, because the exposure times required for damage is long (> 30min), the impact of thermal radiation from hydrogen fires on structures and equipment is not generally significant since personnel are able to evacuate the building before significant structural damage occurs.

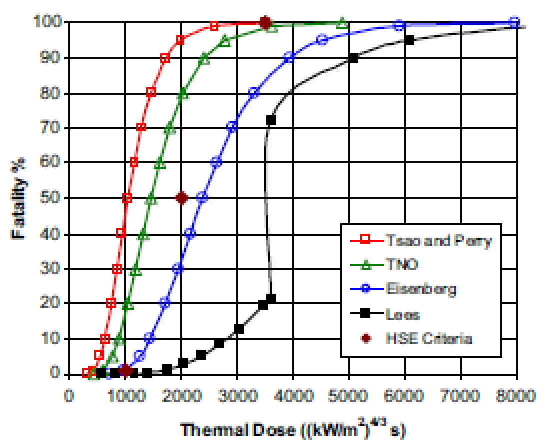


Figure 1. Comparison of thermal radiation probit models

Similar to thermal exposures, there are probit models available to predict the level of harm to people and structures from blast overpressures. Significant increases in pressure can cause damage to pressure-sensitive organs such as the lungs and ears. Indirect effects include the impact from fragments and debris generated by the overpressure event, collapse of structures, and heat radiation (e.g., from the fireball generated during a vapor cloud explosion). Large explosions can also carry

Table 3. Probit models to calculate fatality probability from exposure to overpressures. Where P_s is peak overpressure (Pa), i is the impulse of the shock wave (Pa*s), v_{debris} is the velocity of the debris (m/s), m_{debris} is the total mass of debris (kg).

Reference	Fatality model
Eisenberg - Lung hemorrhage [28]	$Y = -77.1 + 6.91 * ln(P_s)$
HSE - Lung hemorrhage [29]	$Y = 1.47 + 1.371 * ln(P_s)$
TNO - Head impact [26]	$Y = 5 - 8.49 * ln((2430/P_s) + 4.0 \times 10^8/(P_s * i))$
TNO - Structure collapse [26]	$Y = 5 - 0.22 * ln(V)$ Where $V = (40000/P_s)^{7.4} + (460/i)^{11.3}$
TNO - Debris impact [26]	For fragments >4.5kg $Y = -13.19 + 10.54 * ln(v_{debris})$ For fragments >=0.1kg $Y = -17.56 + 5.3 * ln(0.5 * m_{debris} * {v_{debris}}^2)$ For fragments >=0.001kg $Y = -29.15 + 2.1 * ln(m_{debris} * {v_{debris}}^{5.115})$

a person some distance resulting in injury from collisions with structures or from the resulting violent movement. Probit models for the effects of overpressures are provided in Table 3. These probits are implemented in the Matlab scripts in Appendix C.7.

LaChance et al. [23] recommend the use of the TNO probit models, and suggests that indirect effects from overpressure events represent the most important concern for people. The overpressures required to cause fatal lung damage are significantly higher than the values required to throw a person against obstacles or to generate missiles that can penetrate the skin. In addition, a person inside a structure would more likely be killed by the facility collapse than from lung damage. For this reason, we use the TNO probit model for structural collapse in this analysis.

2.6 Risk analysis and management

The models developed during cause analysis and consequence analysis are integrated together to produce an overall estimate of the system risk. This is accomplished using available software packages such as SAPHIRE [4] or by developing programs (e.g., in Matlab).

The Fatal Accident Rate (FAR) and Average Individual Risk (AIR) are commonly used metrics for expressing the fatality risk for a platform. FAR and AIR are expressed as a function of the Potential Loss of Life (PLL). The PLL expresses the expected number of fatalities, per dispenser-

[4] https://saphire.inl.gov/

year. PLL is expressed as follows:

$$PLL = \sum_{n} \sum_{j} (f_{nj} \times c_{nj}) \tag{6}$$

where n is one of the possible accident scenarios in the ESDs, j is the type of personnel consequence (e.g., immediate fatality, fatality during evacuation), $f_n j$ is the frequency of an accident scenario n with personnel consequence j, and $c_n j$ is the expected number of fatalities for accident scenario n with personnel consequence j. $f_n j$ comes from the ESDs and $c_n j$ comes from the consequence analysis. In this work, we are only considering immediate fatalities.

The FAR is the expected number of fatalities in a group, per 100 million exposed hours. The FAR for a particular facility can be calculated using the PLL, as well as the average staffing of the facility. FAR is calculated using Equation 7.

$$FAR = \frac{PLL \times 10^8}{Exposed\ hours} = \frac{PLL \times 10^8}{N_{staff} \times 8760} \tag{7}$$

where N_{staff} is the average number of personnel in the facility, and dividing by 8760 converts from years to hours.

The AIR expresses the average number of fatalities per exposed individual. It is based on the number of hours the average worker spends in the facility.

$$AIR = H \times FAR \times 10^{-8} \tag{8}$$

where H is the annual number of hours the individual spent in the facility.

For risk management, the risk analyst should communicate the results of the analysis to the stakeholders. The estimated risk level should be compared to the threshold(s) for unacceptable risk. If the estimated risk level is above the threshold, the risk analyst should provide guidance to the stakeholders to reduce the risk level. Once the estimated risk level is below the threshold, the risk analyst should work with the stakeholders to develop a risk management approach that continues to allocate reasonable resources to reduce the risk. Due to the complexity and uncertainties involved in predicting performance in engineered systems, there will always be a level of subjectivity attached to any risk assessment result. To account for these uncertainties, it is important to continue to allocate resources to reduce the assessed risk.

3 System description

The system description documents the assumptions and premises regarding both the system design and the operational environment. The system is broken down into four sub-systems: the facility, the dispenser, the personnel, and the vehicle & fuel cell. Since the purpose of this activity is to inform codes and standards, we are analyzing a generic indoor fueling facility rather than for an existing facility. Generic P&IDs and component lists were developed based on NFPA 2 requirements. These were used to explore the objectives described in Section 1.2.

3.1 Dispenser description

Figure 2 contains the Piping & Instrumentation Diagram (P&ID) for a code-compliant dispenser for indoor, non-public, fast fill applications. NFPA 2 specifies the requirements for the dispenser, and these requirements are referenced in Tables 4 and 5. Table 4 also include several optional components, which may or may not be required depending on the inclusion of other components. These are included in the current report to enable future work intended to evaluate different code-compliant dispenser configurations.

Dispenser operating assumptions:

- Dispenser delivery pressure is 35MPa (5000 psi). This is used to characterize release conditions.
- Dispenser internal temperature is 15°C. This is used to characterize release conditions.
- Dispenser operates for up to 5min per fueling event.
- All tubing in the dispenser is 3/8" OD (Outer Diameter), 0.065" wall, ASTM A269 seamless 316 stainless steel tubing. This is relevant to characterizing the release sizes and estimating discharge rates.

Table 4: Dispenser system indoor components. A $\star$ denotes that the component is optional, because the code requirements could be satisfied by other required components.

P&ID Tag	Description	NFPA 2 Reference
ASV2*	Auto shutoff (solenoid) valve	7.1.21.2 - Requires manual or automatic emergency shutoff valve at the point of use *(Presence of HV1 also satisfies this requirement)* 10.3.3.2.2.7(A) - Requires automatic shutoff valve *(Presence of ASV1b also satisfies this requirement)*
BC1	Breakaway coupling (dispensing hose)	10.3.1.18.6 - Requires breakaway coupling on dispensing hose between dispenser and nozzle
BC2*	Breakaway coupling (vent hose)	*Not required by current code*
BSC1	Building Safety Circuit (logic controller for automatic shutoff valves)	10.3.3.2.2.7(C) - Requires automatic shutoff control when safety systems actuate or fail.

Table 4: (continued)

P&ID Tag	Description	NFPA 2 Reference
		10.3.3.2.2.2(C) - Requires automatic shutoff control when max fuel quantity per event or vehicle fueled to capacity 10.3.3.2.2.2(G) - Requires automatic shutoff if integrity tests (see 10.3.1.11.6 and 10.3.1.11.7) are unsatisfactory 10.3.3.2.2.4(A) and 10.3.3.2.2.5(A)- Requires automatic shutoff upon fire detection or alarm activation 10.3.3.2.2.7(E) - Requires automatic shutoff upon gas detection
D1	Flame and gas detector	10.3.1.19.1 - Requires gas and flame detection capabilities at any point on the equipment *(Code does not specify whether this is achieved by a single or multiple devices)*
GD2⋆	Gas detector	10.3.1.19.1 - Requires gas and flame detection capabilities at any point on the equipment (Code does not specify whether this is achieved by a single or multiple devices, so GD2 is optional is D1 detects both flames and gas.) 10.3.3.2.2.7 (E) - Requires gas detection inside of the dispenser housing with similar requirements to 10.3.1.19.1; *(It is possible that D1 could be designed to satisfy this requirement)*
FLD1	Flow limiting device	10.3.3.2.2.2(F) - Limits max fueling rate to 2kg/min *(Code does not specify whether device is located inside or outside of the building)*
Hose	Flexible dispensing and ventilation hose	10.3.1.8.5 Limits use of hose in the system except for the vehicle fueling hose 10.3.1.14.7 - Requires transfer system capable of depressurization to facilitate disconnection
HV1⋆	Manual valve	10.3.3.2.2.7(B) requires a manual shutoff valve upstream of BC1, unless an automatic shutoff valve is present in a similar location *(Presence of ASV2 satisfies this requirement)*
N1	Nozzle	10.3.1.15.1 Requires SAE J2600 nozzle
PI2	Pressure gauge/indicator (dispenser delivery)	10.3.1.5.3 - Requires device to indicate dispenser discharge pressure
SRV1	Safety (overpressure) relief valve	10.3.1.4.2.3 - Requires overpressure device in the dispenser
Vent	Vent Pipe	Required by 6.16 and by CGA 5.5, 7.1.17; 10.3.1.4.2.3

Table 4: (continued)

P&ID Tag	Description	NFPA 2 Reference
Ventilation⋆	Optional ventilation	10.3.2.2.1.6 requires ventilation. However, 10.3.3.2.2.2 exempts industrial facilities from this requirement if the dispenser meets all of the requirements of 10.3.3.2.2.2(A)-(H).

Table 5. Process control components external to dispenser

P&ID Tag	Description	NFPA 2 Reference
ASV1a	Auto shutoff (solenoid) valve	6.20 - Source Valve (Required for bulk storage) 7.1.21.2 - Requires manual or automatic emergency shutoff valve at bulk source
ASV1b	Auto shutoff (solenoid) valve	7.1.21.2 - Requires manual or automatic emergency shutoff valve at the point where the system piping enters the building 10.3.1.18.4 Requires automatic building isolation valve 10.3.3.2.2.7(A) Requires automatic shutoff valve
E-Stop	Emergency Stop buttons, tied into BSC1.	10.3.1.18.5 - Requires local and remotely located manual shutdown 10.3.3.2.2.6 - Requires an emergency shutdown device similar to 10.3.1.18.5 with more specific location requirements 10.3.3.2.2.6(A) requires a third manual shutdown device on the dispenser.
Fire Alarm	Fire Detection &Alarm System	10.3.3.2.2.4 Requires dispensing area fire detection system 10.3.3.2.2.5 Requires dispensing area manual fire alarm system; system must be able to stop flow of gas and shut down the dispenser.

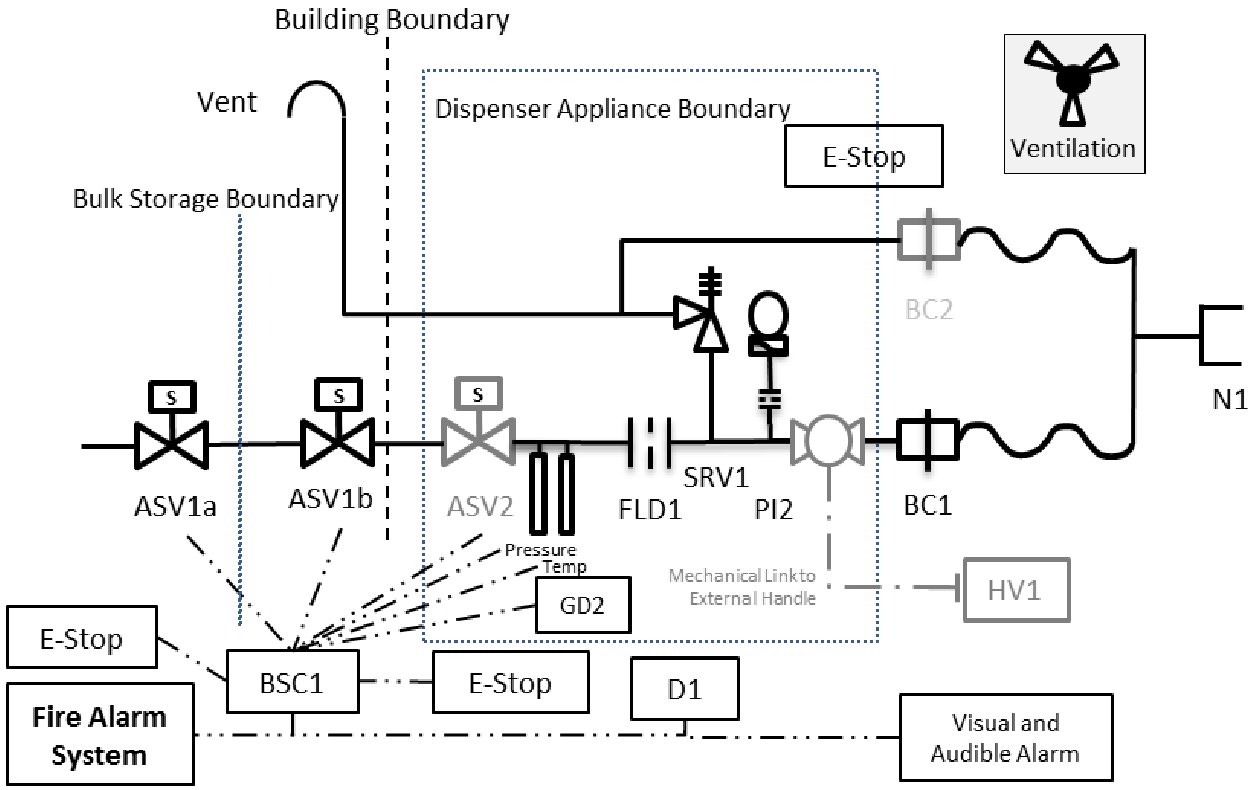


Figure 2. Dispenser P&ID. Grey components are optional.

