**Master's thesis**

**NTNU**
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

Muhammad Faisal

# Permitting Process Using Quantitative Risk Analysis of Facilities Handling Hydrogen

Master's thesis in Reliability, Availability, Maintainability and Safety (RAMS)
Supervisor: Federico Ustolin
Co-supervisor: Lucas Michael Claussner
June 2024

NTNU
Norwegian University of
Science and Technology

Muhammad Faisal

# Permitting Process Using Quantitative Risk Analysis of Facilities Handling Hydrogen

Master's thesis in Reliability, Availability, Maintainability and Safety (RAMS)
Supervisor: Federico Ustolin
Co-supervisor: Lucas Michael Claussner
June 2024

Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

NTNU
Norwegian University of
Science and Technology

# Preface

This thesis is conducted in **RAMS (Reliability, Availability, Maintainability Safety)** at the Faculty of Engineering (IV), as part of my two-year international master's study program with a specialization in RAMS at **NTNU**. This report is written in the course TPK4950 Reliability, Availability, Maintainability, and Safety, master's Thesis, during the spring semester 2024.

The study has been carried out under the supervision of **Federico Ustolin** from the Department of Mechanical and Industrial Engineering at Norwegian University of Science and Technology (NTNU). This report is recommended for the readers who are either master's students or a higher educational qualification with background knowledge in hydrogen safety. It is beneficial if the reader has taken the course in RAMS like safety and reliability analysis, risk analysis and EiT - Hydrogen in transportation for a safe and sustainable future.

Trondheim, 10-06-2024

**Muhammad Faisal**

# Acknowledgment

I would like to acknowledge all the people who have contributed to the work related to this thesis. First of all, I would like to thank my supervisor Federico Ustolin for his continuous support and guidance through weekly meetings and discussions right through the semester. His prior knowledge and expertise within the field of hydrogen safety helped me develop a better understanding of the background and the relevant topics in detail. Furthermore, I would also like to thank my co-supervisor Lucas Michael Claussner who helped me during the writing of my thesis by giving positive feedback for improvements. These key contributors have played a key role and helped me in composing thesis report. Lastly, I want to thank myself for not giving up.

M. Faisal

# Abstract

Hydrogen is a promising alternative fuel due to its clean burning properties and high energy content. However, its low density poses storage challenges. The demand for hydrogen is expected to grow, reaching 180 million tons annually by 2050. This study combines two studies on risk assessment for hydrogen facilities. In the beginning, it explores the regulatory procedures for permitting hydrogen processing facilities and proposes a risk assessment methodology using quantitative risk analysis (QRA). It emphasizes the importance of proper handling and storage due to hydrogen's hazardous nature, and leverages guidelines from Vysus Group for a standardized approach. Later, it focuses on applying HyRAM+ software to assess the safety of hydrogen refuelling stations (HRS). It presents three case studies with varying configurations to analyse how design choices impact risk. The study calculates key risk metrics and examines factors like thermal effects and hydrogen leak dispersion. By considering multiple systems and interactions, this research provides a framework to design safety measures and evacuation procedures for HRS facilities, promoting the safe implementation of hydrogen technologies.

# Contents

# List of Figures

# List of Tables

# 1. Introduction

This chapter provides a brief introduction to the topic under discussion. It starts by giving a brief description of physical properties of hydrogen and short background about hydrogen demand over the years. The purpose of this chapter is to establish the context within which the thesis was created, to understand the significance of the topic under consideration, and to outline the specific objectives of the thesis.

## 1.1. Background

In this era of transition from conventional fuels to green energy and more sustainable sources of energy, and as we move away from fossil fuels, hydrogen emerges as a promising alternative (Kovač et al., 2021). Unlike fossil fuels, it burns cleanly without emitting $CO_2$ during combustion, producing only water vapor (Rievaj et al., 2019). Also, hydrogen contains a specific amount of energy by weight, and hydrogen doesn’t exist freely in nature, it can be produced from abundant resources like water.

