SANDIA REPORT
SAND2015-4500
Unlimited Release
Printed June 2015

Fire Protection Engineering Design Brief Template: Hydrogen Refueling Station

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Abstract

Building a hydrogen infrastructure system is critical to supporting the development of alternate-fuel vehicles. This report provides a methodology for implementing a performance-based design of an outdoor hydrogen refueling station that does not meet specific prescriptive requirements in NFPA 2, *The Hydrogen Technologies Code*. Performance-based designs are a code-compliant alternative to meeting prescriptive requirements. Compliance is demonstrated by comparing a prescriptive-based fueling station design with a performance-based design approach using Quantitative Risk Assessment (QRA) methods and hydrogen risk assessment tools. This template utilizes the Sandia-developed QRA tool, Hydrogen Risk Analysis Models (HyRAM), which combines reduced-order deterministic models that characterize hydrogen release and flame behavior with probabilistic risk models to quantify risk values. Each project is unique and this template is not intended to account for site-specific characteristics. Instead, example content and a methodology are provided for a representative hydrogen refueling site which can be built upon for new hydrogen applications.

ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program. The authors wish to thank Mike Ciotti of the Linde Group, Inc. for his input and collaboration throughout the CRADA (Cooperative Research and Development Agreement) that enabled this work. The authors wish to acknowledge Joe Pratt and other member of the H2First Reference Station design team, who shared insight and design specifications that were incorporated into this template. Finally, the authors would like to thank Chris San Marchi, Isaac Ekoto, Ethan Hecht, and the many other Sandians who have contributed to this work through their hydrogen research. Without your contributions to the field, this design brief would not have been possible.

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3 NOMENCLATURE

AHJ	Authority Having Jurisdiction
AIR	Average Individual Risk
DOE	Department of Energy
EERE	Energy Efficiency & Renewable Energy
FCTO	Fuel Cell Technology Office
HyRAM	Hydrogen Risk Analysis Model
LH2	Liquefied hydrogen
NFPA	National Fire Protection Association
PBD	performance-based design
P&ID	Piping and Instrumentation Diagram
QRA	Quantitative Risk Assessment
SFPE	Society of Fire Protection Engineers
SNL	Sandia National Laboratories

1 INTRODUCTION

1.1 Template Description

This document serves as a template for implementing a performance-based design method for an outdoor hydrogen refueling station. This effort was undertaken by Sandia National Laboratories (SNL) in an effort to facilitate the development of a hydrogen infrastructure in support of developing alternate-fuels vehicles and was sponsored by the U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy (EERE) Fuel Cell Technology Office (FCTO).

Throughout this template, an example hydrogen refueling station is used to illustrate the application of a performance-based design.

1.2 Methodology

This performance-based methodology is based on the Society of Fire Protection Engineer's (SFPE) *Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings* [SFPE 2007]. Prescriptive-based requirements are based on the National Fire Protection Association's (NFPA) *Hydrogen Technologies Code*, NFPA 2, 2011 Edition [NFPA 2 2011]. The prescriptive requirements are followed where possible and are used as a point of comparison to the performance-based design in order to establish a risk-equivalent design.

The SFPE Guide defines a Fire Protection Engineering Design Brief which documents the initial portions of the design and serves as a record of all stakeholder agreements for the methods and performance criteria that will be used in the evaluation of trial designs. The Design Brief includes:

- Project scope
- Project participants and qualifications
- General project information including facility and occupants characteristics
- Project goals
- Stakeholder and design objectives
- Performance criteria
- Design fire scenarios
- Trial designs
- Design assumptions
- Critical design features
- Methods of evaluation
- References
- Record of Agreement on Design Brief information

The purpose of this template is to illustrate how a performance-based design could be structured using available hydrogen risk tools. Because each site, project, and hydrogen application is unique, this template does not cover all aspects typically included in a Design Brief. Specifically, trial designs, design assumptions, critical design features, methods of evaluation, and the record of agreement between all stakeholders are not presented.

The performance-based goals and objectives used in this document are those specified for hydrogen applications in NFPA 2, Chapter 5. Throughout this analysis, the performance criteria are framed in terms of measurable quantities that can be calculated by available Quantitative Risk Assessment (QRA) tools. QRA is a structured approach for analyzing the risk presented by a complex engineering system. This analysis utilizes QRA techniques to quantify the baseline risk values for each hazard scenario of the prescriptive-based design. These baseline risk values are in turn used to establish the risk-equivalency for the performance-based design. This template utilizes the Sandia-developed QRA tool, Hydrogen Risk Analysis Model (HyRAM), to calculate risk values when developing risk-equivalent designs. HyRAM combines reduced-order deterministic models that characterize hydrogen release and flame behavior with probabilistic risk models to quantify risk values. More information on the development and basis of HyRAM is available in references [Groth 2012] and [Groth 2014].

At present, HyRAM utilizes generic statistical data for hydrogen component failure rates and hydrogen ignition events. In future applications, site-specific data should be used when available.

1.3 How to Use this Document

A template of a performance-based design brief is provided in the remaining section of this document. At the beginning of each section, a paragraph in *italics* is included that provides guidance on the type of information intended for the respective section. Following the guidance, example content is provided for a representative hydrogen refueling site. Blanks for site-specific information are provided where appropriate. The focus of this document is to demonstrate an approach to performance-based design using a combination of deterministic and probabilistic analysis specifically provided in the HyRAM toolkit. The deterministic models are those that characterize a hydrogen leak or fire based on physical behavior and validated by experimental results. The probabilistic models are those whose outputs are probability distributions. Because of this, less attention is paid to the details of the site-specific information, beyond that which is necessary to demonstrate the approach.

2 PROJECT SCOPE

2.1 Project Description

This section the template contains general introductory information about the project station and the purpose of the design project.

The scope of this project was to provide a design for a public, retail hydrogen refueling station that utilizes a bulk liquefied hydrogen (LH2) storage tank, vaporizers, compressors, gaseous hydrogen dispensers, and other associated components. The station is new construction and built at an existing gasoline fueling site. The station is located in an urban area in the State of California.

The purpose of conducting this activity was to evaluate an alternative to specific prescriptive separation distances. The intent was to demonstrate that the performance-based design meets the same fire safety goals and objectives as a prescriptive design. This was achieved by comparing a fully code-compliant, prescriptive-based fueling station design with a performance-based design approach utilizing QRA methods.

2.2 Codes and Standards

This section includes citations of the various applicable codes that apply for the project.

The applicable building code was the California Building Code, 2013 Edition. The California Building Code references NFPA 2, *Hydrogen Technologies Code*, 2011 Edition, for regulation of hydrogen applications. NFPA 2 contained material extracted from NFPA 55, *Compressed Gases and Cryogenic Fluids Code*, 2010 Edition. The Occupational Safety & Health Administration (OSHA) issued Regulation 1910.103 which also provided guidance for using hydrogen. California Title 8, Section 5473 was also utilized for determining prescriptive requirements.

Fueling stations are also governed by NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*, 2009 Edition and the International Fire Code (IFC), 2009 Edition.

2.3 Fueling Station Description

This section contains a general description of the fueling station, which may include: site layout figures and piping and instrumentation diagrams. This section also describes the hydrogen fueling station characteristics, including: hydrogen storage tanks, dispensers and associated components, operating parameters, location, barriers or suppression systems, and other applicable details.

The system analyzed was the refueling station shown in Figure 1.The system consisted of the following major components:

- 3500 gallon (910kg) liquid hydrogen (LH2) storage tank with operating parameters of 150 psi and -260 ^{o}F

- Vaporizer (kg/hr rating)
- Three compressors
- A bank of high pressure gaseous hydrogen storage cylinders (300, 600, and 900 bar) for cascade filling of vehicles
- Underground, jointless stainless steel piping from storage bank to dispenser island
- 1-2 dual hose dispensers
- Station rated at a 300 kg/day capacity

This station was based on the near-term liquid station designed as a reference station under the H2First initiative [Pratt 2014]. The near-term station used a cryogenic liquid storage tank and ambient air evaporator to supply hydrogen to the compressor. The piping and instrumentation diagram (P&ID) for this station is included in Figure 2.