3.2 Facility Description

The facility description was generated by the authors based on a generic warehouse design. The NPFA 2 refueling task group approved the selections regarding the facility.

- The warehouse is a free-standing industrial frame structure. The type of structure is relevant to determining the probability of structural damage from explosion loads.
- Warehouse interior dimensions are: 100m (length) x 100m (width). This is relevant to determining worker positions in the warehouse for consequence analysis.
- Warehouse ceiling height: 7.62m (25ft). This is the minimum ceiling height required by NFPA 2 Section 10.3.3.2.2.2(E). This is relevant to determining explosion loads.
- Facility has a single dispenser. This is relevant to determining consequences.
- Facility temperature is 15°C. Facility pressure is atmospheric (101.325 kPa). This is based on standard room temperature assumptions. This is used to characterize release conditions.
- Dispenser is located on the ground floor of the warehouse, centered along one wall. This is relevant to determining explosion loads.
- No sources for piloted ignition are present in fueling area. NFPA 2.7.1.23 Requires ignition source control, and NFPA 2 Section 10.3.1.16 assigns the electrical classification within 4.6m (10ft) of the dispenser to Class 1, Division 2. This is relevant to selection of ignition

probability model.

- Dispenser has a protective casing and is located on a 6in high curb. Two guard posts (4inches in diameter) are located at the front corners of the dispenser. NFPA 24.14.1 requires use of guard posts or curbs to protect the dispenser from vehicle damage. This allows us to exclude vehicle collisions and debris from the QRA.
- Hydrogen from outdoor storage enters the facility via 3/8" OD 0.065" wall ASTM A269 seamless 316 stainless steel tubing. This tubing runs along the ceiling and down the exterior wall closest to the dispenser. This is relevant to characterizing leak sizes.
- The length of hydrogen piping inside the building is 20m. NFPA 2 Section 10.3.1.7.6.1 requires piping to be run as directly as possible (this minimizes piping). This is relevant to assessing leak frequency.

3.3 Personnel assumptions

The personnel assumptions were generated by the authors based on a generic warehouse design. The assumptions were approved by the NPFA 2 refueling task group.

- There are 50 employees in the warehouse at any given time. This is relevant to determining personnel fatality rates.
- There are no members of the public in the warehouse. This is relevant to determining the threshold for unacceptable risk.
- Warehouse personnel each work 2000 hours per year. This is a standard, full-time work schedule. This is relevant to determining personnel fatality rates.
- Workers locations in the warehouse are derived from a random normal distribution centered at the dispenser (μ=0, $\sigma = (shortest\ building\ length\ from\ dispenser)/3$). The σ value was set at 1/3rd of the building size since 3 standard deviations encompasses 99.7% of the possible positions. 68% of people will be located within 1 standard deviation of the mean.
- Operators are trained on the use of the dispenser. NFPA 2 Section 10.3.2.1.2 requires dispensing to be done by qualified operators. This assumption is relevant to selection of the human error rate.

3.4 Vehicle and fuel cell descriptions

The vehicle and fuel cell descriptions assumptions were generated by the authors based on a generic warehouse design. The descriptions were approved by the NPFA 2 refueling task group.

- 20 vehicles in the fleet. Each vehicle is operated 24 hrs/day and 250 days/yr. This is relevant to determining the number of dispenser demands.
- Each vehicle is fueled once every 12 hours. This is relevant to determining the number of dispenser demands.
- Total fueling events[5]: 10000 fuelings/yr.

[5] $20\ vehicles * 2\ fuelings/day * 250\ operating\ days/yr = 10000\ fuelings/yr$

4 Cause Analysis

After finalizing the facility description, the next step is to identify the possible accidents that are relevant to the analysis. This requires several tasks. The first task is to characterize the accident initiators in greater detail. The second task is to systematically determine the range of scenarios (accidents) that could occur after a hydrogen release. The third task is to systematically identify the events that can lead to releases of hydrogen from the dispenser[6].

4.1 Hazards

The hazards related to use of hydrogen are primarily related to the release of hydrogen from an enclosure. This results in high pressure gas release and can result in fires and explosions. Hydrogen is flammable in concentrations between 4% and 74% in air, and it is explosive in concentrations between 15% and 59% in air. Hydrogen is unlikely to self ignite due to its high auto-ignition temperature. However, hydrogen has a lower ignition energy than comparable gasoline-vapor mixtures, and static electricity is sufficient to ignite hydrogen mixtures. Due to hydrogen's low electro-conductivity, the flow of gaseous hydrogen (GH_2) can generate electrostatic charge and ignite the hydrogen/air mixture. Other mechanisms for spontaneous ignition of hydrogen are described in [30].

There are two hazards associated with releases of hydrogen from indoor fueling of vehicles: exposure to thermal radiation (including direct flame contact) from jet fires and exposure to overpressures from hydrogen releases or deflagrations. Both of these hazards can affect people, property, structures, and the environment directly or indirectly.

High pressure gases escaping from an enclosure can propel debris at high velocity. Due to the high flammability of hydrogen gas, it is assumed that the occurrence of fires associated with hydrogen releases will render the risk of debris injuries to be negligible. Future analysis should evaluate this hazard to ensure that debris provides a small contribution to overall risk.

Hydrogen can also cause oxygen displacement, which can lead to asphyxiation. However, since hydrogen is highly buoyant and diffusive, oxygen displacement is only a concern in extremely small, well-sealed spaces. Since the indoor refueling space is relatively large and the ceilings are high, hydrogen is expected to either diffuse or ignite before reaching a high enough concentration for suffocation at the ground level. Therefore, for GH_2 vehicle fueling, asphyxiation is not a significant hazard.

[6] We are not considering potential releases from vehicles, because these releases are assumed to be unrelated to fueling. Future analyses should explore whether a release from a vehicle during fueling is a significant risk contributor. Future analyses could also evaluate risks associated with indoor use of hydrogen beyond fueling.

4.2 Initiating events and root causes

Appendix A contains the FMEA that was used to develop a full set of initiating events and root causes, and notes on which events were screened out. In indoor fueling operations, the initiating event for all scenarios is a release of hydrogen gas from the dispenser.

Release characteristics vary widely, and different types of releases are associated with different causes and different consequences. For this work we evaluate five releases categories, which are associated with a non-dimensionalized area: the percentage of flow area of the dispenser piping. There is little hydrogen-specific data available for prediction, and classifying the releases in terms of non-dimensional flow area of the piping allows us to use leak frequency data assembled from similar industries to make predictions. There are five release sizes of interest: 0.01%, 0.1%, 1%, 10%, 100% of dispenser pipe flow area. We conservatively assume that releases flow from an equivalent diameter circular hole. For the code-compliant dispenser in Section 3.1, the pipe flow area is $4.87\times10^{-5}\text{m}^2$.

Hydrogen releases from the dispenser can occur through one of several mechanisms:

1. Leaks from individual components (0.01%, 0.1%, 1%, 10%, and 100% releases), including separation of a component or unintended operation;
2. Shutdown failures [7] (100% releases only);
3. Accidents (100% releases only).

The root causes of these releases are modeled in the FT (fault tree) shown in Figure 3. The basic event "LeakFreq" is the total frequency of leaks from all of the indoor components; this basic event is relevant to all five release categories. The remaining events in the FT are only applicable for the 100% release category[8].

4.3 Exposure Scenarios

The ESD (event sequence diagram) in Figure 4 illustrates the possible scenarios that could occur after a hydrogen release. There are three possible outcomes from a hydrogen release scenario: jet fires, explosions, and un-ignited releases.

The ESD includes several events that influence the occurrence of the end states. The first event is leak detection and isolation. If the leak is detected and isolated before ignition occurs, the release will not be ignited, and there will be no risk-significant consequences. If the leak is not detected and isolated, there is potential for immediate ignition or delayed ignition. Immediate ignition of a hydrogen release is assumed to result in a jet fire, and delayed ignition of a hydrogen release is assumed to result in an explosion. If ignition does not occur, the un-ignited release does not result

[7] This event is very unlikely due to the degree of redundancy among shut-down components. However, it's important to consider this in the QRA because it helps users evaluate the trade-offs when removing/adding components.

[8] Shutdown failure would result in 100% release through the dispensing nozzle. The accidents included in this analysis would result in significant damage to the dispenser, so releases from these accidents are assumed to be 10%.

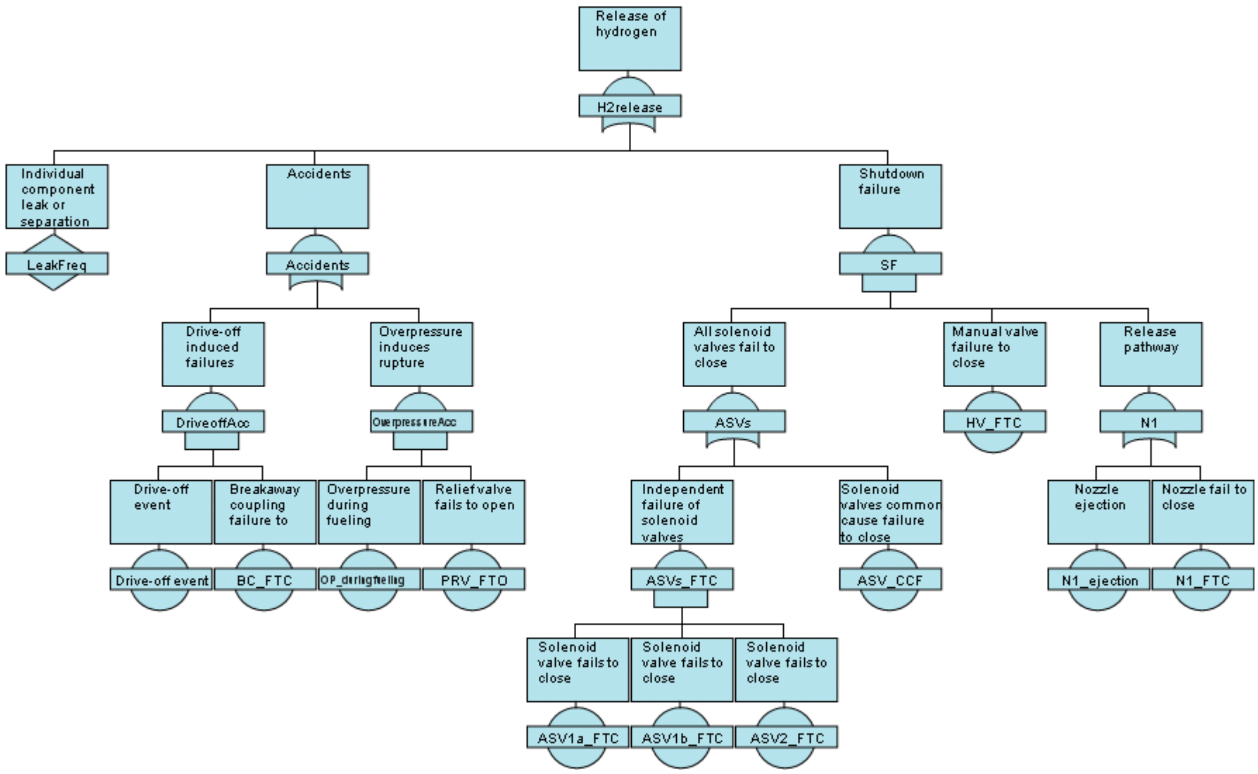


Figure 3. Fault tree for root causes of releases from a hydrogen dispenser. Individual component leaks (LeakFreq) is relevant to all releases sizes. Accidents and shutdown failures are relevant to 100% release only.

in risk-significant consequences.

4.3.1 Leak detection and isolation

Early detection and isolation of a hydrogen leak stops the release of hydrogen. If this occurs before the hydrogen is ignited, and there is no subsequent ignition, the leak is mitigated and there is no additional risk.

Hydrogen flames and hydrogen gas are invisible to the naked eye under most conditions. Hydrogen fires emit a pale blue light in the dark, but they are best detected by flame detectors. Hydrogen flames can also be detected by use of manual detection methods, such as waving a broom through the suspected fire area, or by unintentional contact with the flame. Small hydrogen leaks can be detected by use of leak detection fluid (bubble testing), and larger leaks often emit audible cues. Table 6 presents leak detection options for different release sizes relevant to this analysis.

NFPA 2 Section 10.3.1.19.1 requires both gas and flame detection capacity to be present at the

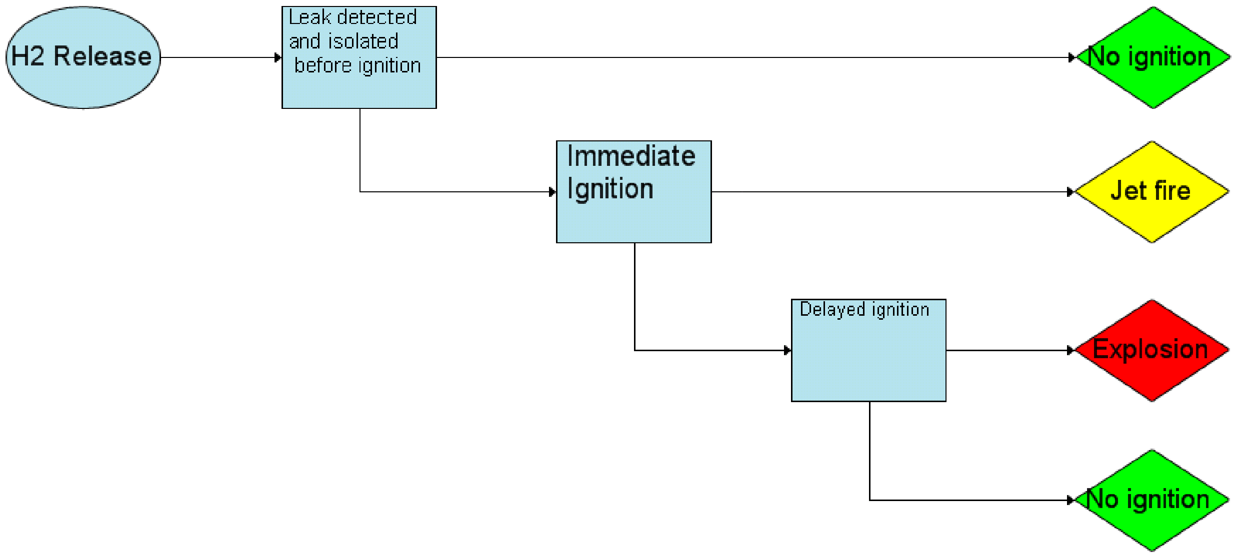


Figure 4. ESD model for hydrogen release scenarios

dispensing site. The detectors must be capable of shutting down the dispenser if gas or a flame is detected within thresholds. NFPA 2 Section 10.3.3.2.2.7(E) requires the gas detection system to sound an alarm and shut down the dispenser if 1% (by volume) hydrogen concentration is detected within 1m of the dispenser. NFPA 2 does not specify whether gas and flame detection capabilities can be integrated into one detector unit or if they must be achived by separate detectors.