Hydrogen gas ($H_2$) exhibits unique physical properties, making it distinct from other common fuels. At 0°C and 1 bar, its gaseous density is 0.0890 kg/m³, which is less than that of natural gas. When in liquid form at -253°C and 1 bar, hydrogen has a density of 70.79 kg/m³, roughly one-sixth that of natural gas. Hydrogen's boiling point is -252.76°C at 1 bar, significantly lower than liquefied natural gas (LNG), which boils at about 90°C higher. In terms of energy, hydrogen has a lower heating value (LHV) of 120.1 MJ/kg, which is three times that of gasoline. However, its energy density is 0.01 MJ/L, approximately one-third of natural gas. The specific energy (LHV) of hydrogen is 8.5 MJ/L, also about one-third that of LNG. When it comes to combustion, hydrogen's flame velocity is 346 cm/s, eight times that of methane, and it has an ignition range of 4-77% in air by volume, which is six times wider than methane's. The autoignition temperature of hydrogen is 585°C, much higher than gasoline's 220°C. Additionally, hydrogen requires an ignition energy of just 0.02 MJ/L, making it ten times easier to ignite compared to methane (IEA, 2019).

## 1.2. Hydrogen Demand

Hydrogen is increasingly regarded as a viable substitute to conventional fuels and natural gas, serving as a valuable complement to other sustainable energy alternatives such as electricity and advanced biofuels. Notably, hydrogen fuel cell electric vehicles (FCEVs) come with distinct advantages, including shorter refilling times, extended vehicle mileage capabilities, and reduced space requirements for storage.

Projections indicate that the North American FCEV market is poised for significant growth, with expectations to reach a milestone of one million units in circulation by the year 2030. By 2020, hydrogen demand is projected to reach approximately 80 million tons annually and is predicted to soar to over 183 million tons annually by 2050, as illustrated in Figure 1.1 below.

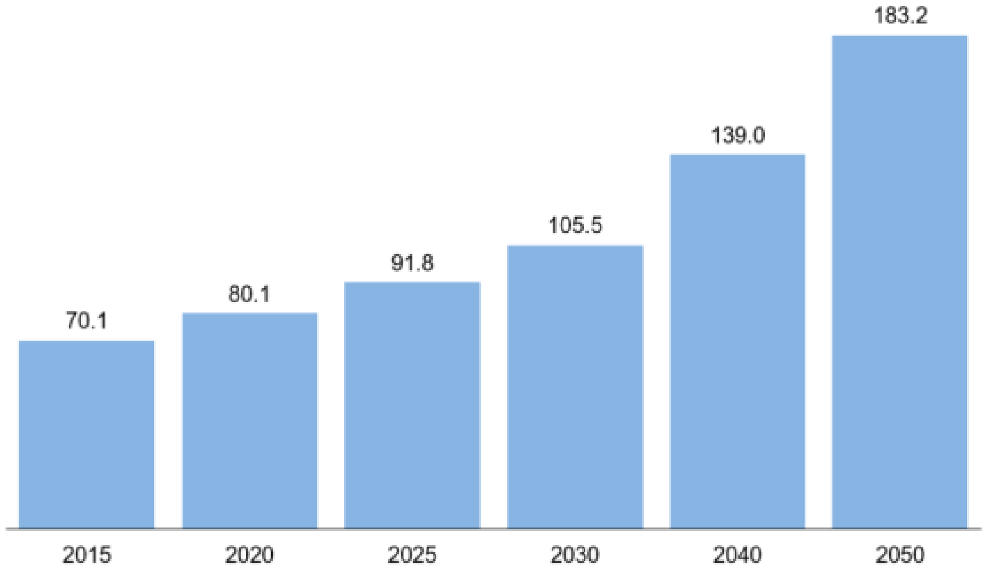


***Figure 1.1 World Hydrogen Demand (million tons/year) (Tanvir, 2019)***

Gas producers and startups are building fuelling stations and hydrogen liquefaction plants. Hydrogen storage is vital for various applications, including power, transport, and research on improving storage methods is ongoing worldwide.

With the passage of time, excitement around fuel cell vehicles as a clean alternative to gasoline-powered cars is increasing. These vehicles boast impressive efficiency and produce zero emissions from the tailpipe, making them a frontrunner in the fight against climate change. Recognizing the potential of hydrogen as a sustainable fuel source, the European Commission recently highlighted its ability to decarbonize various industries, particularly transportation, in the coming years.

Before 2021, the number of hydrogen-powered vehicles on the road globally remained limited, including cars, trucks, and even public transportation vehicles. The infrastructure to support these vehicles was also in its early stages, with only a handful of hydrogen refuelling stations available worldwide (Ajanovic & Haas, 2018).

## 1.3. Hydrogen Refuelling Station (HRS)

The increase in number of hydrogen fuel cell vehicles is resulting in demand for dedicated hydrogen filling stations. Building these stations require cautious planning, robust and advance engineering, and safe construction of infrastructure to meet the needs of these vehicles (Li et al., 2018).