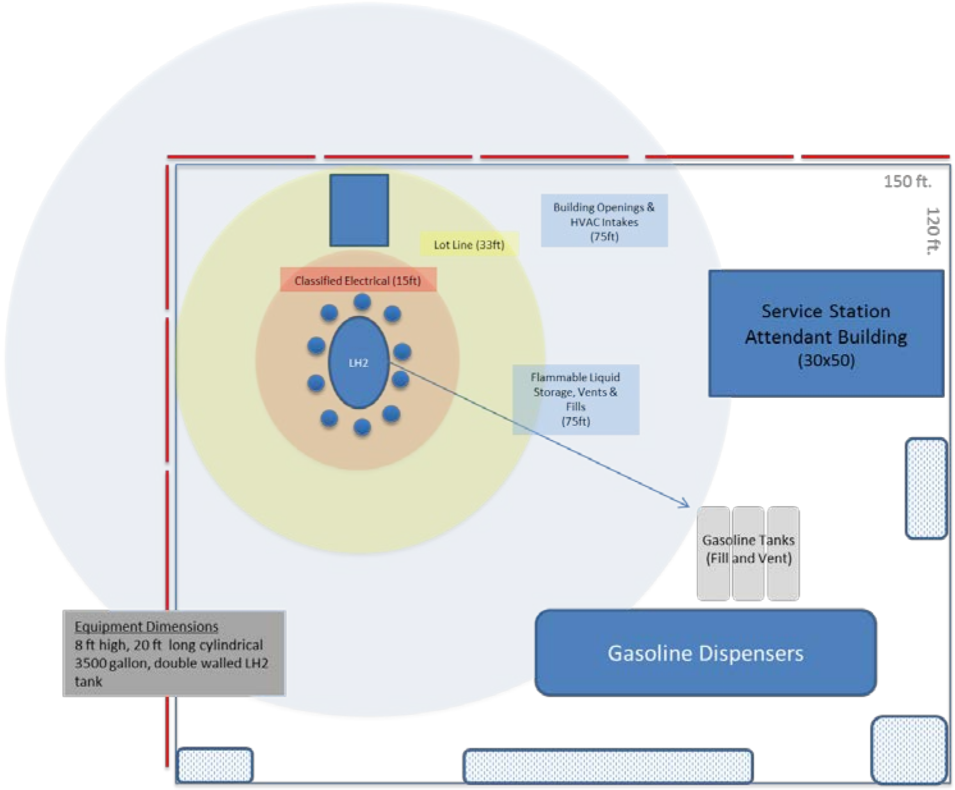


Figure 1. Example Hydrogen Refueling Station Layout

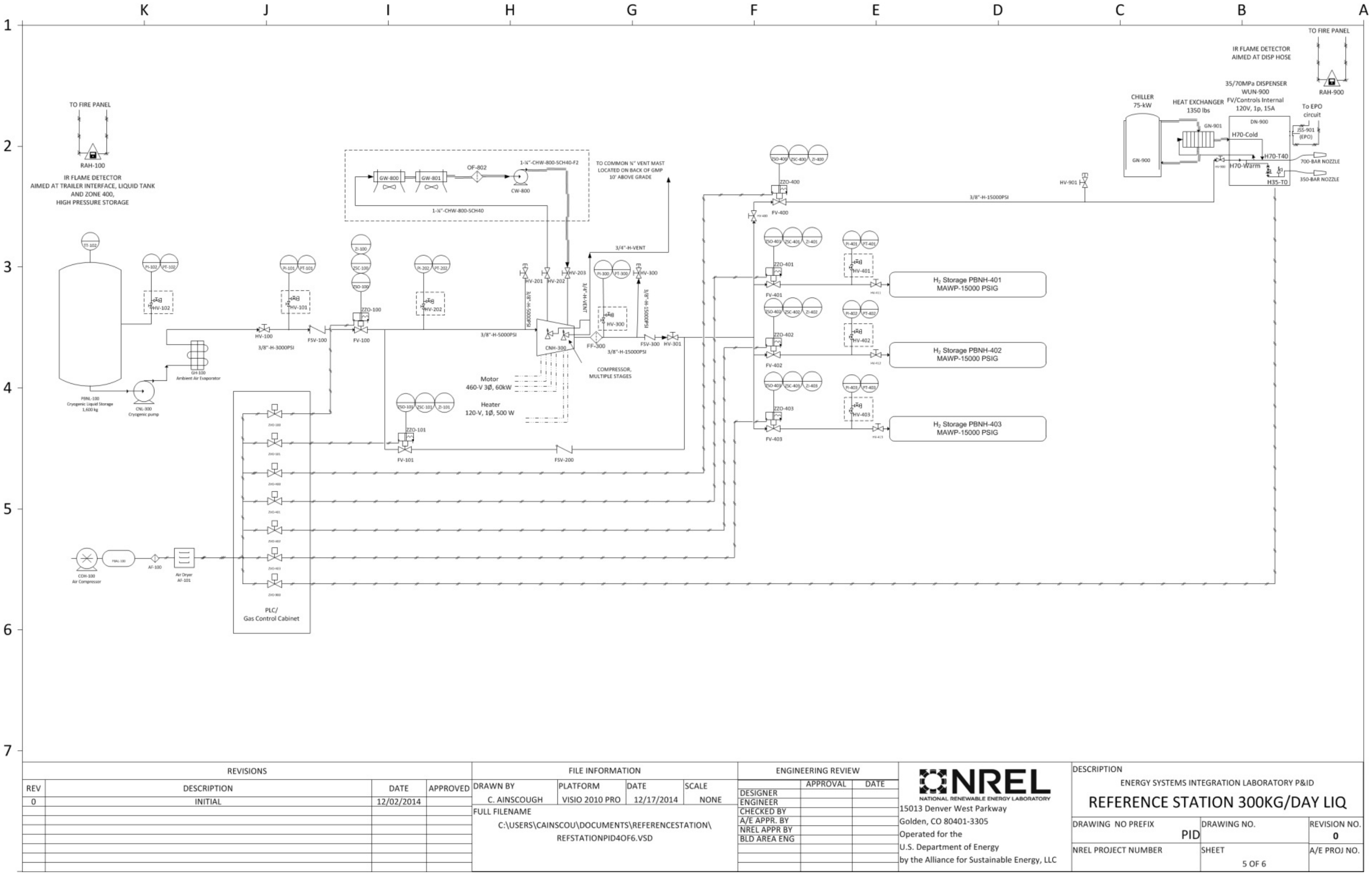


Figure 2: P&ID 300 kg/day Station

2.4 Stakeholders

In this section of the template all stakeholders in the project are identified. Because stakeholders can have differing goals and objectives for the project, it is essential that all the proper stakeholders are identified. This is critical in order to obtain acceptance of the performance-based strategies and, ultimately, the final design used in the project. The applicable entities are identified in a list. The names and contact information for each entity needs to be provided in the Design Brief. The level of responsibility and authority over the project also needs to be listed.

The stakeholders for this project are listed in Table 1.

Table 1: Project Stakeholders

Stakeholder Entity	Name	Organization	Contact Information
Station owner			
Station operator			
Hydrogen system owner and hydrogen provider			
Insurance entities			
Design Team responsible for performance-based design			
Authorities Having Jurisdiction (AHJ) for fire and building codes			
Emergency responders			

2.5 Submittal Schedule

Based on the local building permit department for the jurisdiction of the project site, a submittal schedule should be developed and included in this section of the template. Each specific project deliverable must be identified as well as the approval authority.

An example submittal schedule is provided in Table 2.