Table 6. Methods for detecting the presence of unignited hydrogen releases of different sizes.

Release size (% of pipe diameter)	Detection Method
$< 0.01\%$	Bubble solution and hand-held gas detectors
$0.01\% - 0.1\%$	Audible leak (70-90dB), indoor/enclosure area combustible gas detectors
$1\% - 100\%$	Audible leak (>100dB), indoor/enclosure area combustible gas detectors

4.3.2 Ignition

In QRA, the word ignition refers to the process that leads to a sustained combustion event. A sustained combustion requires both a source of ignition and additional conditions that allow the combustion process to continue. The initial source of ignition can be a piloted ignition (where a spark or other flame ignites the gas) or non-piloted, spontaneous ignition (mechanisms for spontaneous ignition of hydrogen sources are discussed in [30]). The processes that permit sustained flame have been investigated by many research teams, but this research has not resulted in a model that is suitably predictive for QRA.

In QRA, ignition is typically divided into immediate ignition events and delayed ignition events. Immediate ignition occurs if the leak is ignited within the first seconds after the leak occurs. Delayed ignition allows hydrogen to accumulate before being ignited.

4.4 Scenario probability

According to the ESD in Figure 4, there are two scenarios that lead to risk significant consequences (jet fires and explosion). The ESD encodes the equations that are used to estimate the probability of a jet fire and the probability of an explosion. Recall that the ESD combines the probability of different events, $P(event)$, to estimate these scenario probabilities, and that the notation $P(\overline{event})$ means the probability of non-occurrence of an event, which is equal to $P(\overline{event}) = 1 - P(event)$. According to the ESD, the probability of a jet fire is quantified using Equation 9:

$$f(Jet fire) = f(H_2\ release) \times P(\overline{Leak\ isolated}) \times P(Immediate\ ignition) \tag{9}$$

The probability of an explosion is quantified using the Equation 10:

$$\begin{aligned} &f(Explosion) = \\ &f(H_2\ release) \times P(\overline{Leak\ isolated}) \times P(\overline{Immediate\ ignition}) \times P(Delayed\ ignition) \end{aligned} \tag{10}$$

4.4.1 Initiating Event probability

The probability of the initiating event in the ESD comes from quantifying the FT in Figure 3. To quantify this FT, we need information regarding the probability of releases from individual components as well as probabilistic information about the basic events leading to accidents and shutdown failures.

Probability distributions for the releases from different components used in for hydrogen systems were presented in SAND2009-0874 [7]. These distributions, which are reproduced in Appendix B, are used to quantify the probability of “LeakFreq” in the FT using annual frequency data. The release frequency from each component type is calculated by multiplying the number of components of each type by the mean frequency of releases for that component. Use of this release frequency data requires counts of the following dispenser components: compressors, cylinders, filters, flanges, hoses, pipes, valves, instruments, and joints. The part count for the code-compliant dispenser described in Section sec:systemdescription is presented in Table 7. These part counts are multiplied by the mean release frequencies from Appendix B to obtain an annual frequency of releases from individual components, which is inserted into the FT in Figure 3.

Table 7. Part count for the code-compliant dispenser (described in Section 3). Note: There are no compressors, cylinders, filters, or flanges in the dispensing system.

- Hose: 1 hose (3m length)
- Pipe: 20m
- Valves: 5 (ASV2, HV1, BC1, SRV1, N1)
- Instruments: 3
- Joints: 35
  - 2 crimps per hose
  - 3 joints per ASV or HV
  - 2 joints per regulator
  - 4 joints for BC1 (3 joints, 1 body seal)
  - 3 joints for nozzle (1 interior joint to compensate for interlocked valves, 1 unconnected end, 1 body seal)
  - 1 joint per instrument
  - 14 joints from piping (assumed 4 elbows, 1 tee connecting dispenser sense line to main line, and 1 tee connecting main process piping to SRV).

The probability of accidents and of shutdown failures is obtained from combining basic event probabilities, as seen in the FT. Generic probabilities for the basic events (per demand) are presented in Appendix B. To obtain the frequency of accidents and shutdown failures, the probability per demand is multiplied by the expected number of demands per year (i.e., the annual number of fueling events calculated in Section 3.4).

The FT is presented within the Matlab model in Appendix C.1. Solving the FT in Figure 3 results in the mean annual release frequencies in Table 8.

Table 8. Release rate and mean frequency of leaks of the 5 different sizes for the generic dispenser configuration.

Release size	Mean release frequency (/yr)
0.01%	3.48×10^{-2}
0.10%	5.03×10^{-3}
1%	1.51×10^{-3}
10%	1.18×10^{-3}
100% (leaks only)	7.13×10^{-4}
100% (all causes)	7.68×10^{-4}

4.4.2 Detection and isolation probability

The probability of failed detection and isolation of hydrogen releases is related to the probability of failure of the gas and flame detection capacity required by NFPA 2 Section 10.3.1.19.1. There is limited data on the effectiveness of gas detectors and flame detectors. However, according to Vinnem, [10], gas and fire detection systems are Safety Integrity Level (SIL) 2 systems; a SIL 2 system must have an unavailability less than 1×10^{-2}).

However, there remains substantial uncertainty about the functioning of these detectors. While the SIL levels are descriptive as to detector failure rate on demand, there is always uncertainty about when the detector is demanded. Ventilation, detector placement, leak location all contribute to the difficulty of detecting gas and flames. For this reason, we assign 10% probability of leak detection and isolation[9] in the QRA model.

4.4.3 Ignition Probability

According to SAND2009-0874 [7], hydrogen ignition probabilities are available from two sources: one set was generated for the HYSAFE program [31] from a summary of existing ignition models used in hydrogen risk assessments, and one set was generated for the Canadian Hydrogen Safety Program [32] by adapting non-hydrogen ignition values suggested in Cox, Lee, & Ang [33]. Both approaches provide ignition probabilities as a function of the hydrogen release rate.

The hydrogen release rate and other jet exit conditions can be predicted using a notional nozzle model based on Birch [34] and the Abel-Noble equation of state. These three models are included in the Matlab scripts presented in Appendices C.2 and C.3. The maximum mass flow rate from the generic dispenser for the five release sizes is presented in Table 9.

Table 9. Peak mass flow rates for the five releases sizes

Release size	Max. mass flow rate (kg/s)
0.01%	9.39×10^{-5}
0.10%	9.39×10^{-4}
1%	9.39×10^{-3}
10%	9.39×10^{-2}
100%	0.939

The hydrogen-specific ignition probabilities suggested by the two sources are shown in Table 10. As indicated, values are presented for both immediate and delayed ignition. The HYSAFE work found that immediate ignition probabilities in literature range from 0.0001 to 0.9, and delayed

[9]Failure of isolation after detection is assumed to be negligible compared to detection failure. Typically, isolation valves have unavailability less than 1×10^{-3}.

ignition probabilities range from 0.004 to 0.5. The HYSAFE probabilities in Table 10 are for self-ignition only and thus are not totally appropriate for use in this study. For the work documented in [7], the values from [32] values were used; these values are also used in the current QRA work.

Table 10. Ignition Probabilities

Canadian Hydrogen Safety Program [32]			HYSAFE [31]	
Hydrogen release rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability	Hydrogen Release rate (kg/s)	Immediate Ignition Probability
$<$0.125	0.008	0.004	0.01 - 0.1	0.001
0.125 - 6.25	0.053	0.027	0.1 - 1	0.001 (add 0.001 when P$>$100bar)
$>$6.25	0.23	0.12	1 - 10	0.01 (add 0.01 when P$>$100bar)
			$>$10	0.1 + (0.01 or 0.02)

4.4.4 Final scenario probabilities

Equations 9 and 10 are used to combine the probability information to get frequencies for the two risk-significant end states. These equations are implemented in the Matlab scripts in Appendix C.1. The expected frequencies for the risk-significant end states are in Table 11.

Table 11. Expected frequencies(/yr) for the two undesired scenarios that could result from hydrogen releases.

Release size	Jet fire	Explosion
0.01%	2.51×10^{-4}	1.24×10^{-4}
0.10%	3.62×10^{-5}	1.80×10^{-5}
1%	1.09×10^{-5}	5.39×10^{-6}
10%	8.51×10^{-6}	4.22×10^{-6}
100%	3.66×10^{-5}	1.77×10^{-5}

5 Consequence Analysis

After finalizing the accident scenarios and scenario frequencies, the next step is to determine the consequences associated with each scenario. This involves determining the physical effects of the accidents, as well as the personnel response to those physical effects.

5.1 Physical effects of the accidents

The dominant damage mechanism from jet flames is heat flux, and the dominant damage mechanism from explosions is overpressure [14].

Heat flux at a given distance from a jet flame can be predicted from the jet exit conditions with the model developed by Houf [15]. The jet exit conditions are be predicted using a notional nozzle model based on Birch [34] and the Abel-Noble equation of state; these models are implemented in the Matlab scripts in Appendices C.2 and C.3. The thermal effects of a jet flame resulting from these jet exit conditions are predicted by the Houf model, which is implemented in the Matlab script in Appendix C.5.

Overpressure effects resulting from hydrogen explosions were based on experiments and analysis described in [18, 19, 1]. Figure 5 displays the predicted overpressures from FUEGO/FLACS simulation for 3 different release sizes in a 1000m^3 room with no ventilation. The simulations were performed for an 0.8kg, 35MPa tank with $1/4$inch line size. For the QRA, we conservatively used the maximum predicted overpressure value for each release size; this assumption, which ignores the mitigating effect of long ignition delays, is intended offset the smaller line size used in the simulations. For 0.1% and 0.01% release sizes, we assumed that the resulting overpressure was half of the overpressure of the 1% leak. This assumption is supported by the overpressure reduction trend seen in Figure 5.

While the generic warehouse facility being analyzed is significantly larger than the 1000m^3 room used in the experiments, the presence of walls and shelving inside the warehouse reduces the free volume around the dispenser. The results of the experiments and analyses on the 1000m^3 room can be used to represent the overpressure effects around a dispenser without the mitigating effects of the entire warehouse volume.

Since there is no first-order model for predicting impulse effects for QRA purposes, we use the results of simulations to provide the inputs for the QRA calculations. The impulse of the shock wave is also based on simulation data. Houf [19] ran simulations for peak overpressure and impulse on tunnel sidewalls for three 1.67kg, 70MPa hydrogen tanks; Figure 6 provides the impulse for a 100% release from these tanks. We used the maximum impulse from Houf's experiment (4000 Pa·s) as the expected impulse for the 100% leak, and we assumed that smaller leaks produce half of the impulse as the next-larger leak. Due to the large amount of gas released in simulation result, this assumption is believed to be very conservative and should be revisited in future QRA activities.

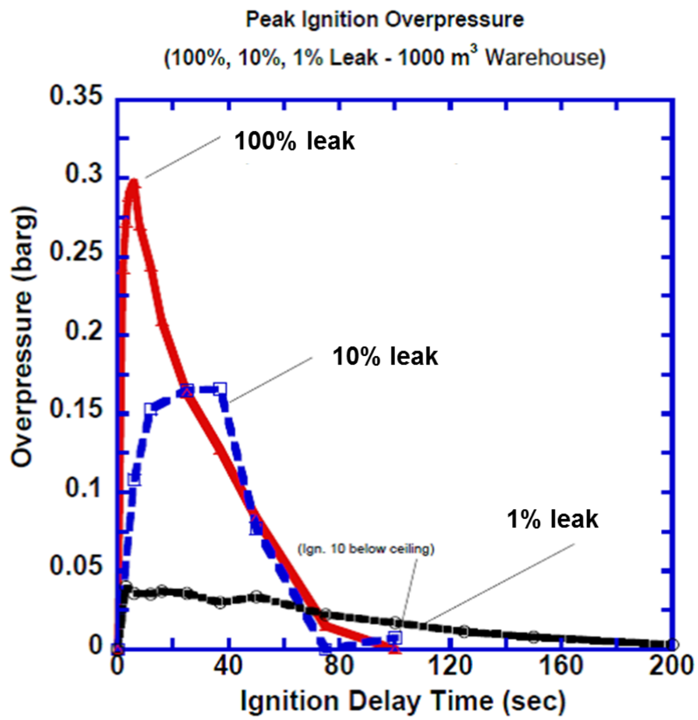


Figure 5. FUEGO/FLACS predicted overpressures for three release sizes. Releases are from a 0.8kg, 35MPa H_2 tank ($1/4''$ line size) into a well-sealed, unventilated $1000m^3$ warehouse.

5.2 Personnel response to accident loads

Exposure to jet fires and explosions can lead personnel injury or death due to direct flame contact, effects from thermal radiation, and effects from overpressure events. Exposures to flames or high radiant heat fluxes can result in first, second, or third degree burns. In addition, high air temperatures can result in breathing difficulty and respiratory damage. Overpressure events can cause direct fatalities or can result in damage to the building, which can lead to indirect fatalities.

We use probit models to determine the probability of fatality for each of the 50 workers inside the generic warehouse facility based on the exposures experienced by the worker. Worker positions (axial and radial) were randomly generated by the Matlab scripts in Appendix C.4. Positions were generated from a normal distribution centered at the dispenser, with a standard deviation $1/3$rd the length of the building. The standard deviation was selected because in a normally distributed system, 99.7% of the data points are within 3 standard deviations of the mean. To represent the person fueling a vehicle, one worker was assumed to be located at the minimum allowable distance from the dispenser.