The design and infrastructure of a hydrogen refuelling station (HRS) is almost same as a conventional gas filling station, but they also contain some additional components required to optimize the system with hydrogen powered vehicles. Additionally, storage, compression and dispensing of hydrogen demand some modifications and make HRS different from typical gas station. Design and components of Hydrogen Refuelling Station (HRS) are discussed in detail in “Methodology” Section.

# 2. State of the art on Risk Assessment with Focus on Hydrogen Technologies

This chapter summarizes the findings and results of the specialization project conducted in the previous semester. It offers a brief introduction to the DSB Theme Report and DSB Guidance Report, explaining how these documents are utilized to implement risk assessment techniques for facilities handling flammable substances.

## 2.1. Directorate for Social Security and Emergency Preparedness (DSB) Report

The guidelines are used in quantitative risk assessments to establish risk contours around facilities handling hazardous substances. These contours are crucial in defining consideration zones for land-use planning and aim to minimize variations in assessment outcomes due to differences in historical data, tools, and methodologies. The guidelines are specifically designed for assessing risks associated with incidents that could potentially pose a threat to the nearby population in the vicinity of facilities dealing with hazardous substances. The regulatory framework for acceptable risks to third parties near such facilities is outlined in two Norwegian DSB reports, namely the DSB Theme Report ((DSB), 2012) and the DSB Guidance Report ((DSB), 2016). The guidelines are applicable to all hazardous plants, regardless of their size or risk level. Risk assessments should be comprehensive, using realistic estimates and avoiding overly conservative or optimistic approaches. Key terms such as iso-contour, risk contour, consideration zone, best estimate, top event, sample space modelling, and sample space are defined.

This report also provides a detailed process for preparing a quantitative risk analysis for plants handling hydrogen and other hazardous substances. The process involves understanding the plant, selecting the appropriate approach and methodology, considering external conditions, design, and barriers. The process follows steps defined in NS 5814:2008 and shown in Table 1, which can be used for mapping the plant and providing essential elements for the initial phase of the project.

***Table 1. Table Risk assessment steps covered by NS 5814:2008 (Vysus, 2021)***

| | Steps covered |
|---|---|
| **Not Covered** | Defining framework conditions |
| | Establishing risk acceptance criteria |
| | Implementation |
| **Planning** | Describing problems and formulating objectives |
| | Organizing work |
| | Selecting data sources and method |
| | Defining system description |
| **Risk Analysis** | Identifying hazardous events |
| | Cause, frequency and consequence analysis |
| | Calculating risk |
| **Risk evaluation** | Comparing with criteria of risk acceptance |
| | Identifying measures for effectiveness and control |
| | Discussing, documenting and concluding |

When dealing with modifications or expansions of an existing plant, it is crucial to draw upon operational and maintenance experience, as well as documentation from past incidents, accidents, audits, and internal audits. The individual conducting the analysis should have a thorough understanding of the subject and should begin with a site visit.

Further activities, methodologies, and tool selections are planned based on the plant's complexity, surrounding environment, and underlying assumptions. Mitigative measures should be evaluated for these conditions, and residual risk should be factored into the calculation of risk contours. To ensure accuracy and adherence to the "As Low as Reasonably Practicable" (ALARP) principle, the design and protective barriers of the plant should be considered.

## 2.2. Risk Assessment

### 2.2.1. Risk Analysis

#### Identification of Hazards, barriers & Unwanted Events

HAZID is a crucial component of a QRA, identifying potential hazards on a plant by examining systems, tools, and organizational conditions (Huser, 2021). It aims to identify effective barriers to mitigate the problem's effects. HAZID can be used for fault tree studies and HAZOP reports. The risk analysis should also detail the movement of dangerous materials and the events that occur during movement and transfer, with transfer actions being the most significant contributor to risk numbers.

#### Top Events Establishment and Developing of Event Tree

Risk analysis and Hazard Identification (HAZID) professionals collaborate with companies to determine top events for analysis. These decisions should be substantiated and documented in the analysis report. Event trees can be used to understand how events, actions, or barriers can change an event. HAZOP studies and reliability analyses are used to determine the likelihood of safety systems failing or being activated. Response times should also be clear. Leak frequencies are determined using different methods, such as plant information and frequency format. Complex models require more specific details about leak origins, which can be changed during the planning phase or by using similar plant information. Simple models can accurately represent design conditions, while more in-depth analysis is needed. A visual representation of risk contours is provided in Figure 2.1, showing that as leak rates increase and representative spreading decreases, the frequency decreases. If the frequency for all leak scenarios is amplified uniformly by a certain factor, the risk contour expands accordingly.