Table 2: Submittal Schedule

Project Document	Approvals	Schedule
Design Brief	Station owner Hydrogen system owner Insurance Company County Building Dept. County Fire Code Dept.	Prior to 30% Design Review

30% Design review	Station owner Hydrogen system owner	6 months prior to construction
60% Design review	Station owner Hydrogen system owner Insurance Company County Building Dept. County Fire Code Dept.	60 days prior to construction
90% Design review	Station owner Hydrogen system owner Insurance Company County Building Dept. County Fire Code Dept.	30 days prior to construction
100% Design	Station owner Hydrogen system owner Insurance Company County Building Dept. County Fire Code Dept.	Prior to construction
System Commissioning & Acceptance Tests	Hydrogen system owner Insurance Company County Building Dept. County Fire Code Dept.	Prior to public opening of station
As-Built Construction Drawings	Hydrogen system owner County Building Dept. County Fire Code Dept.	Within 90 days of System Commissioning

2.6 Property Location

Include specific property location in formation in this section. This section of the template should also list any potential exposure hazards to or from adjacent properties, for example public bus stops or chemical processing plants. Typical weather data for the location is also included as these parameters are used by the hydrogen release models.

The project site is located at [Address] in [County], [City], California. The site was an active gasoline refueling station with an onsite carwash. The site is located at the intersection of [Street] and [Street]. The site is bordered by public roads to the north and the east. The property adjacent to the site to the west is a fast food restaurant with associated parking lot. The property south of the site is [property description].

Weather (ambient conditions) in this part of California tends to range from [average low temperature and humidity in January] to [average high temperature and humidity condition in August]. The elevation at the site is [elevation in feet and meters] corresponding to an ambient pressure range of [range]. The prevalent wind direction is from the [direction] and ranges from [range] miles per hour.

2.7 Occupant and Use Profile

This section describes occupant characteristics, such as: the expected number of occupants, to include the expected number of persons fueling vehicles, employees, and other persons in close proximity to the fueling station. This section also includes details on the number of discreet vehicle fuelings expected for the hydrogen system, which will be used in the QRA tool.

The majority of the hydrogen system, including the storage tanks, vaporizer, and dispensing equipment, is located outdoors in the open air. The compressors and associated electrical equipment are located in a non-combustible container-type enclosure that is not normally occupied. These enclosures are accessed only for periodic maintenance activities. Therefore, this analysis was primarily concerned with people who are situated outdoors, such as members of the general public who are refueling their vehicles.

For this project, six members of the public were assumed to be onsite, on average. This was based on two people located near the hydrogen dispenser, two people in the vicinity of the door to the convenience store, and two people located near the gasoline pumps. Employees of the station were located in the retail store building onsite and would not be subject to effects of any events associated with the hydrogen system as they were shielded by the building structure. The station was assumed to be open to the public 18 hours per day, 360 days per year (6,480 hr/yr). For the purposes of quantifying the risk, it was estimated that the station fuels 50 vehicles per day. This estimate was based on the rated capacity of the hydrogen system.

2.8 Fire Service Characteristics

This section includes information about responding emergency services and response times.

The site is served by the [City] Fire and Police Departments. The nearest Fire Department is located [Number] miles away at [Address]. Typical response time for emergency responders from this location is [Time] minutes. Nearby fire services that have a memorandum of understanding to provide mutual aid in an emergency are [City] and [City]. Response times for these additional emergency responders are between [Time] and [Time].

3 GOALS AND OBJECTIVES

This section of the template identifies the applicable goals for this project, and discusses any goals presented in NFPA 2 that are not applicable. Stakeholder and design objectives for each goal are also presented. Additional stakeholder goals and objectives can be identified and discussed in this section. For this template, only those mandated by NFPA 2 are included.

The fire safety goal for the hydrogen fueling station was to provide an acceptable level of risk to the public and hydrogen fueling station occupants in the event of a fire or similar emergency. The specific goals for the performance-based design of hydrogen fueling station were stipulated in NFPA 2, *Hydrogen Technologies Code*, 2011 Edition. The performance-based goals and objectives specified in NFPA 2 were identical to the prescriptive goals and objectives. This code structure ensures that performance-based designs meet the intent of the prescriptive code requirements which, by definition, meet the goals and objectives.

A stakeholder objective determines the stakeholder's level of acceptable or sustainable loss. The design objective differs in that it is the performance benchmark against which the predicated performance of a design is evaluated.

3.1 Safety-from-Fire

3.1.1 Goal

The fire safety goal was to provide life safety to facility occupants and the public in the event of a fire or similar emergency.

> *To provide an environment for the occupants in a … facility and for the public near a … facility that is reasonably safe from fire and similar emergencies and to protect fire fighters and emergency responders. [NFPA 2:4.2.3.1]*

3.1.2 Objectives

The stakeholder objectives prescribed by NFPA 2 [4.2.3.1.2] were:

- Facilities shall be designed, constructed, and maintained to protect occupants who are not intimate with the initial fire development for the amount of time needed to evacuate, relocate, or defend in place.
- Facilities shall be designed, located, and constructed to reasonably protect adjacent persons from injury or death as a result of a fire.
- Operations shall be conducted at facilities in a safe manner that minimizes, reduces, controls, or mitigates the risk of fire injury or death for the operators, while protecting the occupants not intimate with initial fire development for the amount of time needed to evacuate, relocate, or defend in place.
- Facilities shall be designed and constructed to provide reasonable access for emergency responders and to provide reasonable safety for fire fighters and emergency responders during search and rescue operations.

The refueling system components containing hydrogen are located outdoors and are not enclosed within a structure, with the exception of the metal structure containing the electrical equipment and compressor that is not normally occupied. Therefore search and rescue operations were not anticipated within a structure.

The design objective was to provide the same level of risk from fire for the performance-based design as is provided by the prescriptive requirements, as calculated by the HyRAM QRA risk metrics baseline values for a station that complies with all prescriptive code requirements.

3.2 Safety-During-Facility-Use

3.2.1 Goals

The Safety-During-Facility-Use goal for this project was to provide an environment for the occupants that is reasonably safe during the normal use of the building. [NFPA 2: 4.2.3.2.1]

3.2.2 Objectives

The stakeholder objective prescribed by NFPA 2 [4.2.3.2.2] was that the performance-based design shall be in accordance with the requirements of the adopted building code. For this project, the California Building Code, 2013 Edition, was the adopted building code.

The design objective was to provide the same level of overall risk for the performance-based design as was provided by the prescriptive requirements, as calculated by the HyRAM QRA risk metrics baseline values for a station that complies with all prescriptive code requirements.

3.3 Safety-from-Hydrogen Hazards

3.3.1 Goal

The safety-from-hydrogen hazards goal prescribed in NFPA 2 was to provide an environment for the occupants in and adjacent to a facility that is reasonably safe from exposures to adverse effects from hydrogen hazards present therein. [NFPA 2: 4.2.3.3.1]

3.3.2 Objectives

The stakeholder objectives prescribed by NFPA 2 [4.2.3.3.2] were:

- The storage, use, or handling of hydrogen in a facility shall be accomplished in a manner that provides a reasonable level of safety for occupants and for those adjacent to a building or facility from health hazards, illness, injury, or death during normal storage, use, or handling operations and conditions.

- The storage, use, or handling of hydrogen in a facility shall be accomplished in a manner that provides a reasonable level of safety for occupants and for those adjacent to a building or facility from illness, injury, or death due to the following conditions:
    - An unplanned release of hydrogen.
    - A fire impinging upon the hydrogen piping or containment system or the involvement of hydrogen in a fire.
    - The application of an external force on the hydrogen piping or containment system that is likely to result in an unsafe condition.

These stakeholder objectives were used to develop the various hydrogen hazard scenarios evaluated by the performance criteria for this project. The design objective was to provide the same level of risk from hydrogen hazards for the performance-based design as was provided by the prescriptive requirements, as calculated by the HyRAM QRA risk metrics baseline values for a station that complies with all prescriptive code requirements.

3.4 Property Protection

3.4.1 Goal

The property protection goal prescribed by NFPA 2 [4.2.4.1] was to limit damage created by a fire, explosion, or event associated with gaseous or liquid hydrogen to a reasonable level to the facility and adjacent property.

