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APPLICATION OF QUANTITATIVE RISK ASSESSMENT FOR PERFORMANCE-BASED PERMITTING OF HYDROGEN FUELING STATIONS

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ABSTRACT

NFPA 2, Hydrogen Technologies Code, allows the use of risk-informed approaches to permitting hydrogen fueling installations, through the use of performance-based evaluations of specific hydrogen hazards. However, the hydrogen fueling industry in the United States has been reluctant to implement the performance-based option because the perception is that the required effort is cost prohibitive and there is no guarantee that the Authority Having Jurisdiction (AHJ) would accept the results. This report provides a methodology for implementing a performance-based design of an outdoor hydrogen refueling station that does not comply with specific prescriptive separation distances. Performance-based designs are a code-compliant alternative to meeting prescriptive requirements. Compliance is demonstrated by evaluating a compliant prescriptive-based refueling station design with a performance-based design approach using Quantitative Risk Assessment (QRA) methods and hydrogen risk tools. 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. Each project is unique and this template is not intended to cover unique, 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.

1.0 INTRODUCTION

This report serves as a template for implementing a performance-based design method for an outdoor hydrogen refueling station. 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 [1]. Prescriptive-based requirements are based on the National Fire Protection Association's (NFPA) Hydrogen Technologies Code, NFPA 2, 2011 Edition [2]. 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. A typical 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. This report focuses on two sections of the Design Brief: performance criteria and design scenarios. These two sections were chosen to demonstrate the use of the hydrogen risk tools in design scenarios to meet performance criteria.

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 [3] and [4].

2. PERFORMANCE CRITERIA

Performance criteria refine 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 are primarily based on risk values calculated by HyRAM. Specifically the average individual risk (AIR) risk metric will be used in the evaluation of design alternatives. The AIR value can also be compared to AIR values for other facilities and occupational hazard values, such as risk exposure at traditional gasoline stations. HyRAM is also used to calculate tenability criteria, such as radiant heat flux, temperature or peak overpressure, using the stand-alone "physics mode" which characterizes hydrogen release behavior as well as jet flame and explosion overpressure effects.

NFPA 2 provides 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 **Error! Not a valid bookmark self-reference.**.

Table 1: NFPA 2 Required Performance Criteria

Criteria Type	Performance Criteria Requirement with NFPA 2 Reference [2]	Specific Performance Criteria
Fire Conditions	No occupant who is not intimate with ignition shall be exposed to instantaneous or cumulative untenable conditions [2:5.2.2.1].	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 [5].
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 [2:5.2.2.2].	The hydrogen system is not located within a building structure that is occupied. The acceptable overpressure exposure is characterized by the Eisenberg probit model for lung hemorrhage [5].

Criteria Type	Performance Criteria Requirement with NFPA 2 Reference [2]	Specific Performance Criteria
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 to cryogenic hydrogen or pre-cooled hydrogen at the dispenser is established for this analysis [2:5.2.2.3].	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 [6]. Also, a localized temperature criteria of no lower than -50 °F (-46 °C) for exposure [7]. This criterion is based on frostbite temperatures for <5 minute exposure time.
Property Protection	The facility design shall limit the effects of all required design scenarios from causing an unacceptable level of property damage [2:5.2.2.4].	The stakeholder for this project should agree on a property protection value for an acceptable value.
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 [2:5.2.2.6].	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 [2:5.2.2.7].	The hydrogen system is not located within a building structure that is occupied. The acceptable overpressure exposure is characterized by the Eisenberg probit model for structure failure to determine if explosion affects the occupied retail store building [5].
Structural Failure	Buildings shall be designed and constructed to reasonably prevent structural failure under fire conditions for sufficient time to protect the occupants [2:5.2.2.8].	The hydrogen system is not located within a building structure that is occupied. The acceptable overpressure exposure is characterized by the Eisenberg probit model for structure failure to determine if explosion affects the occupied retail store building [5].

Probit functions are 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 [3]. To characterize occupant harm from overpressure, several probit models are available in the literature for various effects of overpressure including, lung hemorrhage, head impacts, structural collapse, and debris impact [5]. For this outdoor refueling station, structural collapse is not a credible harm scenario; therefore the Eisenberg probit model for lung hemorrhage is 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 [6].

Because this level could affect a person's ability to judge which direction is safe to move, this value is used as the performance criteria for exposure to liquid hydrogen (hazardous material exposure).

Liquid hydrogen is typically stored at 20 K (-253 °C) 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 15 mph (24 kph) and an air temperature of -40°F (-40°C) could result in frostbite with an exposure time of less than 5 minutes [7]. A localized temperature criteria of no lower than -50 °F (-46 °C) for exposure is used based on frostbite temperatures for <5 minute exposure time.