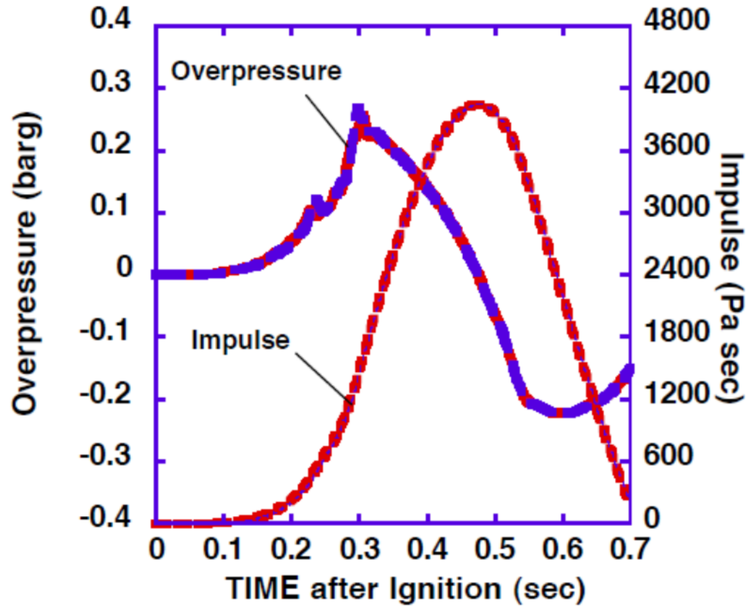


Figure 6. Simulated overpressure and impulse from a 100% release from a 1.67kg, 70MPa tank in a tunnel

5.2.1 Thermal fatalities

For thermal exposures the consequences to the exposed person are a function of radiative heat flux at the person's position and exposure time. Heat flux was calculated at each personnel location using the method described in Section 5.1. Persons were assumed to be exposed to the heat flux for 60s. The probability of fatality from thermal exposure was calculated using the Eisenberg probit model. The expected number of fatalities from a given release size was calculated by summing the probability of fatality for all 50 worker positions. The expected number of fatalities from thermal exposures for the 5 different release sizes is given in Table 12.

Table 12. Expected number of fatalities from thermal exposure due to jet fire, assuming fifty workers inside the facility; this includes one worker standing directly next to the dispenser.

Release size	Expected fatalities
0.01%	0
0.1%	0
1.0%	0.68
10%	3.20
100%	11.05

5.2.2 Overpressure fatalities

The probability of fatality from overpressure exposure was calculated using the TNO probit model for structural collapse. The expected number of fatalities from a given release size was calculated by summing the probability of fatality for all 50 workers. The expected number of fatalities from overpressure exposures for the 5 different release sizes is given in Table 13.

Table 13. Expected number of fatalities from overpressure exposure due to explosions, assuming 50 workers inside the facility.

Release size	Expected fatalities
0.01%	1.59E-4
0.1%	1.59E-4
1.0%	1.78E-2
10%	3.39
100%	15.99

6 Results, Recommendations, and Conclusions

The goal of the current analysis is to provide insight into the objectives articulated in Section 1.2. Objective 1 was to provide screening-level assessment of the fatality risk for a generic, code-compliant indoor fueling system. This risk is expressed by AIR (Average Individual Risk) and FAR (Fatal Accident Rate) values. Objective 2 is to provide science-based and risk-based recommendations to improve NFPA 2, Chapter 10 as possible. Objective 3 is to identify required improvements to the QRA that will provide more detailed insights than screening-level analysis.

6.1 AIR and FAR for the generic system

The AIR and FAR values for the generic system were calculated using the methodology in Section 2.6, implemented in the Matlab script in Appendix C.1. The Potential Loss of Life (PLL) expresses the expected number of fatalities, per dispenser-year. It is calculated by multiplying the scenario frequencies from Table 11 by the expected consequences of each scenario, given in Tables 12 and 13, and then summing over all scenarios. Based on the current analysis, the PLL for the generic system is 7.37×10^{-4} fatalities/yr. The FAR and AIR are calculated from the PLL and from the assumptions about the population of the facility. For the generic dispenser and warehouse, the FAR value is 0.17 worker fatalities in 100 million working hours, and the AIR is 3.36×10^{-6} fatalities per year, per worker.

Finding 1: The expected FAR for indoor fueling activities is a fraction of the FAR associated with the other activities conducted by warehouse personnel.

The BLS (U.S. Bureau of Labor Statistics) provides estimated rates of fatal occupational injuries based on their annual Census of Fatal Occupational Industries [12]. The BLS fatality rate is calculated using Equation 11:

$$Fatality\ rate = \frac{N}{EH} \times 2 \times 10^{-8} \tag{11}$$

where N is the total number of fatal work injuries, and EH is the total number of hours worked by all employees in the calendar year. The BLS rate is given per 100,000 full-time equivalent workers (a full-time equivalent work is one who works 2000 hrs/yr), which is equivalent to 200million working hours. The BLS fatality rate can be divided by 2 to provide a FAR value. FAR values for some selected occupations are provided in Table 14.

Examination of this table shows that the expected fatal accident rate for dispensing activities (FAR=0.17) is significantly lower than the FAR for industrial truck and tractor operators, and for laborers and hand material movers. The risk from indoor fueling is a small fraction of the risk associated with the other activities conducted by warehouse personnel with and without industrial trucks.

Finding 2: For the generic, code-compliant system, the AIR and the FAR values do not exceed the unacceptable risk threshold. However, due to many uncertainties and additional

Table 14. Fatality rates for US industries, based on BLS 2010 statistics [12].

Industry	**FAR**
U.S. Workforce total	1.8
Construction and extraction occupations	5.9
Farming, fishing, and forestry occupations	13.5
Industrial machinery, installation, repair, and maintenance workers	10.4
Industrial truck and tractor operators	3.0
Laborers and freight, stock, and material movers, hand	3.1
Sales and related occupations	1.0

limitations of early-stage analysis, additional analysis is recommended to ensure that code-compliant designs do not exceed the unacceptable risk threshold.

Section 2.2 discussed the thresholds for unacceptable risk for the generic indoor fueling system; these thresholds were an AIR value of 1×10^{-4}/yr and an FAR of 0.3. As mentioned above, the current analysis produced a FAR value of 0.17 worker fatalities per 100 million working hours, and an AIR of 3.36×10^{-6} for the average worker. As can be seen, the expected AIR for indoor fueling is more than an order of magnitude below the unacceptable threshold. Furthermore, the FAR is below the 0.3 threshold, which represents 10% of the FAR for the other activities conducted by warehouse personnel.

However, there are many layers of uncertainty in the QRA process, and at this time these uncertainties prevent us from stating that the fatality risk for all fueling systems and warehouse designs would be below the unacceptable thresholds. The calculated AIR and FAR values are a function of the assumptions in the analysis, including assumptions about the dispenser and facility designs and the operational conditions. The generic system and facility designs used in this analysis will not be applicable to all indoor fueling installations; warehouse size, layout, and number of vehicles vary widely. Sensitivity analysis should be conducted to evaluate the impact of changes to these assumptions on the risk results.

There are also additional uncertainties associated with the analysis, including the lack of hydrogen-specific data and models (e.g., models for ignition probability, overpressure effects, etc.) and the use of simplifying assumptions for early-stage QRA (e.g., use of point values instead of distributions). More detailed QRAs should be conducted to reduce the impact of these simplifying assumptions, and hydrogen specific data and models must be developed and implemented in the QRA process. Until these uncertainties are reduced, it is important to provide defense-in-depth (including safety margins and conservative code requirements). These conservative requirements could be revisited after experience data and more detailed modeling are integrated in the QRA process.

The results in the next section will provide some limited insight into how to reduce risk associated with the code-compliant design based on the current analyses. The results in Section 6.3 discusses gaps in the QRA process that must be filled to reduce the uncertainties in QRA and to enable more detailed insight into how to reduce fatality risk.

6.2 NFPA 2 insights

Sandia conducted experiments and simulation (CFD) analyses to determine if the minimum room volumes in Table 1 were sufficient, and to provide insight into the effects of ventilation. Houf et al. [1] and Ekoto et al. [18] both conducted simulations and experiments for releases from 0.8kg, 35MPa forklift tanks with 1/4inch (6.35mm) tubing. They varied the size of the releases and also varied the structure of the warehouse and the ventilation. These experiments and simulations have been discussed in further detail in the references. This section contains qualitative insights that were developed from evaluation of the experimental and simulation results and from the QRA process.

Recommendation 1: Increase the minimum room volume guidance in NFPA 2 and discourage the use of small fueling rooms. CFD analyses demonstrate that significant overpressures can be generated from explosions in 1000m^3 rooms (see Figure 5). The overpressures in Figure 5 are above the threshold for structural collapse (15-20kPa according to [35]). Reducing the overpressures generated by hydrogen explosion scenarios would reduce the number of fatalities that result from these scenarios, which would directly reduce risk.

Results from [1] demonstrate that increasing the fueling area volume from 1000m^3 to 2000m^3 significantly reduces the explosion overpressures from 100% releases (see Figure 7) from approximately 27kPa to approximately 13kPa. Changing the expected the overpressure from 100% releases in the QRA from 30kPa to 13kPA reduces the expected number of fatalities from explosions from 15.99 down to 1.68, and reduces the FAR from 0.17 to 0.10.

Finding 3: Mechanical ventilation does not provide a substantial reduction in overpressures for immediate ignitions when compared to natural ventilation. Both natural and forced ventilation provide substantial reduction in overpressures compared to well-sealed case.

The experimental results from [1] indicate that hydrogen disperses rapidly, and that forced ventilation has minimal additional effect on hydrogen concentration at specific points in the warehouse, even for large leaks, as seen in Figure 8(a). Furthermore, Figure 8(b) shows that the effect of forced ventilation in the warehouse did not significantly reduce deflagration overpressures for immediately ignited releases. The effect of forced ventilation on non-immediate ignition should be investigated further.

The experimental results from [18] demonstrate that the best way to decrease the peak overpressures is to increase the ventilation area rather than to increase the forced ventilation rate. Ekoto et al. ran tests on the same warehouse with different ignition locations and different types of ventilation; the results[10] are shown in Figure 9. Figure 9(a) shows that changes in the ignition location provide some overpressure reduction, but still results in large overpressures that could lead to structural collapse. Figure 9(b) displays the difference in overpressures between a well-sealed

[10] Ventilation areas and diameters in this paragraph refer to a 1/2.8 scale fueling room

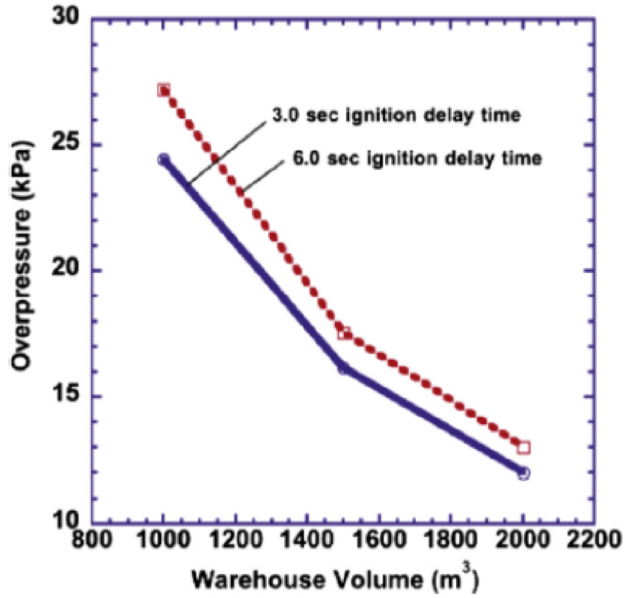
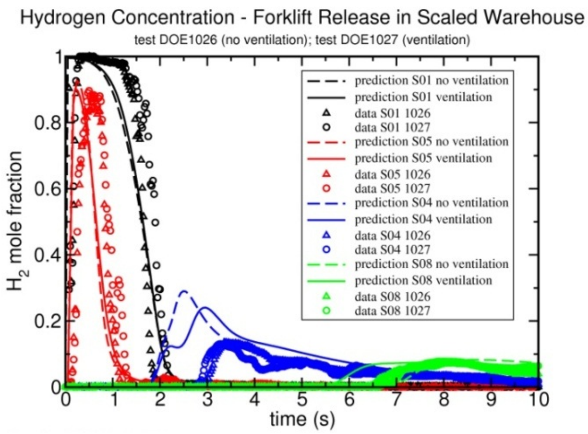


Figure 7. Comparison of peak overpressures for ignited releases in different room volumes (reproduced from [1]).

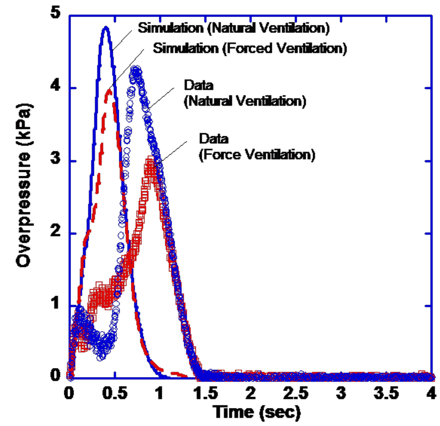
warehouse and with minimal natural ventilation (Test 13) to the same warehouse with a small (5.08cm) ventilation pipe (Test 9); the introduction of the ventilation pipe reduces overpressures for well-sealed warehouses, although overpressures are still high. Figure 9(c) demonstrates that use of pressure relief panels (Tests 7 and 8) also reduces the magnitude of overpressures when compared to the case of a well-sealed (reinforced) warehouse (Test 12). Figure 9(d) demonstrates the effects of going from a well-sealed warehouse (Test 12) to a warehouse with natural ventilation through a 34cm diameter vent (Test 11) and the same warehouse with forced ventilation through a 34cm diameter vent (Test 10); this demonstrates that natural ventilation substantially reduces overpressures, and that the effect of forced ventilation is not significantly greater than the effect of natural ventilation.