3.4.2 Objectives

The stakeholder objectives prescribed by NFPA 2 [4.2.4.2] were:

- **Prevention of Ignition.** The facility shall be designed, constructed, and maintained, and operations associated with the facility shall be conducted, to prevent unintentional explosions and fires that result in failure of or damage to adjacent compartments, emergency life safety systems, adjacent properties, adjacent outside storage, and the facility's structural elements.
- **Fire Spread and Explosions.** In the event that a fire or explosion occurs, the building or facility shall be sited, designed, constructed, or maintained, and operations associated with the facility shall be conducted and protected, to reasonably reduce the impact of unwanted fires and explosions on the adjacent compartments, emergency life safety systems, adjacent properties, adjacent outside storage, and the facility's structural elements.
- **Structural Integrity.** The facility shall be designed, constructed, protected, and maintained, and operations associated with the facility shall be conducted, to provide a reasonable level of protection for the facility, its contents, and adjacent properties from building collapse due to a loss of structural integrity resulting from a fire.
- **Hydrogen Hazards.** The facility shall be designed, constructed, and maintained, and operations associated with the facility shall be conducted, to provide reasonable property protection from damage resulting from fires, explosions, and other unsafe conditions associated with the storage, use, and handling of hydrogen therein.

These stakeholder objectives were also used to develop the various hydrogen hazard scenarios evaluated by the performance criteria for this project. The design objective was to provide the same level of risk from hydrogen hazards for the performance-based design as was provided by the prescriptive requirements, as calculated by the HyRAM QRA risk metrics baseline values for a station that complies with all prescriptive code requirements.

3.5 Public Welfare

A public welfare facility is a building that provides a public welfare role for the community. The hydrogen refueling station does not provide a public welfare role; therefore, the goals and objectives for public welfare given in NFPA 2 did not apply.

4 PERFORMANCE CRITERIA

This section contains a discussion and listing of the performance criteria used to evaluate the performance-based design.

Performance criteria refine the design objectives into values against which the performance of proposed design approaches can be evaluated. For the design of the hydrogen refueling station, the performance criteria were primarily based on risk values calculated by HyRAM. Specifically the average individual risk (AIR) risk metric was used in the evaluation of design alternatives. Calculated values can also be compared to AIR values for other facilities and occupational hazard values, such as risk exposure at traditional gasoline stations.

Tenability criteria, such as radiant heat flux, temperature or peak overpressure, were also used as performance criteria for specific objectives in this project. HyRAM was also used to calculate these values using the stand-alone “physics mode” which characterizes hydrogen release behavior as well as jet flame and explosion overpressure effects.

NFPA 2 also provided specific performance criteria which need to be met for each required design scenario, assumption, and design specification. The performance criteria applicable to this outdoor hydrogen refueling station application are presented in Table 3.

Table 3: NFPA 2 Required Performance Criteria

Criteria Type	Performance Criteria Requirement	Specific Performance Criteria
Fire Conditions	No occupant who is not intimate with ignition shall be exposed to instantaneous or cumulative untenable conditions [5.2.2.1].	Untenable conditions resulting from fire are calculated based on the Tsao and Perry thermal dose probit model which combines both a heat flux intensity and an exposure time. [LaChance 2011]
Explosion Conditions	The facility design shall provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of unintentional detonation or deflagration [5.2.2.2].	The acceptable overpressure exposure is characterized by the Eisenburg overpressure probit function. [LaChance 2011]
Hazardous Materials Exposure	The facility design shall provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of an unauthorized release of hazardous materials or the unintentional reaction of hazardous materials [5.2.2.3] to cryogenic hydrogen or pre-cooled hydrogen at the	The acceptable level of safety for a hydrogen release is considered to be the displacement of oxygen levels (hypoxia) no lower than 12% for more than 6 minutes [SFPE Handbook]. Also, a localized temperature criteria of no lower than -50 ^{o}F (227K) for exposure. [http://www.atc.army.mil/weather/windchill.pdf Criteria is based on frostbite temperatures for <5minute exposure time.

	dispenser is established for this analysis.	
Property Protection	The facility design shall limit the effects of all required design scenarios from causing an unacceptable level of property damage [5.2.2.4].	The stakeholder for this project have agreed on a property protection value of [$XXX] as the acceptable level.
Occupant Protection from Untenable Conditions	Means shall be provided to evacuate, relocate, or defend in place occupants not intimate with ignition for sufficient time so that they are not exposed to instantaneous or cumulative untenable conditions from smoke, heat, or flames [5.2.2.6].	There are no additional performance criteria for untenable conditions above those already defined for fire, explosions, and hydrogen exposure since smoke exposure is not a relevant hazard due to the facility being outdoors
Emergency Responder Protection	Buildings shall be designed and constructed to reasonably prevent structural failure under fire conditions for sufficient time to enable fire fighters and emergency responders to conduct search and rescue operations [5.2.2.7].	A peak overpressure of less than 15 kPa is acceptable to protect against explosion effects incident upon the occupied retail store building.
Structural Failure	Buildings shall be designed and constructed to reasonably prevent structural failure under fire conditions for sufficient time to protect the occupants [5.2.2.8].	The hydrogen system is not located within a building structure that is occupied. The performance criterion for any potential effects from an explosion on the occupied retail store building is 15 kPa for this design.

Probit functions were used in lieu of point values for harm criteria for both fire and explosions because the harm level is a function of both the heat flux intensity and the duration of exposure for thermal radiation. Harm from radiant heat fluxes is expressed in terms of a thermal dose unit which combines the heat flux intensity and exposure time [Groth 2012]. To characterize harm from overpressure, several probit models were available in the literature for various effects of overpressure including, lung hemorrhage, head impacts, structural collapse, and debris impact. For this outdoor refueling station, structural collapse was not a credible harm scenario; therefore the Eisenberg probit model for lung hemorrhage was used.

Personnel exposed to low oxygen concentrations can develop hypoxia, where the body is deprived of adequate oxygen supply. The concentration associated with judgmental incapacitation, and therefore impairs one’s ability to act to prevent injury or move to safety, is approximately 12% oxygen [SPFE 2012]. Because this level could affect a person’s ability to judge which direction is safe to move, this value was used as the performance criteria for exposure to liquid hydrogen (hazardous material exposure).

Liquid hydrogen is typically stored at 20K (-423°F) in a cryogenic, vacuum-insulated storage tank. If a leak were to occur, the liquid hydrogen would be heated and turn into vapors and gases which could freeze human tissue. Prolonged exposure of the skin or contact with cold surfaces, for example the metal storage tank, can cause frostbite. For example, a wind speed of 15mph and an air temperature of -40°F could result in frostbite with an exposure time of less than 5 minutes [USARIEM 2001]. A localized temperature criteria of no lower than -50 ^{o}F (227K)for exposure was used based on frostbite temperatures for <5minute exposure time.

The performance criterion specified for emergency responder protection was correlated to the amount of pressure needed to collapse unreinforced concrete or cinderblock walls [LaChance 2011] and represents the hazard of an outdoor hydrogen explosion impacting the retail store on where employees are located and emergency responders may be expected to conduct search and rescue operations. Because the hydrogen system does not enter the retail store at any time and the air intakes for the building meet the prescriptive separation distances, an internal hydrogen explosion in the retail store was not considered. However, the impact of an external hydrogen explosion is examined. For this reason, the performance criterion of a peak pressure force on the retail building, where emergency responders may conduct rescue operations during an emergency event, was specifically characterized and used to evaluate trial designs.

The performance criterion stipulated by NFPA 2 for public welfare buildings was not addressed in this design brief because it does not apply to the outdoor hydrogen fueling station application. The dismissal of this goal has been approved by stakeholders. As discussed in the Goals and Objectives, the hydrogen refueling station was not considered to be serving a public welfare role; therefore no public welfare performance criteria are used in this design.

5 DESIGN SCENARIOS

This section describes the design fire scenarios that will be evaluated for the outdoor hydrogen fueling station. A design fire scenario is a set of conditions that defines or describes the critical factors for evaluating a proposed hydrogen design. The design scenarios are intended to represent realistic events that could challenge safety systems or responding personnel. NFPA 2 requires that "each scenario be as challenging and realistic as any that could occur realistically" and lists required design scenarios.