The performance criterion specified for emergency responder protection is correlated to the amount of pressure needed to collapse unreinforced concrete or cinderblock walls [5] 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 is 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, is specifically characterized using the Eisenberg probit model for structural failure.

3.0 DESIGN SCENARIOS

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. The design scenarios from NFPA 2 will be translated into plausible scenarios for the representative, outdoor hydrogen refueling station.

3.1 Assumptions

All assumptions made during the development of the design scenario should be identified and listed in the documentation. NFPA 2 assumptions are listed:

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

3.2 Required Design Scenarios

Error! Not a valid bookmark self-reference. provides an overview of each applicable design scenario and scenarios selected for the evaluation of design alternatives, with the appropriate NFPA 2 reference. For this report, only a few of the design scenarios will be discussed in detail to demonstrate the use of HyRAM and other calculations that could be used to calculate risk equivalency for the performance-based design. The Fire Scenario, Explosion Scenario 3 and Hazardous Material Scenario 3 will be analysed in this report. The fire and hazardous material scenario were selected to be included in this analysis because they provide two different demonstrations of HyRAM's capabilities. Explosion Scenario 3 was analyzed because it exhibits another approach to evaluating a design scenario without HyRAM which may be appropriate depending on the design scenario. For a complete template, all design scenarios should be analysed, using HyRAM, another scientific basis or a discussion on why the required design scenario is not applicable to the specific project.

Table 2: Design Scenarios

Required Scenario from NFPA 2 [2]	**Outdoor Refueling 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 [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 [2:5.4.3.1].	Prevention of gaseous hydrogen pressure vessel rupture.	Because of pressure relief devices and leak-before-burst design specification, no credible pressure vessel burst scenario exists for this system.
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 [2:5.4.3.2].	A hydrogen deflagration within the enclosure housing the compressor.	HyRAM peak overpressure and risk metric calculation.
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 [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 Compressed Gas Association (CGA) G-5.5.
Hazardous Material Scenario 1- Unauthorized release of hazardous materials from a single control area [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 [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 [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 [2: 5.4.4.4].	A hydrogen discharge where the interlock fails.	Discussion of layered safety features present in the system.

Required Scenario from NFPA 2 [2]	Outdoor Refueling Station Scenario	Performance Criteria Approach
Building Use Design Scenario 1 - 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. [2:5.4.5.1]	No assembly occupancies exist on or nearby the refueling station and there are no building structure exits or entrances to block, therefore this scenario will not be analyzed.	Not applicable.
Building Use Design Scenario 2 - A fire occurs 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. [2: 5.4.5.2]	There are no partially-occupied buildings with out-of-service suppression systems, therefore this scenario will not be analyzed.	Not applicable.

3.3 Fire Scenario

In this design scenario, a component associated with the hydrogen dispensing equipment is 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 are considered in this scenario. The HyRAM QRA risk tool incorporates the thermal probit model specified in the performance criteria: Tsao and Perry. HyRAM calculates the variety of potential hydrogen leak rates and sizes and resulting jet fire flame lengths and heat fluxes. These parameters in turn provide 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 HyRAM input values for all parameters for the fire design scenario are presented in
Table 3.

Table 3: Baseline Fire Design Scenario HyRAM Input Parameters

HyRAM Input Screen	HyRAM Input Parameter	User Input 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.

HyRAM Input Screen	HyRAM Input Parameter	User Input Value
	Working hours per year	6480 hrs (30 days*12 months*18 hours a day)
	Distribution	Uniform
	Max Distance	120 ft. (36.6 m) distance to lot line
	Min Distance	1 ft. (0.3 m)
Components	Compressors	0
	Cylinders	0
	Valves	7
	Instruments	10
	Joints	10
	Hoses	2
	Pipes (length)	10
	Filters	1
	Flanges	0
Piping	Pipe OD	0.5625 inch (9/16) (1.43 cm)
	Pipe wall thickness	.12575 in (0.32 cm)
	Internal Temperature	15 C (59 F)
	Internal Pressure	900 bar
	External Temperature	15 C (59 F)
	External Pressure	.101325 MPa
Pipe Leak Size for all components: Mean and Variance	0.01%	Default HyRAM values [3]
	0.10%	Default HyRAM values [3]
	1%	Default HyRAM values [3]
	10%	Default HyRAM values [3]
	100%	Default HyRAM values [3]
Ignition Probabilities- **Immediate** Ignition Probability	Hydrogen Release Rate <0.125 kg/s	0.008
	Hydrogen Release Rate0.125-6.25 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 is presumed to occur at the dispenser, only those components containing hydrogen and located at and within the dispenser are included in the component equipment counts. Also, all delayed ignition probabilities within the HyRAM model are set to zero, shown in

Table 3, so that the resulting risk values are based solely on the effects of an immediate jet fire.