Recommendation 2: Install the flow limiting device required by NFPA 2 Section 10.3.3.2.2.2(F) outside of the building. This limits the quantity of gas inside the building, which limits the consequences of accidents and therefore limits the frequency of fatalities. The effect of flow orifices on reducing risk and separation distances has been demonstrated in [36].

Recommendation 3: Require a breakaway coupling on the dispenser vent hose. This can be achieved by modifying the dispenser design requirements to include BC2 or by connecting both the supply hose and the vent hose to BC1. The inclusion of breakaway safety devices reduces the likelihood that a drive-off accident will result in damage to the dispenser. BC1 ensures that hydrogen does not escape from the supply hose during a drive-off accident. However, a drive-off accident could result in damage the dispenser if the vent hose does not detach. To reduce the likelihood of dispenser damage during drive-off events, breakaway coupling should be included on the vent hose.



(a)



(b)

Figure 8. (a) Comparison of measured and predicted hydrogen concentrations with and without forced ventilation at four sensor locations in the warehouse. (b) Comparison of simulation and experimental deflagration overpressure for immediately ignited releases with either forced ventilation (ventilation fans on - 6.3 m^3/min) or natural ventilation (ventilation fans off). Ignition occurred 3s after the initiation of a 6.35mm (100%) release from a 0.8kg tank. (reproduced from [1]).

The estimated frequency of drive-off events is 5.16×10^{-5} per fueling event. Multiplying this by the expected annual number of demands fueling events in the generic warehouse (10,000) results in an annual frequency of 0.51 drive-off events per dispenser. With a breakaway coupling, we multiply the drive-off event frequency by the failure-to-close probability of the coupling (approx. 1.0×10^{-4}) to determine the annual frequency of drive-off related releases from the dispenser (which we conservatively assume results in a 100% release) as 5.12×10^{-5}/yr; this makes a small contribution to the frequency of 100% releases (7.68×10^{-4}/yr, as shown in Table 8). Without a breakaway coupling attached to the vent hose, we assume that 1% of drive-offs result in damage to the dispenser, and the frequency of 100% leaks would become 5.88×10^{-3}/yr instead of 7.68×10^{-4}/yr. Changing this assumption increases the FAR from 0.17 to a FAR of 1.21.

6.3 Necessary improvements for indoor fueling QRA

Performing early-stage QRA on the generic dispenser design has demonstrated that the QRA process can be used to gain insight into safety improvements for indoor fueling. However, this activity has exposed some QRA shortcomings that must be addressed before QRA techniques can be widely applied to assess indoor fueling facilities.

Finding 4: There are several key areas that must be addressed to provide comprehensive

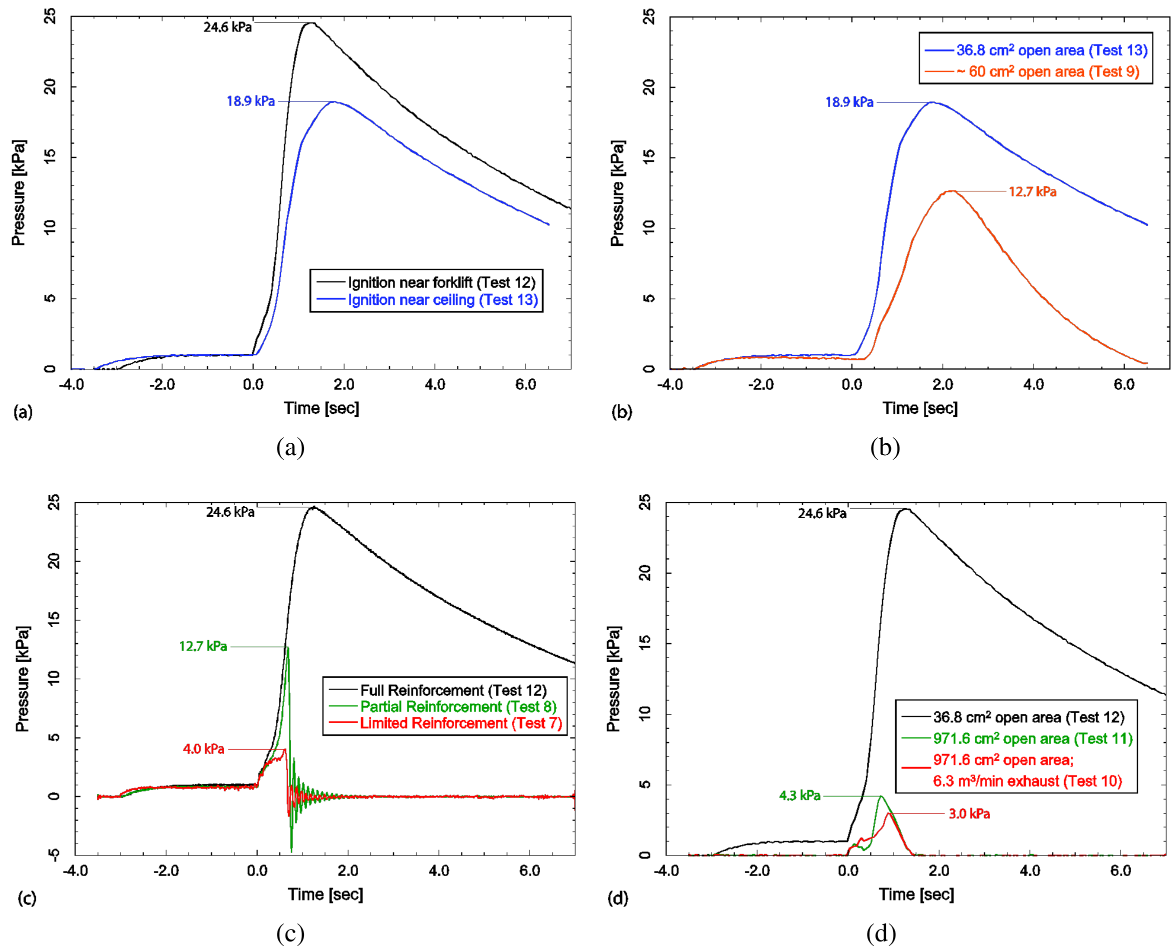


Figure 9. Warehouse overpressures comparison for (a) well-sealed conditions, (b) a moderate increase in open area, (c) inclusion of pressure relief panels, and (d) large increase in open area plus active/passive ventilation (reproduced from [18]).

QRA for indoor fueling The QRA process provides important insights, but these insights are only as detailed and only as reliable as the information used to produce the analysis. LaChance et al. [4] described the necessary features for a comprehensive QRA, and Pasman [37] has identified several QRA gaps that are relevant to the hydrogen infrastructure. In this section, we discuss the gaps that are relevant to indoor fueling.

Gap 1. A defensible probability model for ignition. Current ignition probability models greatly oversimplify the complicated ignition process, and lack an underlying scientific basis for their use. A credible ignition model is a critical element for future indoor fueling QRA. Research should seek a more detailed, scientifically-based ignition model. Additional work will be required to validate the model for indoor fueling use.

Gap 2. Probability models for gas and flame detection, and other indoor-only components. There is not sufficient information on the accuracy of flame and gas detection in the hydrogen industry. In this analysis, we conservatively assigned a 10% probability of leak mitigation to reflect uncertainty in the range of the detection zone. Future work should seek to reduce this uncertainty by assessing the impact of detector location on detection probability.

Gap 3: Simplified models for predicting loads from deflagration and detonation for different release sizes. Due to the computational complexity of CFD codes, it is not possible to perform a complete CFD analysis for every possible accident scenario. However, for QRA it is essential to gain high-level insights into the magnitude and likelihood of these events. Future research must develop a simplified predictive model that balances the precision of the predictive model with the usability requirements of QRA. It is important to emphasize the need for both deterministic behavior models, as well as representative probability models that can be used to abridge the detailed deterministic information for QRA purposes.

Gap 4: Hydrogen-specific data for refining QRA modeling assumptions. The QRA process relies heavily on industry and application-specific data to provide meaningful insights. Current data collection efforts in the hydrogen fueling industry were not designed to inform QRA, and these frameworks are not sufficient to provide the detailed information necessary to enhance QRA. However, as the hydrogen fueling industry matures, there will be ample opportunity to collect data specifically intended for QRA. However, it may take years to gather enough information and data to produce robust QRA models, so it is urgently important to begin planning and testing an industry-wide framework for QRA data collection activities.

Gap 5: Consideration of human, software, and organizational failure drivers The FT and ESD models must be expanded to include plausible human failures, software failures, and organizational failures that can result in indoor refueling releases. Understanding the operating environment, not just the physical system, is critical to creating a truly comprehensive understanding of the safety of indoor fueling. Research efforts should begin to address these complex failure drivers, even if only qualitative insight can be produced.

6.4 Summary and Conclusion

For several decades, Quantitative Risk Assessment has been an important part of ensuring the safety of industrial systems. More recently, QRA has become an important part of the codes and standards development process, which now uses QRA-generated insights to help inform code decisions [5]. This report documents the first QRA for an indoor gaseous hydrogen fueling system, which is an early step in the development of the QRA approach intended to inform NFPA 2 *Hydrogen Technologies Code*, Chapter 10 “GH_2 Vehicle Fueling Facilities” [3]. There were three objectives for this activity: to provide the first QRA-informed insights into the safety of indoor fueling; to provide science- and risk-based recommendations for NPFA 2, Chapter 10; to identify gaps in existing QRA techniques that limit the level of detail or the credibility of the insights required for NFPA 2.

Sandia established a generic, code-compliant hydrogen dispenser and warehouse design. Using established QRA techniques from the nuclear and offshore oil industries, we conducted a design-stage QRA on this generic dispenser. The results of this analysis showed that the expected fatal accident rate for the generic system is a small fraction of the rate associated with warehouse operations. However, the current QRA results cannot be used to confidently state that the current C&S requirements provide adequate margin of safety for all code-compliant installations due to variability in warehouse size and configuration, number of vehicles being fueled, etc. To ensure a high level of safety, installation-specific QRAs or additional sensitivity studies must be performed.

Sandia leveraged the results of the QRA work and the results of previously conducted experiments to provide several high-level recommendations for modifications to NFPA 2 Chapter 10. However, the screening-level QRA cannot provide more detailed insights into specific code-changes due to the limited scope of the QRA. In order to use the QRA models as a framework for understanding the trade-offs between various possible code requirements, it is necessary to expand the analysis to include the more detailed models and more explicit treatment of uncertainty in the data.

The established QRA methods must be further adapted for hydrogen applications. Hydrogen-specific data would go a long way into providing higher-fidelity QRA results. Several additional models should be developed to ensure complete consideration of risk drivers; this includes models for human, software, and organizational failures as well as additional component failure models. Furthermore, a science-based hydrogen ignition model and a first-order model for overpressure effects are critical necessities for hydrogen QRA.

Regardless of the QRA results, it is important to continue efforts to reduce risk of fatalities. The QRA results for the generic dispenser show that significant releases are unlikely events (approx. 3.47×10^{-2}/yr, approximately one leak in a dispenser that operates for 28 years). The releases that do occur are likely to be small releases that present no threat to facility personnel. However, if large leakages occur and ignite, the resulting situation could result in loss of life. The analysis detailed in this report finds a low likelihood of death for workers in the generic warehouse facilities. However, a low likelihood of death does not guarantee that no deaths with occur; in fact, no analysis can ever provide this guarantee. However, by integrating the QRA process with the codes and standards development process, we can increases our confidence that fatalities will be a rare event for the hydrogen fuel cell industry.

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A Failure Modes and Effects Analyses

Dispenser							
Part No.	**Type**	**Function**	**Failure Mode**	**Cause**	**Local Effect**	**System Effect**	**Notes for QRA**
ASV1a, ASV1b	Valve	Start/stop flow into building	Fails open	valve stem damage; spring failure; signal failure; solenoid failure	Internal leakage (large)	Large H2 leakage into dispenser if both valves fail and HV1 remains open.	Screen out (Exterior to building)
			Fail closed (fully)	spring failure; solenoid failure; singal failure;	No flow	No flow	Screen out (Exterior to building)
			External Leak	seal failure; spring failure; cracked housing; solenoid failure; seat failure	Localized gas release	None (leakage is outdoors)	Screen out (Exterior to building)
			Delayed response	signal failure; sticking piston;	Internal leakage (medium) or slow flow.	Internal leakage (medium) or slow flow.	Screen out (Exterior to building)
HV1	Valve	Start/stop flow into building	See ASV1a	valve stem damage; spring failure; human failure (Unable to manipulate; no attempt to manipulate)	See ASV1a	See ASV1a	Screen out (Exterior to building)
HV2	Valve	Start/stop dispensing	Fails open	valve stem damage; spring failure; human failure (unable to manipulate; no attempt to manipulate); signal (link) failure	Internal leakage (large)	Large H2 release if ASV1a, ASV1b, ASV2 and N1 also fail	Screen out (redundant components to ensure safety function is achieved)
			Fail closed (fully)	spring failure; human failure (unable to manipulate; no attempt to manipulate); signal (link) failure	No flow	No flow	Screen out (no safety consequences if gas is not flowing)
			External Leak	seal failure; spring failure; cracked housing; seat failure; human failure (unable to manipulate; no attempt to manipulate)	Localized gas release	Accumulation of H2 above HV2	Include in QRA
			Delayed response	sticking piston; human action delayed	Internal leakage (medium) or slow flow.	Internal leakage (medium) or slow flow.	Screen out (minor effect)
ASV2	Valve	Start/stop dispensing	Fails open	valve stem damage; spring failure; signal failure; solenoid failure	Internal leakage (large)	Large H2 release if ASV1a, ASV1b, HV2 and N1 also fail	Screen out (redundant components to ensure safety function is achieved)
			Fail closed (fully)	spring failure; solenoid failure; singal failure;	No flow	No flow	Screen out (no safety consequences if gas is not flowing)
			External Leak	seal failure; spring failure; cracked housing; solenoid failure; seat failure	Localized gas release	Accumulation of H2 above ASV2	Include in QRA
			Delayed response	signal failure; sticking piston;	Internal leakage (medium) or slow flow.	Internal leakage (medium) or slow flow.	Screen out (minor effect)
PI1	Instrument	Instrumentation	External Leak	Improper torque; gasket failure; corrosion; improper sealant	Localized gas release	Potential accumulation of H2	Include in QRA