5.1 Assumptions

All assumptions made during the development of the design scenario need to be identified and listed in this section. For this template, the assumptions prescribed specifically by NFPA 2 are listed.

- For fire scenarios, only a single fire source was assumed to be present. Multiple, simultaneous fire events were not considered.
- For the hazardous material release scenarios, multiple simultaneous unauthorized releases of hazardous materials from different locations were not considered.
- Combinations of multiple events were not considered.

5.2 Required Design Scenarios

Table 4 provides an overview of each design scenario selected for the evaluation of design alternatives. Each scenario is discussed in more detail.

Table 4: Design Scenarios

Required Scenario	Outdoor Fueling Station Scenario	Performance Criteria Approach
Fire- Performance-based building design for life safety affecting the egress system shall be in accordance with this code and the requirements of the adopted building code. [NFPA 2:5.4.2]	Hydrogen fire resulting from a leak at the hydrogen dispenser.	HyRAM jet fire risk calculation.
Explosion Scenario 1- Hydrogen pressure vessel burst scenario shall be the prevention or mitigation of a ruptured hydrogen pressure vessel. [NFPA 2:5.4.3.1]	Prevention of gaseous H2 pressure vessel rupture	Pressure relief devices and leak-before-burst design specification for all hydrogen storage vessels.

Required Scenario	Outdoor Fueling Station Scenario	Performance Criteria Approach
Explosion Scenario 2- Hydrogen deflagration shall be the deflagration of a hydrogen-air or hydrogen-oxidant mixture within an enclosure such as a room or within large process equipment containing hydrogen. [NFPA 2:5.4.3.2]	A hydrogen deflagration within the enclosure housing the compressor.	Evaluation of potential for deflagration conditions and HyRAM peak overpressure
Explosion Scenario 3- Hydrogen Detonation shall be the detonation of a hydrogen-air or hydrogen-oxidant mixture within an enclosure such as a room or process vessel or within piping containing hydrogen. [NFPA 2: 5.4.3.3]	Venting of hydrogen from the liquid storage tank forms localized H2/air mixture in the vent pipe that detonates.	Prevention of detonation by meeting vent pipe length to diameter ratio specified by CGA G-5.5
Hazardous Material Scenario 1- Unauthorized release of hazardous materials from a single control area. [NFPA 2: 5.4.4.1]	Release of hydrogen from liquid storage tank	HyRAM characterization of liquid hydrogen release (localized hypoxia levels and temperature)
Hazardous Material Scenario 2- Exposure fire on a location where hazardous materials are stored, used, handled, or dispensed. [NFPA 2: 5.4.4.2]	An unrelated vehicle fire at the gasoline dispensing pump.	Flame radiation from vehicle fire calculation using SFPE calculation methods
Hazardous Material Scenario 3- Application of an external factor to the hazardous material that is likely to result in a fire, explosion, toxic release, or other unsafe condition. [NFPA 2: 5.4.4.3]	Seismic event where a pipe bursts (100% leak size on largest pipe).	HyRAM risk metric calculation
Hazardous Material Scenario 4- Unauthorized discharge with each protection system independently rendered ineffective. [NFPA 2: 5.4.4.4]	A hydrogen discharge where the interlock fails.	Discussion of layered safety features present in the system

5.2.1 Fire Scenario

In this design scenario, a component associated with the hydrogen dispensing equipment was assumed to develop a leak, ignite immediately and result in a jet fire. Because explosive conditions are dealt with independently in other design scenarios, only the effects of a fire were considered in this scenario. The HyRAM QRA risk tool incorporates the thermal probit model specified in the performance criteria: Tsao and Perry. HyRAM calculated the variety of potential hydrogen leak rates and sizes and resulting jet fire flame lengths and heat fluxes. These parameters in turn provided the resulting thermal dose that is weighed against the probit model to arrive at a potential harm value. HyRAM was used to calculate the baseline risk value for a station compliant with all prescriptive requirements in order to form a comparison basis for the risk values. The input values for all parameters in the HyRAM baseline fire risk calculation are presented in Table 5.

Table 5: Baseline Fire Design Scenario HyRAM Input Parameters

HyRAM Input Screen	Parameter	Value
System Parameters - Vehicles	Number of Vehicles	50
	Fuelings Per Vehicle Day	1
	Vehicle Operating Days	360
	Annual demands (calculated from categories above)	18,000
Model Parameters - Physical Consequence	Notional Nozzle	Birch2
	Flame Radiation Model	Ekoto/Houf (curved flame)
	Deflagration Model	None - Fire scenario only
Model Parameters - Harm	Thermal Probit	Tsao and Perry
	Thermal Exposure	60 sec
	Overpressure Probit	None - Fire scenario only
Occupants	Population	6 people, based on 2 at H2 dispenser, 2 in the gasoline dispenser and 2 entering store.
	Working hours per year	6480 hrs (30 days*12 months* 18 hours a day)
	Distribution	Uniform
	Max Distance	120 - distance to lot line
	Min Distance	1 - no internal huggers
Components	Compressors	0
	Cylinders	0
	Valves	7
	Instruments	10
	Joints	10
	Hoses	2
	Pipes (length)	10

HyRAM Input Screen	**Parameter**	**Value**
	Filters	1
	Flanges	0
Piping	Pipe OD	0.5625 inch (9/16)
	Pipe wall thickness	.12575 in
	Internal Temperature	15 C
	Internal Pressure	900 bar
	External Temperature	15 C
	External Pressure	.101325 MPa
Pipe Leak Size for **all components**: Mean and Variance	0.01 %	Default HyRAM values
	0.1 %	Default HyRAM values
	1 %	Default HyRAM values
	10 %	Default HyRAM values
	100 %	Default HyRAM values
Ignition Probabilities- **Immediate** Ignition Probability	Hydrogen Release Rate <0.125 kg/s	0.008
	Hydrogen Release Rate 0.125-6.25 kg/s	0.053
	Hydrogen Release Rate >= 6.25 kg/s	0.23
Ignition Probabilities- **Delayed** Ignition Probability	Hydrogen Release Rate <0.125	0 - fire only
	Hydrogen Release Rate 0.125-6.25	0 - fire only
	Hydrogen Release Rate >= 6.25 kg/s	0 - fire only

Because the leak was presumed to occur at the dispenser, only those components containing hydrogen and located at and within the dispenser were included in the component equipment counts. Also, all delayed ignition probabilities within the HyRAM model were set to zero so that the resulting risk values are based solely on the effects of an immediate jet fire.

The HyRAM risk result for these input parameters is:

AIR Fire: 1.05 E-04 fatalities per year

This value represents the fire risk presented by a hydrogen refueling station that was fully compliant with the prescriptive requirements of the applicable codes. This baseline value was used as the comparison value when comparing various trial designs.

5.2.2 Explosion Scenario 1 – Pressure Vessel Burst

All hydrogen storage containers in the system will be equipped with pressure relieving devices designed to operate and limit the pressure to the maximum allowable working pressure for cylinder and associate piping. Each stage of the compressed hydrogen storage was identified, along with the maximum allowable working pressure at which the components were rated. For this template, example stages and pressures are listed in Table 6.

Table 6: Pressure Rating for Hydrogen Storage Containers

Component	Normal Operating Pressure (bar)	Maximum Allowable Working Pressure (bar)
Liquid storage tank	8	12
Low and Middle Pressure Cylinders	765	850
High Pressure Cylinders	900	1000

In the case that a pressure relief device were to fail by not opening (stuck shut), all cylinders are designed according to a leak before burst specification using the criteria set out in ASME Boiler and Pressure Vessel Code Section VIII Division III Article KD-141 using standard fracture toughness KIc. This extra layer of protection from pressure vessel burst is not required by the California Building Code or NFPA 2.

Given this extra level of protection, no credible pressure vessel burst scenario existed for this system.

5.2.3 Explosion Scenario 2 – Deflagration

This scenario consisted of a leak developing in a compressor located in the modular container enclosure housing electrical equipment and hydrogen compressors. A mass of hydrogen escaped into the enclosure prior to finding an ignition source. A subsequent deflagration developed.