The HyRAM-calculated AIR for fire based on these input parameters is 1.05 E-04 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 will be used as the comparison value when comparing various trial designs when considering the protection from fire objectives.

3.4 Explosion Scenario 3 – Detonation

This scenario gives an example of validating a performance-based scenario not using HyRAM but instead using a different scientific approach.

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. CGA 5-5, *Hydrogen Vent Systems*, sets guidelines for the design of ventilation components [9]. "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" [9].

NFPA 2 requires vent stacks for bulk liquid hydrogen systems to be designed and built according to [9]. The vent stack on the liquid hydrogen storage tank will be considered in this scenario. This vent is 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 is 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 from the tank down to a tank pressure of 120 psi. To prevent the possibility of a detonation in the vent stack, CGA G-5.5 requires a Length to Diameter (L/D) ratio of higher than 100:1.

The vent pipe consists of 3 inch (7.62 cm) (nominal) diameter schedule 40 stainless steel pipe. The inner diameter (ID) of this pipe is 3.042 inches (7.73 cm). The length of the vent pipe is 300 inches (7.62 m). The corresponding L/D ratio is:

L/D = 300 inches/3.042 inches = 98.6:1

The L/D ratio for this vent pipe meets the critical ratio required by the code. As a result, no credible detonation scenario exists for this project.

3.5 Hazardous Material Scenario 3 – External Event

This scenario demonstrates another way to use HyRAM to evaluate a performance-based design scenario.

In this design scenario, it is assumed that a seismic event occurs that results in a 100% leak of the largest pipe in the hydrogen system due to shearing. Because explosive conditions are dealt with independently in other design scenarios, only the effects of a fire are considered in this scenario. The HyRAM QRA risk tool incorporates 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 provide the resulting thermal dose that is weighed against the probit model to arrive at a potential harm value. Table 4 includes the HyRAM external event design scenario input values that have changed from the values in
Table 3. All other inputs correspond to those in
Table 3.

Table 4: Baseline External Event Design Scenario HyRAM Input Parameters

HyRAM Input Screen	Parameter	Value
Components	Compressors	0
	Cylinders	0
	Valves	0
	Instruments	0

HyRAM Input Screen	Parameter	Value
	Joints	0
	Hoses	0
	Pipes (length)	10
	Filters	0
	Flanges	0
Piping	Pipe OD	1.315 inch (3.34 cm) (1 inch nominal)
	Pipe wall thickness	.179 in (0.45 cm)
	Internal Pressure	10 bar
Pipe Leak Size for Pipe component only: Mean	0.01%	0
	0.10%	0
	1%	0
	10%	0
	100%	1
Pipe Leak Size for all components except Pipe: Mean	0.01%	0
	0.10%	0
	1%	0
	10%	0
	100%	0

The HyRAM-calculated AIR for fire based on these input parameters is 1.81 E-02 fatalities per year.

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. The AIR value represents the external event risk presented by a hydrogen refueling station that is fully compliant with the prescriptive requirements of the applicable codes. This baseline value will be used as the comparison value when comparing various trial designs when considering the protection from fire objectives.

3.6 Summary of Baseline Design Scenario Results

Table 5 provides a summary of the performance criteria results for each design scenario. The next step would be to make various “trial designs” that do not meet specific prescriptive requirements which may be infeasible given site specific conditions. These trail designs are evaluated against the baseline prescriptive criteria established in Table 5.

Table 5: Summary of Baseline Performance Criteria Results

Outdoor Refueling 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 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.

Outdoor Refueling Station Scenario	Baseline Result
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

CONCLUSION

Performance-based design is an emerging field that is useful for unique applications that cannot comply with prescriptive code requirements for many reasons. This template supports the expansion of performance-based design for hydrogen refueling applications by streamlining analysis, when possible, and allowing for flexibility as the technology advances. The HyRAM toolkit provides a practical, efficient methodology for performing QRA and is designed to analyze different types of hydrogen projects, two of which are demonstrated in this report.

The initial stages of a performance-based Design Brief are documented in this report, and the next steps are to analyze all eight applicable, required design scenarios using HyRAM or other tools to create a baseline analysis for a code-compliant design. A separation distance—or another prescriptive-based code requirement—will be altered and new risk metrics will be evaluated against the performance criteria based on the changes. Since the HyRAM software is fast to run, multiple iterations can be evaluated with limited effort to determine the best and safest path forward. This framework documents the performance-based process which will support the hydrogen safety research community.

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