Dispenser							
Part No.	**Type**	**Function**	**Failure Mode**	**Cause**	**Local Effect**	**System Effect**	**Notes for QRA**
			Fail high	Incorrect/loss of signal; Calibration error (display or diaphragm); diaphragm failure;	Incorrect signal to operator	Underfill of vehicle tank	Screen out (no safety consequences if tank is underfilled)
			Fail low	Incorrect/loss of signal; Calibration error (display or diaphragm) ; diaphragm failure;	Incorrect signal to operator	Overpressure in vehicle tank	Include in QRA, unless code requires instruments to fail high
			Fail in place	Incorrect/loss of signal; display needle sticking	Incorrect signal to operator	Underfill of vehicle tank or Overpressure in vehicle tank	Include in QRA, unless code requires failed instruments to shutdown the system
			Fail to display	Incorrect/loss of signal; needle detaches	No signal to operator	Underfill of vehicle tank or Overpressure in vehicle tank	Include in QRA, unless code requires failed instruments to shutdown the system
Tubing	Pipe	Convey H2 through dispenser	External Leak	Leakage though joints or threading; pipe leakage or cracking; fabrication or installation errors	Localized gas release	Accumulation of H2 above leak	Include in QRA
			Rupture/ separation	Bursting; buckling; fatigue; overpressure (includes induced overpressure from failed components and a large overpressure from storage); improper design, installation, maintenance (components, materials, etc)	Localized gas release	Large H2 release if ASV1a, ASV1b, HV1 also fail	Include in QRA with 100% leak data
			Blockage	Upstream component failures	High pressure	Pipe rupture	Screen out (unlikely to affect safety)
FO1	Pipe	Flow control	See tubing (treat as a joint)	See tubing (treat as a joint)	See tubing (treat as a joint)	See tubing (treat as a joint)	Include in QRA as a joint
F1	Filter	Particle Separation	Flow blockage	Plugging	No flow or reduced flow	No flow	Screen out (no safety consequences if gas is not flowing)
			Fluid contamination	channeling; fatigue; disintigration; media migration	Contamination of H2 downstream	Contaminated H2	Screen out (unlikely to impact safety during refueling)
			External Leak	Cracking; fatigue or manufacturing	Localized gas release	Accumulation of H2 above F1	Include in QRA as a joint
R1	Regulator	Flow pressure control	Outlet pressure high	calibration error; diaphragm failure; valve stem damage; spring failure;	High downstream pressure	increased failure potential for downstream components; Potential overpressure in	Screen out if FO1 design provides redundancy
			Outlet pressure low	calibration error; diaphragm failure; valve stem damage; spring failure;	Low pressure downstream	Slow flow	Screen out (no safety consequences)

Dispenser							
Part No.	**Type**	**Function**	**Failure Mode**	**Cause**	**Local Effect**	**System Effect**	**Notes for QRA**
			External Leak	seal failure; spring failure; cracked housing; seat failure; maintenance error	Localized gas release	Accumulation of H_2 in building	Include in QRA
PRV1	Valve	Safety - Relieve excess pressure	Premature relief	spring or diaphragm failure; maintenance or calibration error	Gas venting	Venting - large product loss	Include in QRA if venting is indoors or could leak
			Fail to relieve	mechanical failure; ice or water blockage; maintenance, installation, or calibration error	Overpressure in system	Increased rupture potential	Include in QRA
			Internal leak	Improper torque; gasket failure; corrosion; improper sealant	Leakage into vent	Venting -- minor product loss	Screen out (no safety consequences, goes to vent)
			External Leak	Improper torque; gasket failure; corrosion; improper sealant	Leakage into building	Accumulation of H_2 in building	Include in QRA
Ho1	Hose	Deliver fluid	Flow blockage	Inner tube deterioration (thermal, chemical, material); abrasion (contaminated fluid); seal damage	No flow	No flow	Screen out (no safety consequences)
			Fluid contamination	Inner tube deterioration (thermal, chemical, material);	Contamination of H_2 downstream	Contaminated H_2	Screen out (unlikely to impact safety during refueling)
			External Leak	Cracking or fracture (from abrasions, stretching, bending, severe inner tube deterioration); seal damage; improper connection; crimp leakage	Localized gas release	Accumulation of H_2 above leak	Include in QRA
			Hose separation or rupture	Drive-offs; improper assembly; use of wrong fittings; operator error	Large external leak	Large H_2 release	Include in QRA
Ho2	Hose	Vent excess fluid	Flow blockage	Inner tube deterioration (thermal, chemical, material); abrasion (contaminated fluid); seal damage	No flow	Unable to vent excess gas	Screen out (unlikely to impact safety due to small amount of H_2 in this hose)
			External Leak	Cracking or fracture (from abrasions, stretching, bending, severe inner tube deterioration); seal damage; improper connection; crimp leakage	Localized gas release	Release of small amount of H_2 into building	Screen out (unlikely to impact safety due to small amount of H_2 in this hose)
			Hose separation or rupture	Improper assembly; use of wrong fittings; operator error	Localized gas release	Release of small amount of H_2 into building	Screen out (unlikely to impact safety due to small amount of H_2 in this hose)
BC1	Breakaway coupling	Safety - stop flow	Failure to separate	misalignment; mechanical/design failure; human (operator) failure	Does not detach	Increased potential of delivery hose (Ho1) rupture	Include in QRA --relevant after drive-off (only)
			Valve fails to close after separation	misalignment; mechanical/design failure	Failure to stop flow out of dispenser	External leak (large); hose whip could induce other effects	Include in QRA -- only relevant after drive-off or unintended separation

Dispenser							
Part No.	**Type**	**Function**	**Failure Mode**	**Cause**	**Local Effect**	**System Effect**	**Notes for QRA**
			Unintended separation	misalignment; mechanical/design failure; human (operator) failure; connector failure	Early separation	Dispenser out of service	Include in QRA -- only relevant if gas is flowing.
			External leak	Mechanical/design failure	Localized gas release	External leak (small)	Include in QRA
N1	Nozzle	Deliver fluid	Fails open	valve failure; nozzle damage; operator error	Failure to stop flow out of dispenser	Large H2 release if dispensing is not shut down	Include in QRA
			Fails closed	valve failure; nozzle damage; operator error	No flow	No flow	Screen out (no safety consequences)
			Ejection during dispensing	operator error; improper seating of nozzle	Nozzle ejection	operator injury; potential damage to dispenser	Include in QRA
			Leakage (external or internal)	valve failure; improper installation, maintenance, or operation	Failure to stop flow out of dispenser	External leak (large)	Include in QRA
			Failure to vent	valve failure; vent blockage	Failure to vent	External leakage (small)	Include in QRA
Vent	Pipe	Vent excess H2	External Leak	Leakage though joints or threading; pipe leakage or cracking; fabrication or installation errors	Localized gas release if venting happens	Accumulation of H2 in building during venting	Screen out (improbable when compared to leakage from main system components)
			Rupture/ separation	Burst failure; buckling; fatigue; overpressure; improper design, installation, maintenance (components, materials, etc)	Localized gas release	H2 release during venting	Screen out (unlikely that gas will be in the vent if it breaks)
			Blockage	Icing; Missing vent cap	High pressure; lack of venting	Pipe rupture; lack of venting capability; potential ignition in vent	Include in QRA - could induce nozzle failure
			Excess air/H2 mixing	Improper design (too long); water and ice inside vent	Potential fire in vent	Potential widespread fire	Include in QRA
GD1	Detector	Gas detection	Failure to detect at 1%	Miscalibration; mechanical failure; power failure; Inadequate gas detector placement (design)	Fails to detect H2	No gas detection and therefore no alarm	Include in QRA
			Premature detection (below 1%)	Miscalibration; mechanical failure;	False alarm	Closes relief valves	Screen out (no safety consequences)
			Fail to trigger alarm	Signal failure; safety circuit failure; power failure	Fails to alarm	No alarm	Include in QRA

Dispenser							
Part No.	**Type**	**Function**	**Failure Mode**	**Cause**	**Local Effect**	**System Effect**	**Notes for QRA**
FD1	Detector	Flame detection	Failure to detect flame	Miscalibration; mechanical failure; Power failure; Inadequate flame detector placement (design)		No flame detection and therefore no alarm	Include in QRA
			False detection	Miscalibration; mechanical failure;	False alarm	Closes relief valves	Screen out (no safety consequences)
			Fail to trigger alarm	Signal failure; safety circuit failure; power failure	Fails to alarm	No alarm	Include in QRA
External	Accidents		External fire	Building fire; electrical short;	Fire	Fire or explosion	Include in QRA
External	Accidents		Vehicle collision with dispenser	Operator error	Hydrogen release and sparks	Fire or explosion	Screen out -- code requires bollards around dispenser to prevent collisions
External	Accidents		Excess heat	Building HVAC system failure plus weather conditions	Overheating	Hydrogen release	Screen out - Must be over 500F to fail a tank.
External	Accidents		Excess cold	Building HVAC system failure plus weather conditions	Components failure (e.g. brittle failure of pipes)	Hydrogen release	Screen out -- Would induce component failures, which should be covered under individual component leaks
External	Accidents		External damage	Debris or materials from the room impacts dispenser	Component damage	Hydrogen release	Include in QRA
External	Human error		Air/H2 mixture in system	Failure to purge system before/after maintenance	Air/H2 mixture in system	Fire or explosion upon return to service	Screen out -- code requires purging before maintenance and return to service
External	Human error		Use of wrong components	human error; supply problems	Unintended separation of components	Hydrogen release (large)	Include in QRA

Fuel Cell							
Part No.	**Type**	**Function**	**Failure Mode**	**Cause**	**Local Effect**	**System Effect**	**Notes for QRA**
Interface			Loss of communications	Vehicle software failure; vehicle sensor failure; dispenser software failure	Overfill of tank (potential rupture)	Potential hydrogen release	Include in QRA
			External Leaks	External leaks from components (including those listed below)	Localized gas release	Release of H_2 into building	Count 8 valves, 3 instruments (might treat as a joint), 1 FC, 20 pipes, 27 joints
Receptacle		Accept gas from dispenser	Fails open	valve failure; nozzle damage; operator error	Failure to stop flow out of FC	External leak (large)	Include in QRA, only relevant to refueling risk if nozzle ejection occurs
			Leakage (internal)	nozzle does not seal onto receptacle; check valve failure; improper installation, maintenance, or operation;	Failure to stop flow out of FC	External leak (large)	Screen out (only relevant to refueling risk if nozzle ejection occurs, and consequences will be low for small internal leaks)
FC: PS-1	Instrument	Instrumentation	Fail high	Incorrect/loss of signal; Calibration error (display or diaphragm); diaphragm failure;	Incorrect signal to dispenser	Underfill of vehicle tank	Screen out (no safety consequences)
			Fail low	Incorrect/loss of signal;Calibration error (display or diaphragm) ; diaphragm failure;	Incorrect signal to dispenser	Overpressure in vehicle tank	Include in QRA, unless code requires instruments to fail high
			Fail in place	Incorrect/loss of signal; display needle sticking	Incorrect signal to dispenser	Underfill of vehicle tank or Overpressure in vehicle tank	Include in QRA, unless code requires failed instruments to shutdown the system
			Fail to communicate	Loss of signal;	No signal to dispenser	Underfill of vehicle tank or Overpressure in vehicle tank	Include in QRA, unless code requires failed instruments to shutdown the system

Fuel Cell							
Part No.	**Type**	**Function**	**Failure Mode**	**Cause**	**Local Effect**	**System Effect**	**Notes for QRA**
FC: V-1	Valve	Safety - Relieve excess pressure	Premature relief	spring or diaphragm failure; maintenance or calibration error	Venting	Large hydrogen release	Include in QRA
			Fail to relieve	mechanical failure; maintenance, installation, or calibration error	Blockage	Overpressure in system - increased rupture potential	Include in QRA
FC: Tank	Tank	Storage	Rupture	Overpressure (beyond 1.25 x Pdesign)	Large external leak and sparks	Large H2 release & ignition	Include in QRA
			Overheating	Excessive filling speed	Tank cracking	Large H2 release & ignition	Include in QRA

B Leak frequencies and failure probabilities

B.1 Failure probabilities and frequencies

The failure probabilities and frequencies in this section were assembled from generic data from the offshore oil, process chemical, and nuclear power industries.