The enclosure dimensions are 2.72 m wide by 4.28 m long by 3.2 m tall, with a corresponding total volume of 101.3 m^3. It is estimated that the equipment takes up 45% of this volume. The remaining volume of air is 55.7 m^3, which is used as the available volume for calculating potential explosive concentrations of hydrogen.

The most likely leak size for a compressor is 0.01% of the pipe diameter, based on calculations documented in [LaChance 2009]. Using the rated capacity of the compressors, 27 kg/hr (0.45 kg/min), a value of 0.0045 kg/min was used to represent this leak rate. The flow rate provided by the exhaust ventilation system was 23.4 m^3/min. The exhaust vent for the enclosure was a 2.1 m by 0.75 m vent in the ceiling; however the vent was a raised rectangular shape equipped with louvers to prevent rain from entering the enclosure. A value of 50% of the vent size was used in the model to represent the available vent area. The Lowesmith model [Ekoto, 2011] was run to determine the steady state hydrogen concentration that will accumulate from the most frequent leak rate. The height of the accumulated hydrogen layer and the resulting hydrogen concentration in this layer are shown in Figure 3. The resulting hydrogen concentration was 0.8% hydrogen, well below the 4% lower explosive limit for hydrogen.

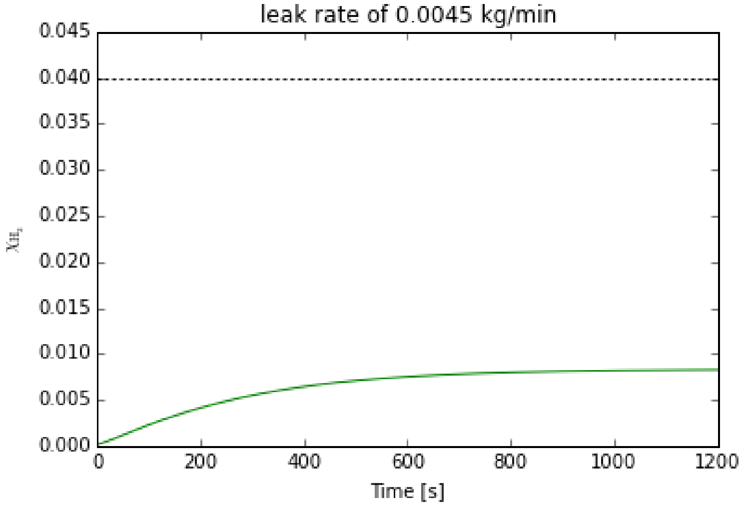


Figure 3: Hydrogen Concentration Resulting From Most Probable Compressor Leak Rate

Further analysis was conducted to determine the leak rate that would result in a hydrogen concentration at least 4%. Using an iterative process of varying the leak size and rate, it was determined that a leak rate of 0.0497 kg/min would be necessary to achieve a 4% concentration of hydrogen in the enclosure. See Figure 4 for the Lowesmith model results for a 4% mole fraction of hydrogen. This was compared to the corresponding rated capacity for the compressor. For this leak sixe, the maximum mass flow rate necessary to cause an explosive mixture of hydrogen and air cannot be reached by this compressor, even with a 100% leak size. Additionally, the ventilation in the enclosure is designed to run whenever the compressor is operating, therefore, a potentially explosive atmosphere will be prevented.

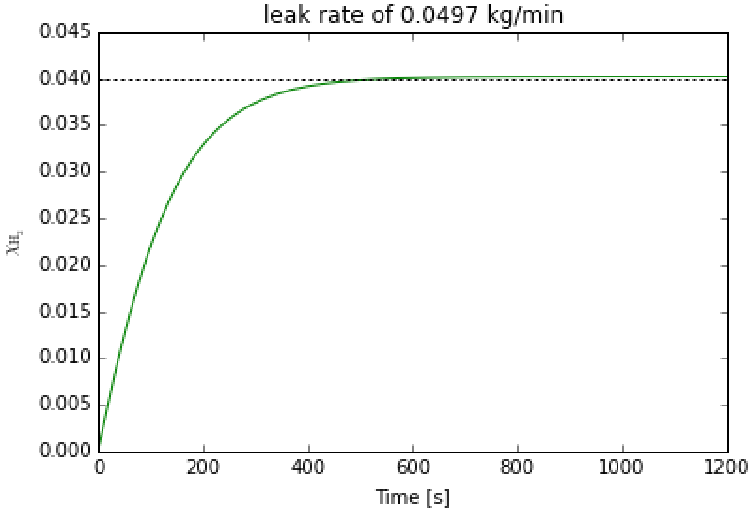


Figure 4: Compressor Leak Rate Required to Achieve a Steady –State Hydrogen Concentration of 4%

The peak overpressure correlation equation used in HyRAM is shown in Equation 1 [Bauwens 2011].]

$$\text{Equation 1} \qquad \boldsymbol{\Delta p = p_0 \left\{ \left[\frac{V_T + V_{H2}}{V_T} \frac{V_T + V_{H2}/\chi_{stoich}(\sigma - 1)}{V_T} \right]^{\gamma} - 1 \right\}}$$

where p_0 is the ambient pressure, V_T and V_{H2} are the total enclosure volume and expanded volume of hydrogen following the release, respectively, χ_{stoich} is the hydrogen-air stoichiometric mole fraction, σ is the expansion ratio for stoichiometric hydrogen-air combustion, and γ is the air specific heat ratio.

This equation can be used to calculate the potential peak overpressure in an enclosure. However, because the most probable leak rate resulted in a steady state concentration well below the lower explosive level for hydrogen, a potential explosion was not a credible scenario.

5.2.4 Explosion Scenario 3 – Detonation

Given that the hydrogen components are located outdoors where hydrogen will readily disperse due to its low density and natural buoyancy, the most conservative credible scenario for a detonation to occur is in the vent stack from the liquid hydrogen storage tank. “Hydrogen-air mixtures can exist in the vent system at concentrations with in the flammable range. This can lead to a deflagration or detonation of the hydrogen-air mixture inside the vent stack… This typically occurs when the hydrogen flow initially starts and before the residual air has been purged from the vent piping” [CGA G-5.5, 2014]

NFPA 2 required vent stacks for bulk liquid hydrogen systems to be designed and built according to CGA G-5.5, *Hydrogen Vent Systems*.

The vent stack on the liquid hydrogen storage tank was considered in this scenario. This vent was expected to be used routinely to bleed off excess pressure that may build up in the tank due to normal heat gain to the cryogenic hydrogen. The vent was operated via a manual valve. The operating procedures for the system specify that the tank will be vented once it achieves a pressure of more than 150 psi. The hydrogen vapor will be vented form the tank down to a tank pressure of 120 psi. To prevent the possibility of a detonation in the vent stack, the CGA G-5.5 publication required a Length to Diameter (L/D) ratio of less than 100:1.

The vent pipe consisted of 2 inch (nominal) diameter schedule 40 stainless steel pip. The inner diameter (ID) of this pipe was 2.067 inches. The length of the vent pipe was 25 feet (300 inches). The corresponding L/D ratio was:

L/D = 300 inches/2.067 inches = 145:1

The L/D ratio for this vent pipe has almost a 50% safety factor above that required by the code. As a result, no credible detonation scenario existed for this project.