Table B.1. Probability distributions for component failure probability

Component	Failure Mode	Distribution type	Parameters
Nozzle	Pop-off	$p \sim \text{Beta}(\alpha, \beta)$	$\alpha = 0.5$, $\beta = 610415.5$
BC	Failure to close	$p \sim \text{Beta}(\alpha, \beta)$	$\alpha = 0.5$, $\beta = 5031$
PRV	Premature open	$p \sim \text{Beta}(\alpha, \beta)$	$\alpha = 4.5$, $\beta = 310288.5$
PRV	Failure to open	$p \sim \text{Lognormal}(\mu, \sigma)$	$\mu = -11.74$, $\sigma = 0.67$
HV	FTC (human error)	(Expected value)	$E(p) = 0.001$
ASV	Failure to close	(Expected value)	$E(p) = 0.002$
ASV	Common cause failure (3 valves, beta factor method)	(Expected value)	$E(p) = 1.28 \times 10^{-4}$
Nozzle	Failure to close	(Expected value)	$E(p) = 0.002$

Table B.2. Probability distributions for accident frequency

Accident	Distribution type	Parameters
Drive-off	$p \sim \text{Beta}(\alpha, \beta)$	$\alpha = 31.5$, $\beta = 610384.5$
Overpressure during fueling	$p \sim \text{Beta}(\alpha, \beta)$	$\alpha = 3.5$, $\beta = 310289.5$

B.2 Component leak frequencies

Table B.3. Parameters of lognormal distribution for leak frequencies for individual components

Component	Leak size	μ	σ
Compressors	0.01%	−1.72	0.21
	0.1%	−3.92	0.48
	1%	−5.14	0.79
	10%	−8.84	0.84
	100%	−11.34	1.37
Cylinders	0.01%	−13.84	0.62
	0.1%	−14.00	0.61
	1%	−14.40	0.62
	10%	−14.96	0.63
	100%	−15.60	0.67
Filters	0.01%	−5.25	1.98
	0.1%	−5.29	1.52
	1%	−5.34	1.48
	10%	−5.38	0.89
	100%	−5.43	0.95
Flanges	0.01%	−3.92	1.66
	0.1%	−6.12	1.25
	1%	−8.33	2.20
	10%	−10.54	0.83
	100%	−12.75	1.83
Hoses	0.01%	−6.81	0.27
	0.1%	−8.64	0.55
	1%	−8.77	0.54
	10%	−8.89	0.55
	100%	−9.86	0.85
Joints	0.01%	−9.57	0.16
	0.1%	−12.83	0.76
	1%	−11.87	0.48
	10%	−12.02	0.53
	100%	−12.15	0.57
Pipes	0.01%	−11.86	0.66
	0.1%	−12.53	0.69
	1%	−13.87	1.13
	10%	−14.58	1.16
	100%	−15.73	1.71
Valves	0.01%	−5.18	0.17
	0.1%	−7.27	0.40
	1%	−9.68	0.96
	10%	−10.32	0.68
	100%	−12.00	1.33
Instruments	0.01%	−7.32	0.68
	0.1%	−8.50	0.79
	1%	−9.06	0.90
	10%	−9.17	1.07
	100%	−10.20	1.48

C Matlab scripts

C.1 Main Script

All analysis were conducted in Matlab version R2012a.

```
%This code runs the QRA calculations for process equipment associated with
%the use of hydrogen as a vehicle fuel. This supplements the QRA work
%documented in SAND2012-10150.
%
%Created by Katrina Groth, 2012.

clear all %Ensure that variables are empty
load('LeakFreqData.mat'); %Open H2 leak frequencies
load('ComponentFailureData'); %Open component failure probabilities

%% System description / parameters

%%% Begin user input
   % Number of components in your system
    Component(1).numberinsys = 0; %number of Compressors
    Component(2).numberinsys = 0; %number of Cylinder
    Component(3).numberinsys = 0; %number of Filters
    Component(4).numberinsys = 0; %number of Flanges
    Component(5).numberinsys = 1; %number of Hoses
    Component(6).numberinsys = 35; %number of Joints
    Component(7).numberinsys = 20; %Length of Pipes [m]
    Component(8).numberinsys = 5; %number of Valves
    Component(9).numberinsys = 3; %number of Instruments

  % System operating parameters
    SysParam.PipeOD = 0.375; % Pipe outer diameter [inches]
    SysParam.PipeWallThick= 0.065; %Pipe wall thickness [inches]
    SysParam.InternalPresMPa = 35; %System pressure [MPa]
    SysParam.InternalTempC = 15; %System temperature [C]
    SysParam.ExternalPresMPa = .101325; %External pressure [MPa]
    SysParam.ExternalTempC = 15; %External temperature [C]

    %Discharge coefficient of the hole; (1.0 is a conservative value,
    %0.6 is the suggested value for screening.)
    C_D=1.0; %[Unitless]

  % Warehouse specifics
    nworkers = 50; %Number of workers in the building
    maxdist=50; %Shortest distance from dispenser to wall [m]
    mindist=0; %Minimum distance from worker to dispenser [m]
    yearlyworkinghours=2000; %Average employee working hours[per year]
    nvehicles=20; %number of vehicles in the fleet
    nfuelingspervehicleday=2;%Num. of times each vehicle is fueled [/day]
    nvehicleoperatingdays=250;%Num. of days each vehicle is operated [/yr]
```

```
  % Fatality model selection
    ThermalProbit = 'Eisenberg'; %Select thermal probit model.
    %Options are 'Eisenberg', 'Tsao', 'TNO', and 'Lees'. Eisenberg is
    %recommended.
    OPProbit = 'Collapse' ; %Select overpressure probit model.
    %Valid options are 'Lung_Eisenberg', 'Lung_HSE', 'Head_impact',
    %'Collapse' and 'Debris'. Head_impact, collapse, or debris are
    %recommended. Collapse assumes that the probability of collapse is also
    %the probability of worker death.
    t_expose_thermal=60; %Person's flame exposure time [s]


  % Overpressure consequences
    P_s= [2.5e3 2.5e3 5e3 16e3 30e3]; %Peak explosion overpressure [Pa]
    impulse=[250 500 1000 2000 4000]; %Impulse of shock wave [Pa*s]

%%% End user input

%Fuel parameters for Hydrogen gas
    H2.MW = 2.016; % %Molecular weight of fuel [kg/kmol]
    H2.k = 1.41; %Heat capacity ratio [unitless]; (Also known as gamma)
    H2.cnum = 0; % number of carbon atoms in fuel molecule  [unitless]
    H2.hnum = 2; % number of hydrogen atoms in fuel molecule  [unitless]
    H2.LFL = 0.04; %Lower flammability limit in air [percent]
    H2.Tad = 2390; %adiabatic flame temperature [K]
    H2.b = 7.691e-3; %Coeff. for non-ideal gas density calculation [m^3/kg]
    H2.DHc = 118.83e6; % heat of combustion [J/kg]

    format shortG;
%% Calculation of the leak frequency, LeakFreq
   %LeakFreq is the annual frequency of leaks from the 5 hole sizes ([0.01%
   %0.1% 1% 10% 100%] of flow area).
   %The following obtains the annual leak frequency (at each size)
   %by multiplying mean for each component by number of components. Since
   %the leaks are assumed to be mutually exclusive events, we can add the
   %frequencies together.

    %Get the mean frequency from the parameters given for each component:
      means=arrayfun(@(x) lognstat(x.mu, x.sigma), Component, ...
          'UniformOutput', false);
    %Multiply frequency by  the number of components of each type:
      lambdas=arrayfun(@(x,y) x{:}*y.numberinsys, means, Component, ...
          'UniformOutput', false);
    %Sum the frequency of leaks for all components to get the frequency of
    %each leak size
      LeakFreq=sum(cell2mat(lambdas),2);

%% Calculation of non-leak contributors to 100% releases.
    %This section contains Fault Trees for the non-leak contributors:
    %Shutdown failure, Accidents. Rare event approximation is used.

 % Calculate number of times the dispenser is used per year:
    nfuelings=nvehicles*nfuelingspervehicleday*nvehicleoperatingdays;
```

```
 % Calculate frequency of Accidents
    %Calculate expected frequency of driveoffs
     p_driveoff=betastat(Driveoff.alpha,Driveoff.beta); %Prob. of driveoffs
     p_BC_FTC=betastat(BC_FTC.alpha,BC_FTC.beta);%Prob. of BC fail to close
     pDriveoffrelease=p_driveoff*p_BC_FTC; %Prob. of drive-off releases, ...
         per demand
    fDriveoffs=nfuelings*pDriveoffrelease; %Expected num. of drive-offs ...
        releases, per year

    %Calculate expected frequency of overpressure-induced ruptures
     p_fuelingOP=betastat(OPduringfueling.alpha, OPduringfueling.beta); ...
         %Prob. of OP
     p_PRV_FTO=lognstat(PRV_FTO.mu, PRV_FTO.sigma); %Prob. of PRV FTO
     p_OPrupture = (p_fuelingOP*p_PRV_FTO); %Prob of OPruptures per demand
    fOPrupture=nfuelings*p_OPrupture; %Expected num. of OPruptures per year

  fAccidents=fDriveoffs+fOPrupture; %Expected num. of accidents, per year

 % Calculate expected frequency of shutdown failures
    p_Nozzle_popoff=betastat(Nozzle_popoff.alpha, Nozzle_popoff.beta);
    pShutdownFailure=((ASV_FTC.mean)^3+ASV_CCF3.mean)*HV_FTC.mean*...
      (p_Nozzle_popoff+Nozzle_FTC.mean);%Prob. of shutdown fail per demand
    fShutdownFailure=nfuelings*pShutdownFailure; %Expected num. of ...
        shutdown failures per year

 % Expected frequency of non-leak contributors (/yr)
    fOtherFailures=[0;0;0;0;fAccidents+fShutdownFailure];%Annual frequency

%Frequency of hydrogen releases per year from all causes
 fH2release=LeakFreq+fOtherFailures


%% Calculate parameters of the break
  %Calculate break area [m^2] and equivalent break diameter [m]
    % Calculates the hole area and equivalent diameter for the break sizes
    PipeDiamInch= SysParam.PipeOD - SysParam.PipeWallThick;
    PipeDiamMetric=25.4*PipeDiamInch/1000;  %[m]
    PipeAreaMetric=pi/4*PipeDiamMetric^2; %[m^2]

    breakareas=PipeAreaMetric*[.0001;.001;.01;.1;1];
    equivdiam=sqrt(breakareas*4/pi); % [m]

%% Calculate parameters of the gaseous discharge from the break
    ExternalTempK=SysParam.ExternalTempC+273.15;
    ExternalPresPa=SysParam.ExternalPresMPa*10^6;
    InternalPresPa=SysParam.InternalPresMPa*10^6;
    InternalTempK=SysParam.InternalTempC+273.15;

    [jet.M_eff,jet.T_eff,jet.rho_eff,jet.U_eff,jet.A_eff,jet.D_eff,...
        jet.m_dot,jet.P_throat,jet.T_throat,jet.rho_throat] = ...
        NozzleModel(ExternalPresPa,ExternalTempK,InternalTempK,...
        InternalPresPa,equivdiam',C_D,2);

gasdischargerate=jet.m_dot; %Gas discharge rate for the 5 leak sizes
```

```
%% Assigns ignition probabilities to the 5 leak sizes
%Using the ignition probabilities from Tchouvelev, which are a
%deterministic function of gas discharge rate.

    for i=1:length(gasdischargerate),%<-----------------------------------
        if gasdischargerate(i)<0.125, %Tiny leaks (<0.125 kg/s)       %  !
            PIgnite.immed(i) = 0.008;                                  %  !
            PIgnite.delayed(i) = 0.004;                                %  !
        elseif gasdischargerate(i)>6.25, %Large leaks (>6.25 kg/s)    %  !
            PIgnite.immed(i) = 0.23;                                   %  !
            PIgnite.delayed(i) = 0.12;                                 %  !
        else %Everything else                                          %  !
            PIgnite.immed(i) = 0.053;                                  %  !
            PIgnite.delayed(i) = 0.027;                                %  !
        end                                                            %  !
    end %--------------------------------------------------------------->!

%% Calculate annual frequency of end states (jet fires and explosions)
% With gas and flame detection
  Pdetectisolate=.10; %Probability of gas and flame detection & isolation
  fJetfire=fH2release.*(1-Pdetectisolate).*(PIgnite.immed');
  fExplosion=...
    fH2release.*(1-Pdetectisolate).*(1-PIgnite.immed').*(PIgnite.delayed');

% Without gas and flame detection
  %fJetfire=fH2release.*(PIgnite.immed');
  %fExplosion=fH2release.*(1-PIgnite.immed').*(PIgnite.delayed');

fJetfire %Frequency (per year) of jetfires for the 5 leak sizes
fExplosion %Frequency (per year) of explosion for the 5 leak sizes

%% Calculate consequences

% Generate the positions of the n workers in the building with respect to
% dispenser position
  WorkerDist='Normal'; % Assumed distribution of worker positions
  [positions]=GeneratePositions(nworkers,mindist,maxdist,WorkerDist);

% Calculate Thermal consequences at each worker's location
   axial =positions(:,1);%Worker axial distances from release point [m]
   radial =positions(:,2);%Worker radial distances from flame center [m]
   q_rad=arrayfun(@(x,y) FlameRadiation(SysParam, H2, jet, x, y),...
       axial, radial,'UniformOutput', false);
   q_rad=cell2mat(q_rad);

%%% Future: we'll calculate overpressure consequences here instead of
%%% using user input lines for P_s and impulse.

%% Calculate harm probabilities
%Calculates thermal harm
    PThermalFatal=ThermalFatality(q_rad, t_expose_thermal, ThermalProbit);

%Calculates overpressure harm
```

```
    if strcmp(OPProbit,'Lung_Eisenberg')||strcmp(OPProbit,'Lung_HSE')
        POverpressureFatal=OverpressureFatality(OPProbit, P_s);
    else
        POverpressureFatal=OverpressureFatality(OPProbit, P_s, impulse);
    end

%% Calculates expected number of fatalities from each type of exposure
% Expected number of fatalities from thermal exposures
  EFatal.jetfire=sum(PThermalFatal,1) %Sums thermal fatality prob.

% Expected number of fatalities for overpressure exposure
  EFatal.explosion = nworkers.*POverpressureFatal %Sum of OP fatality prob


%% Calculate PLL, FAR, and AIR
PLL=fJetfire.*(EFatal.jetfire')+fExplosion.*(EFatal.explosion');
totalPLL=sum(PLL)

FAR=totalPLL*10^8/(nworkers*8760) %E(#Fatalities) per 10e8 operating hours
AIR=yearlyworkinghours*FAR*10^-8 %Average individual risk (fatalities/yr)
```

C.2 Function: Nozzle Model

```
function [Meff,Teff,rhoeff,Ueff,Aeff,Deff,mdot,pt,Tt,rhot] = ...
    NozzleModel(pamb,Tamb,T0,p0,diam,CD,Num)

% Notional nozzle models that reproduce the jet exit conditions. See the
% model .m file for more information about each individual model.
%
% INPUTS:
%   pamb    = ambient pressure [Pa]
%   Tamb    = ambient Temperature [K]
%   T0      = stagnation (reservoir) Temperature [K]
%   p0      = stagnation (reservoir) pressure [Pa]
%   diam    = effective diameter of the release [m]
%   CD      = release discharge coefficient
%   Num     = Notional nozzle model selector [1 - 5]
%
% OUTPUTS
%   Meff    = effective exit Mach number at the exit
%   Teff    = effective gas temperature at the exit [K]
%   rhoeff  = effective jet gas density at the exit [kg/m^3]
%   Ueff    = effective jet release velocity at the exit [m/s]
%   Aeff    = effective leak area at the exit [m^2]
%   Deff    = effective leak diameter at the exit [m]
%   mdot    = mass flow rate [kg/s]
%   pt      = Gas pressure at the nozzle throat [Pa]
%   Tt      = Gas temperature at the nozzle throat [K]
%   rhot    = gas density at the nozzle throat [kg/m^3]
```

```
At        = diam.^2*pi/4.*CD;% Jet exit area [m^2]
b         = 7.691e-3; % m^3/kg
gamma     = 1.409;
Ru        = 8314.5;
MW        = 2.016; % g/mol
Rgas      = Ru./MW;
rhoamb    = pamb./(Rgas.*Tamb+pamb.*b); % Able-noble EOS
rho0      = p0./(Rgas.*T0+p0.*b);

switch Num
    case 1
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % Birch Model
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        [Meff,Teff,rhoeff,Ueff,Aeff,Deff,mdot,pt,Tt,rhot] = ...
            BirchModel(pamb,rho0,T0,gamma,b,Rgas,At);
    case 2
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % Birch2 Model
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        [Meff,Teff,rhoeff,Ueff,Aeff,Deff,mdot,pt,Tt,rhot] = ...
            Birch2Model(pamb,rho0,T0,gamma,b,Rgas,At);
    case 3
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % Ewan and Moodie Model
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        [Meff,Teff,rhoeff,Ueff,Aeff,Deff,mdot,pt,Tt,rhot] = ...
            EwanMoodieModel(pamb,rho0,T0,gamma,b,Rgas,At);
    case 4
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % Yuceil and Otugen Model
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        [Meff,Teff,rhoeff,Ueff,Aeff,Deff,mdot,pt,Tt,rhot] = ...
            YuceilOtugenModel(pamb,rho0,T0,gamma,b,Rgas,At);
    case 5
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % Harstad and Bellan Model
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        [Meff,Teff,rhoeff,Ueff,Aeff,Deff,mdot,pt,Tt,rhot] = ...
            HarstadBellanModel(rhoamb,pamb,p0,rho0,T0,gamma,b,Rgas,At);
end
```

C.3 Function: Birch 2 Model

```
% Birch2Model uses the second set of relationships developed by Birch et
% al. (Combust Sci Tech Vol 52 (1987) 161 - 171) to compute the effective
% area, velocity, and temperature after the Mach disk for an underexpanded
% jet.
%
% An additional feature that has been added to the model is the
```

```
% inclusion of the Abel-Noble equation of state so that non-ideal gas
% characteristics for HYDROGEN can be captured.
%
% The model is similar to the Birch1 model, except that it also accounts
% for the conservation of Momentum along with the conservation of MASS.
% The model makes the following assumptions:
%
% 1) The effective temperature after the Mach disk is equal to the
%    stagnation temperature
% 2) The static pressure at the Mach disk is assumed to be ambient pressure
%
% No attempt is made to account for the change in entropy across the shock
%
% Created by Isaac Ekoto (March 10, 2011)
%************************************************************************
function [M2,T2,rho2,V2,Aeff,Deff,mdot,pt,Tt,rhot] = Birch2Model...
    (pamb,rho0,T0,gamma,b,R_H2,At)
% Determine the conditions at the throat
f0       = @(rhot)ThroatDensity(rho0,rhot,1,gamma,b);
rhog     = rho0/((1+(gamma-1)/2)^(1/(gamma-1))); % guess density value
rhot     = fzero(f0,rhog); % temporary throat density [kg/m^3]
Tt       = T0/(1+(gamma-1)/(2*(1-rhot*b)^2)); % temperature at throat [K]
ct       = (1/(1-rhot*b))*sqrt(gamma*R_H2*Tt); % throat speed of sound [m/s]
mdot     = rhot*ct*At; % Mass flow rate [kg/s]
pt       = rhot*R_H2*Tt/(1-b*rhot); % throat pressure [Pa]

xi       = pt/pamb; % ratio of throat and ambient presures
T2       = T0;% Effective Temperature [K]
rho2     = pamb/(R_H2*T2 + b*pamb); % Effective density [kg/m^3]
V2       = (1 + (1-b*rhot)*(xi-1)/(gamma*xi))*ct; % Effective Velocity [m/s]
c2       = (1/(1-b*rho2))*sqrt(gamma*R_H2*T2); % speed of sound at Mach ...
   disk [m/s]
M2       = V2/c2; % Mach number upstream of Mach disk
Aeff     = mdot/(rho2*V2); % Effective Area [m^2]
Deff     = sqrt(Aeff*4/pi); % Effective Diameter [m]

% Function used to iteratively compute the throat density
function y  = ThroatDensity(rho0,rho,M,gamma,b)
X    = rho0/(1-b*rho0);
Y    = rho/(1-b*rho);
Z    = (1+((gamma-1)/(2*(1-rho*b)^2))*M^2)^(1/(gamma-1));
y    = X-Y*Z;
```

C.4 Function: Generate Positions

```
function [positions] = ...
   GeneratePositions(nworkers,mindist,maxdist,WorkerDistribution)
% This function generates the positions (distance from the dispenser for
% personnel in the warehouse. One [unlucky] person is always assumed to be
% standing as close to the dispenser as permitted (this represents the
```

```
% person fueling the vehicle).

%Inputs:
%   nworkers = number of workers in the warehouse
%   mindist = the minumum distance between the worker and the dispenser
    %(usually 0, unless there is an exclusion zone)
%   maxdist = the maximum distance between the worker and the dispenser
    %(to be conservative, select the shortest building dimension when
    %estimating maxdist)
%   WorkerDistribution = indicates whether workers are assumed to be
    %uniformly or normally distributed within the space


%Resets the random number generator to the default startup settings so that
%rand produces the same random numbers as if you restarted Matlab:
rng('default');

switch WorkerDistribution
    case 'Normal'
        %Generates "random" positions for personnel based on normal distrib
        mu=0;
        sigma=maxdist/3;  % I set the Stdev at 1/3rd of the building size ...
            since 99.7% of people are within 3 standard deviations. 68% of ...
            people will be within 1 standard deviation.
        positions=mu+sigma.*randn(nworkers,2); %Generates positions
        positions=abs(positions); %Forces the results to be positive

        for i=1:size(positions, 1), %Loops over all of the positions to ...
            make sure no one is positioned closer than the minimum distance ...
            from the dispenser
            for j=1:size(positions, 2),
                if positions(i,j)<mindist
                    positions(i,j)=mindist;
                end
            end
        end

    case 'Uniform'
        %Generates pseudorandom positions for personnel based on uniform
        %distribution around dispenser
        positions = mindist + (maxdist-mindist).*rand(nworkers,2);
end

%Position the person refueling 0.1m from the minimum distance from the
%dispenser
positions(1,1)= mindist+.1;
positions(1,2)= mindist+.1;

end
```

C.5 Function: Flame Radiation

```
function [q_rad] = FlameRadiation(SysParam,Fuel,jet,axial,radial)
%Calculates the radiant fraction, flame residence time, visible flame
%length, and heat flux using model from Houf 2007.

    %%%%% Constants
    XO2_air = 0.2095;
    Xfuel = 1./(1+(Fuel.cnum+Fuel.hnum/4)./XO2_air);%Stoich. fuel ratio
    R  = 8314.4621; %Universal gas constant [Pa*m^3/(kmol*K)]
    MWair   = 28.97; %Molecular Weight of air [g/mol]
    MWtotal= Xfuel.*Fuel.MW + (1-Xfuel).*MWair;%Mixture molec weight[g/mol]
    fs = Xfuel.*Fuel.MW./MWtotal; %Mass fraction of fuel at stoichometry
    g  = 9.81; %Gravity [m/s^2]

    %%%Calculated parameters
    ExtTempK=SysParam.ExternalTempC+273.15;
    ExtPresPa=SysParam.ExternalPresMPa*10^6;
    rho_air= (ExtPresPa*MWair)/(R*ExtTempK); %Air density [kg/m^3]


%% Compute the flame Froude number (Fr_f)
    deltaT_f = Fuel.Tad - ExtTempK;%Adiabatic minius ambient flame temp [K]

[Fr_f] = (jet.U_eff.*fs^1.5)./(((jet.rho_eff./rho_air).^0.25).*...
    ((deltaT_f/ExtTempK)*g*jet.D_eff).^0.5);

%% Compute visible flame length (L_vis, [m])
    L_star = zeros(size(Fr_f)); %Non-dimensional flame length
    for i = 1:length(Fr_f)
        if Fr_f(i) < 5
            L_star(i) = (13.5*Fr_f(i)^0.4)/(1+0.07*Fr_f(i)^2)^0.2;
        else
            L_star(i) = 23;
        end
    end
    d_star= jet.D_eff.*(jet.rho_eff./rho_air).^0.5; %jet momentum diam [m]

L_vis = L_star.*d_star/fs; % visible flame length [m]

%% Compute flame residence time (tau_flame, [ms])
    rho_flame=ExtPresPa.*MWtotal./(R*Fuel.Tad);%flame density [kg/m^3]
    W_flame= 0.17*L_vis; % flame width [m]

tau_flame = (rho_flame.*(W_flame.^2).*L_vis.*fs)./(3*jet.rho_eff.*...
    (jet.D_eff.^2).*jet.U_eff)*1000; %[ms]

%% Compute the radiant fraction (X_rad)
    X_rad = zeros(size(tau_flame));
    tau_cutoff  = 10;
    for i = 1:length(tau_flame)
        if tau_flame(i) <= tau_cutoff,
            tau_flame(i)= tau_cutoff;
        end
        X_rad(i) = -0.080435 + 0.082737*log10(tau_flame(i));
```

```
    end

    % Fit to normalized radiant power curve, C*
    S_rad = X_rad.*jet.m_dot.*Fuel.DHc; %[W]


    Xbar_temp    = axial./L_vis;
    val1         = -1.9571*(abs(Xbar_temp-0.6352))*1.4092;
    C_star        = 0.85985*exp(val1);
    C_star_max    = 0.87;
% Radiative heat flux [W/m^2] at distance (axial, radial):
    q_rad   = C_star.*S_rad./(4*pi*radial.^2);

end
```

C.6 Function: Thermal fatality probability

```
%THERMALFATALITY calculates the probability of a single fatality, given a
%thermal exposure
% Inputs
% q_rad is the flux (in W/m^2)
% t_expose_thermal is the exposure time  (in seconds)
%ThermalProbit tells us which ar

function [ThermalFatalityProb] = ThermalFatality(q_rad, t_expose_thermal, ...
    ThermalProbit)
%calculates the probability of a single fatality, given a thermal exposure

V = (q_rad).^(4/3).*t_expose_thermal; %Thermal Dose in (W/m^2)^4/3 s  ...
    (Multiply by 1e-4 to get kW)

% Determine which function to call for calculating fatality probability

switch ThermalProbit
    case 'Eisenberg'
        Y=-38.48+2.56*log(V);
    case 'Tsao'
        Y=-36.38+2.56*log(V);
    case 'TNO'
        Y=-37.23+2.56*log(V);
    case 'Lees'
     %Assumes clothing is present (reduces V into V'=0.5*V
     %Remove the factor 0.5 if clothing ignition occurs.
     Y=-29.02+1.99*log(0.5*V);
    otherwise
     error('***WARNING: Invalid ThermalProbit selected. Valid options are ...
        Eisenberg, Tsao, TNO, and Lees. Selected option must be enclosed ...
        in single quotation marks. ')
     return
end
```

```
ThermalFatalityProb=normcdf(Y,5,1);

return
```

C.7 Function: Overpressure fatality probability

```
%OVERPRESSUREFATALITY calculatest the probability of a single fatality,
%given exposure to an overpressure (OP).

%INPUTS
    % OPProbit = Indicates which probit functions to run. Choices are
    % Lung_Eisenberg, Lung_HSE, Head_impact, Collapse, Debris
    % P_s = the peak overpressure (in Pa)
    % varargin (indicates optional argument) - if there is an input here,
    % it's assigned to the variable "impulse," which is the impulse of the
    % shock wave (in Pa*s)

%OUTPUT
    % OPFatalityProb = the probability of a single fatality from OP effects

function [OPFatalityProb] = OverpressureFatality(OPProbit, P_s, varargin)

impulse=varargin{1};

% This switch statement allows users to select the OP probit model to use.
switch OPProbit %<----------------------------------------------------------
    case 'Lung_Eisenberg'                                                 % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%     !
        %Eisenberg - Lung hemorrhage                                        !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%     !
        Y=-77.1 + 6.91*log(P_s);                                          % !
    case 'Lung_HSE'                                                       % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%     !
        %HSE - Lung hemorrhage                                              !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%     !
        Y=1.47+1.371*log(P_s);                                            % !
    case 'Head_impact'                                                    % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%     !
        %TNO - Head impact                                                  !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%     !
        Y=5-8.49*log((2430./P_s)+4e8./(P_s.*impulse));                    % !
    case'Collapse'                                                        % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%     !
        %TNO - Structural collapse                                          !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%     !
        V =(40000./P_s).^7.4+(460./impulse).^11.3;                        % !
        Y=5-.22*log(V);                                                   % !
    case 'Debris'                                                         % !
```

```
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        %TNO - Debris impact                                              !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        frag_mass=input('Enter mass of (individual) fragments (kg): ');% !
        v_debris=input('Enter debris velocity [m/s]: ');                % !
        if frag_mass>=4.5, %mass of the fragments [in kg]               % !
            Y=-13.19+10.54*log(v_debris);                               % !
        elseif frag_mass>=0.1                                           % !
            m_debris=input('Enter total mass of debris [kg]: ');        % !
            Y=-17.56+5.3*log(0.5*m_debris*v_debris^2);                  % !
        elseif frag_mass>=0.001                                         % !
            m_debris=input('Enter total mass of debris [kg]: ');        % !
            Y=-29.15+2.1*log(m_debris*v_debris^5.115);                  % !
        else                                                            % !
            error('Debris fragments must be larger than 0.001kg')       % !
        end                                                             % !
    otherwise                                                           % !
        error('Invalid OP probit selected. %s %s, %s, %s, %s,  %s.',...% !
            'Valid options are','''Lung_Eisenberg''','''Lung_HSE''',...% !
            '''Head_impact''','''Collapse''','and ''Debris''')          % !
        return                                                          % !
end %-------------------------------------------------------------------->!

%TNO Lung hemorrhage requires the person's mass, so we don't calculate it
%TNO whole body impact model produces lower probabilities than head
%impact model, which means head impact fatalities will dominate whole
%body impact fatalities. So we don't include TNO whole body fatalities.


OPFatalityProb=normcdf(Y,5,1); % Calculates fatality probability
return;
```

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