5.2.5 Hazardous Material Scenario 1 – Unauthorized Release

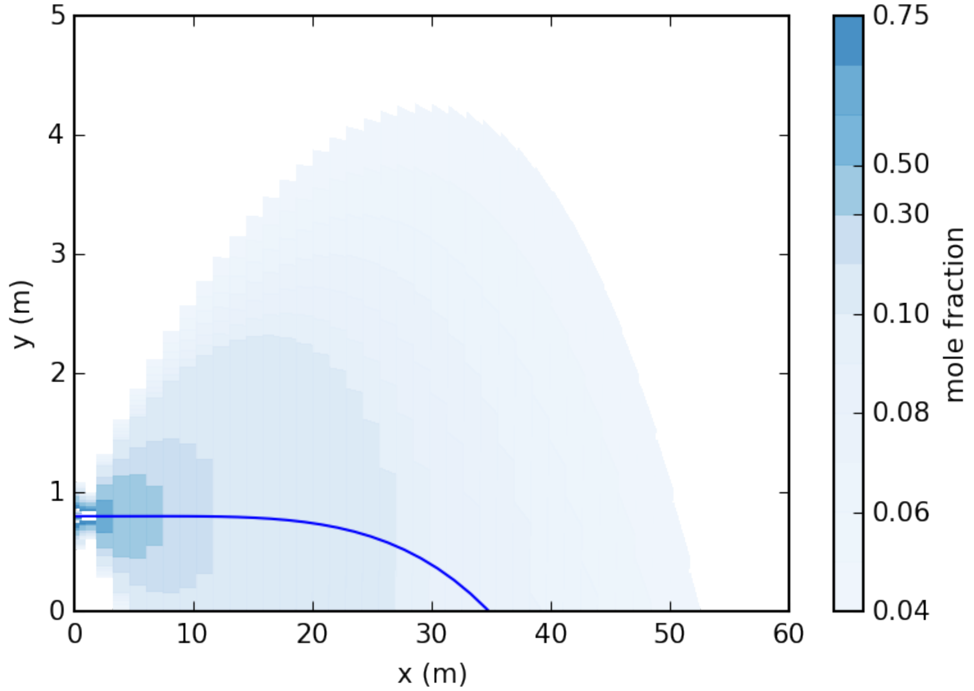
This scenario involved the release of hydrogen from the liquid storage tank. The release point considered was from a 2.54 cm diameter stainless steel pipe that is part of the pressure build circuit located at the end of the cylindrical tank. The cold plume hydrogen release model was used to characterize the temperature gradient from the release point as well as the hydrogen concentration. To evaluate the oxygen displacement hazard, the hydrogen concentration was used to determine when the oxygen level went below the performance criteria. The input values to the cold plume model are shown in Table 7.

Parameter	Value	Units
Release orifice (pipe size)	2.54	cm
Release location (height)	0.8	m
Tank pressure (initial)	10	bar
Tank temperature (saturation)	31.6	K

Table 7: Input Values for Cold Plume Hydrogen Release Model

The results of the cold plume model are show graphically in Figure 4. The plot shows the trajectory and concentration of the stream of saturated liquid hydrogen. It is likely that the release will have a mixture of liquid and vapor phase hydrogen, but the liquid is the most conservative and was used in this analysis. The shaded region shows the flammable extent for the plume. This simulation does not take into account pooling and flow along the ground, nor does it include wind effects. This was the most conservative estimate for the extent of the hydrogen plume.

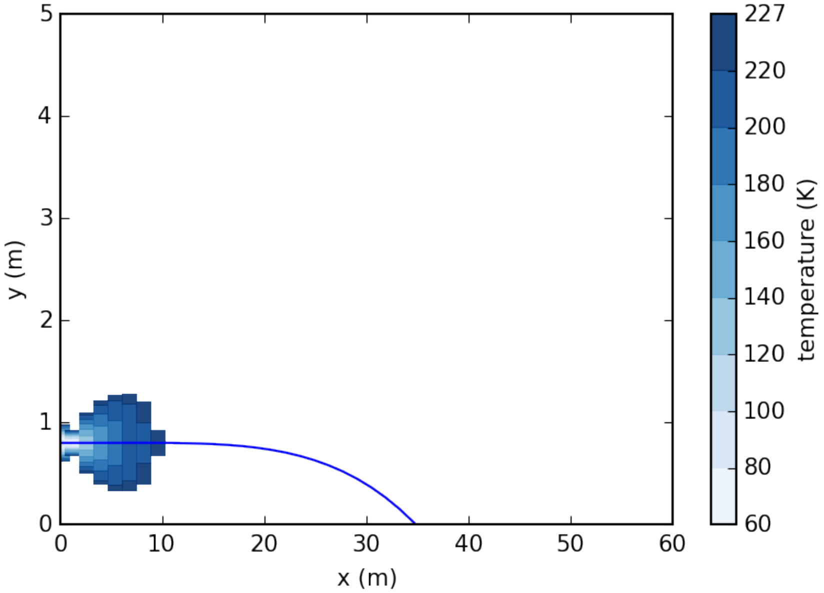
Figure 5: Hydrogen Concentration Results of Cold Plume Hydrogen Release Model



The performance criterion for hypoxia was 12%. To evaluate the extent of this region, the sea level ratio of O_2 to N_2 (20.8 % O_2 and 79.1 % N_2) was used to read the hydrogen concentration resulting in 12 % O_2. The corresponding hydrogen value was calculated as 42.3% H_2. The shaded region corresponding to this value was within 5 meters of the release point.

The temperature gradient resulting from the model for this scenario is shown in Figure 5. The shaded region depicts the temperature gradient up to the performance criteria of 227K (-50 F). For this scenario, the performance criteria extends to 10 m.

Figure 6: Temperature Gradient Results of Cold Plume Hydrogen Release Model



5.2.6 Hazardous Material Scenario 2 – Exposure Fire

The scenario was required to consider an exposure fire where hazardous materials are stored, used, handled, or dispensed. At a gasoline station, the most likely exposure fire is a vehicle fire and this is most likely to occur at the dispensing pumps or on the public street due to an accidental collision. This scenario analyzed the impact of a vehicle fire on the hydrogen dispenser system. The dispenser area was chosen for analysis over the hydrogen storage area because the dispenser is located closer to potential exposure fires (i.e. a vehicle fire). The nearest location from the hydrogen dispenser where a hydrocarbon-powered vehicle is anticipated was at the gasoline dispenser. This location was analyzed in order to provide the most conservative value for the exposure fire hazard. A hydrogen-fueled vehicle, utilizing the hydrogen dispenser, would be located closer to the hydrogen system, however, this vehicle was not considered in this scenario because NFPA 2 [NFPA2: 10.3.1.14.13] stated specifically that vehicles shall not be considered a source of ignition.

NFPA 502, the *Standard for Road Tunnels, Bridges, and other Limited Access Highways,* stated that the representative heat release rate for a single passenger vehicle is equal to 5 MW [8]. The SFPE Guide, Chapter 10, titled "*Fire Hazard Calculations for Large, Open Hydrocarbon Fires*" provided a calculation method for radiative heat flux based on heat release rate and distance from the point source to the target.

The distance from the nearest gasoline dispenser where the exposure fire is assumed to take place to the hydrogen dispenser was 6.7 m. The heat flux is expressed by Equation 2.

$$\text{Equation 2} \qquad \boldsymbol{q''} = \frac{\boldsymbol{Q\chi_r}}{\boldsymbol{4\pi R^2}}$$

Where:
Q = 5 MW (heat flux from vehicle fire)
χ_r = 0.3 (radiative heat fraction)
R = 6.7 m (distance from center of fire to the edge of the target)

The resulting incident heat flux becomes:

$$q'' = \frac{5000kW * 0.3}{4 * \pi * (6.7m)^2} = 2.7kW/m^2$$

This exposure heat flux value for the prescriptive requirement was compared to the performance-based requirement if the distance between the gasoline fueling dispenser and the hydrogen is impacted by the trial designs.

5.2.7 Hazardous Material Scenario 3 – External Event

In this hazardous material scenario, it was assumed that a seismic event occurs that results in shearing motion that is of a largest enough magnitude to result in a 100% leak of the largest pipe in the hydrogen system. Because explosive conditions are dealt with independently in other design scenarios, only the effects of a fire were considered in this scenario. The HyRAM QRA risk tool incorporated the thermal probit model specified in the performance criteria for protection from untenable conditions: Tsao and Perry. For the scenario, the HyRAM inputs were set to force a 100% leak of the largest pipe. These parameters provided the resulting thermal dose that was weighed against the probit model to arrive at a potential harm value. HyRAM was used to calculate the baseline risk value for a station compliant with all prescriptive requirements in order to form a comparison basis for the risk values. The input values for all parameters in the HyRAM baseline fire risk calculation are presented in Table 8.

Table 8: Baseline External Evental Design Scenario HyRAM Input Parameters

HyRAM Input Screen	**Parameter**	**Value**
System Parameters - Vehicles	Number of Vehicles	50
	Fuelings Per Vehicle Day	1

HyRAM Input Screen	Parameter	Value
	Vehicle Operating Days	360
	Annual demands (calculated from categories above)	18,000
Model Parameters - Physical Consequence	Notional Nozzle	Birch2
	Flame Radiation Model	Ekoto/Houf (curved flame)
	Deflagration Model	None - Fire scenario only
Model Parameters - Harm	Thermal Probit	Tsao and Perry
	Thermal Exposure	60 sec
	Overpressure Probit	None - Fire scenario only
Occupants	Population	6 people, based on 2 at H2 dispenser, 2 in the gasoline dispenser and 2 entering store.
	Working hours per year	6480 hrs (30 days*12 months* 18 hours a day)
	Distribution	Uniform
	Max Distance	120 - distance to lot line
	Min Distance	1
Components	Compressors	0
	Cylinders	0
	Valves	0
	Instruments	0
	Joints	0
	Hoses	0
	Pipes (length)	10
	Filters	0
	Flanges	0
Piping	Pipe OD	1.315 inch (1 inch nominal)
	Pipe wall thickness	.179 in
	Internal Temperature	15 C
	Internal Pressure	10 bar
	External Temperature	15 C
	External Pressure	.101325 MPa
Pipe Leak Size for Pipe component only:	0.01 %	0
	0.1 %	0
	1 %	0

HyRAM Input Screen	**Parameter**	**Value**
Mean	10 %	0
	100 %	1
Pipe Leak Size for all components except Pipe: **Mean**	0.01 %	0
	0.1 %	0
	1 %	0
	10 %	0
	100 %	0
Ignition Probabilities- **Immediate** Ignition Probability	Hydrogen Release Rate <0.125 kg/s	0.008
	Hydrogen Release Rate 0.125-6.25 kg/s	0.053
	Hydrogen Release Rate >= 6.25 kg/s	0.23
Ignition Probabilities- **Delayed** Ignition Probability	Hydrogen Release Rate <0.125	0 - fire only
	Hydrogen Release Rate 0.125-6.25	0 - fire only
	Hydrogen Release Rate >= 6.25 kg/s	0 - fire only

The HyRAM risk result for these input parameters was:

AIR Fire: 1.81 E-02 fatalities per year

This value represents the fire risk presented by a hydrogen refueling station that is fully compliant with the prescriptive requirements of the applicable codes. This baseline value was used as the comparison value when comparing various trial designs when considering the protection from fire objectives. It is important to note that this risk value is conditional based on the occurrence of an earthquake that shears off the largest hydrogen pipe in the system, and is considered a conditional risk value.

5.2.8 Hazardous Material Scenario 4 – Discharge with Protection System Out of Service

This scenario consisted of an unintentional hydrogen release with each protection system independently rendered ineffective. In this example, the analyzed protection system had interlocks that were responsible for shutting down the release of hydrogen. Because there was no sprinkler system or other emergency egress protection system, the interlock was the only protection system that is available for an evaluation of this type.

The interlocks consisted of fault-tolerant digital logic controllers which shut down the flow of hydrogen at several air-operated, fail-safe shut-off valves. If air pressure is lost at any time, these valves close automatically. Therefore the reliability of the digital logic controllers was the only value examined in this analysis. The failure rates reported in the literature covering a wide variety of manufactures and models in the chemical process and nuclear safety industries were considered. The probability that a controller with redundant processors will recover from a single processor failure by successfully switching the control function(s) to the other processor ranged from 98.37% to 99.59% [Paula 1991].

If the controller failed to activate the interlocks, the hydrogen release would continue until detected manually and an emergency stop button activated. Because the hydrogen system is located outdoors, the hydrogen will mix with the air and rise rapidly due to the inherent buoyancy. The hazardous materials release scenarios examined previously did not credit the interlocks activating when potential consequences were calculated by the risk analysis. Therefore, the risks of a hydrogen release resulting in a jet flame or an explosion, without the interlocks, are already included in the analysis. Also, given the very high reliability values for digital controllers, no additional risk scenarios were credible.

5.2.9 Scenarios Not Application to this Installation

The scenarios in Table 9 were considered not applicable for an outdoor fueling station. The justification for not including the scenario is included in the table below.

Table 9: Design Scenarios Not Applicable to Outdoor Hydrogen Application

Non-applicable Scenarios	Justification for Exclusion
Building Use Design Scenario 1 involves an event in which the maximum occupant load is in the assembly building and an emergency event occurs blocking the principal exit/entrance to the building. [NFPA 2:5.4.5.1]	No assembly occupancies exist on or nearby the refueling station and there were no building structure exits or entrances to block.
Building Use Design Scenario 2 involves a fire in an area of a building undergoing construction or demolition while the remainder of the building is occupied. The normal fire suppression system in the area undergoing construction or demolition has been taken out of service. [NFPA 2: 5.4.5.2]	No partially-occupied buildings with out-of-service suppression system were present to analyze.

5.2.10 Summary of Baseline Design Scenario Results

Table 10 provides a summary of the performance criteria results for each design scenario. For each trial design, design scenarios which involve any changes to the parameters used in calculating the results will be evaluated and compared.

Table 10: Summary of Baseline Performance Criteria Results Table 10: Summary of Baseline Performance Criteria Results

Outdoor Fueling Station Scenario	Baseline Result
Fire- Hydrogen fire resulting from a leak at the hydrogen dispenser.	AIR Fire = 1.85 E-04 fatalities per year
Explosion Scenario 1 - Prevention of gaseous H2 pressure vessel rupture	Prevention of vessel rupture achieved by leak before burst design criteria
Explosion Scenario 2- A hydrogen deflagration within the enclosure housing the compressor	Prevention of a potentially explosive atmosphere inside the compressor enclosure.
Explosion Scenario 3- Venting of hydrogen from the liquid storage tank forms localized H2/air mixture in the vent pipe that detonates.	Vent pipe length to diameter ratio to prevent detonation is present with a 45% additional safety factor.
Hazardous Material Scenario 1- Release of hydrogen from liquid storage tank	The hypoxia criterion of 12% O_2 is met within 5 m of the release point. The temperature criterion of 227 K extends to 10 m from the release point.
Hazardous Material Scenario 2- An unrelated vehicle fire at the gasoline dispensing pump.	Incident heat flux from exposure fire: $q'' = 2.7kW/m^2$
Hazardous Material Scenario 3- Seismic event where a pipe bursts (100% leak size on largest pipe).	AIR Fire = 1.81 E-02 fatalities per year
Hazardous Material Scenario 4- A hydrogen discharge where the interlock fails.	No additional risk scenarios are credible because the interlocks are not credited in the above hazard scenarios.

6 TRIAL DESIGNS

Trial fire safety designs are potential design solutions that are evaluated to determine which designs could be used to meet the fire safety goals and objectives established for the project. Trial designs may not meet some or all of the prescriptive requirements. All trial designs will meet the critical design features. These are features which, by definition, must be satisfied to be a viable design. Each trial design will be evaluated against the performance criteria calculated in Chapters 2-5 to determine which trial designs are viable options as being risk equivalent according to the principles of performance based design. Since trail designs are case-specific, an example will not be given in this template.

7 CONCLUSIONS

This performance-based methodology is intended to compare a hydrogen fueling station that meets all prescriptive-based requirements, based on the NFPA *Hydrogen Technologies Code*, NFPA 2, 2011, with designs that make alterations to a specific requirement. These alterations are site-specific and are not included in this design brief template which is only intended to establish an approach using QRA tools to meet the performance-based design requirements in NFPA 2. HyRAM provides one method to establish risk-equivalent designs.

A completed design brief should also include more information on trial designs, design assumptions, critical design features, methods of evaluation, and the record of agreement between all stakeholders. Once complete, it should be presented to the appropriate stakeholders for review and approval.

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