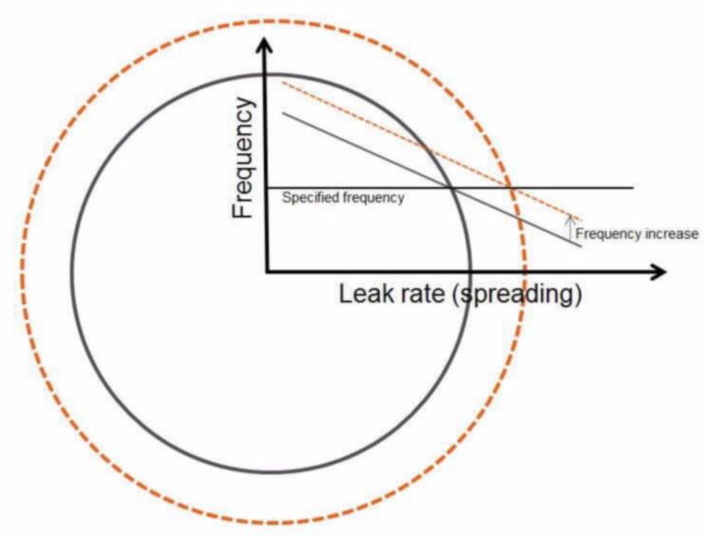


***Figure 2.1 Illustration of how the selection of frequency model affects risk contour (Vysus, 2021)***

### Leak Frequency Models

Leak frequency models are essential tools for assessing failures in process plants. The UK Health and Safety Executive (HSE) model provides detailed information on failure frequencies, particularly for equipment with leakage as the failure mode. It includes data for specific components like flanges and valves and categorizes requirements by hole size for certain equipment. The OGP model is structured differently, having data for more process components and distinguishing between full leaks, limited leaks, and zero pressure leaks. It also includes frequency assessments for tank ruptures, although these assessments tend to yield slightly lower frequency values. The PLOFAM model is a comprehensive and advanced tool for estimating leak frequencies in process plants, leveraging offshore data from the UK and Norwegian offshore sectors from 1992 to 2015.

The HSE model is generally recommended for leaks from transfer hoses, but generic frequencies for BLEVE events should be evaluated. Assessments should focus on evaluating the likelihood of extended fires exposing tanks containing substances capable of causing a BLEVE. A single event tree should be established to gauge the frequencies of prolonged fires and the probability of them leading to tank exposure. Generic frequencies offered by the HSE should be avoided for unbiased risk contour calculations. For cold BLEVE events, the HSE model is recommended. Historical data of leak frequencies may be available in some plants or companies, but reliability must be proven.

### HyRAM Software

HyRAM, a widely used model for assessing hydrogen leaks, has a degree of uncertainty due to its calculation of frequencies based on hole size and equipment size. To ensure a more accurate risk representation, it is recommended to adjust the frequencies generated by HyRAM downwards by a factor of 10-25. PLOFAM, a model for offshore process leaks in the North Sea, has been validated for onshore process plants but has raised questions about its applicability to onshore plants. HyRAM's reliability may vary when applied to larger equipment. Despite its uncertainty, it is recommended for hydrogen plants due to its ease of use and consistency. It is also recommended for assessing liquid hydrogen leaks, as there are no established models that surpass HyRAM for liquid hydrogen leaks. However, a more rigorously validated model for hydrogen leaks is needed in the long term.

### Leak Dispersion Analysis

Dispersion and explosion analysis require a detailed description of the release process, which involves determining the leak rate out of the hole and the phase and thermodynamic state just outside the hole. Fluid leaks, whether gas or liquid, depend on the fluid type and its thermodynamic state. Advanced leak models are suitable for complex scenarios, while hole and pipe size can affect leak rates. The outcome of a gas leak depends on whether it's a pure gas leak or a multiphase one. In cases with critical flow and an over-expanded jet, precise mixing levels are essential for accurate computational fluid dynamics (CFD) simulations. In two-phase or pure liquid leaks, liquid can atomize, creating a spray where droplets may fall and accumulate as a liquid pool. Special assessments are necessary for liquids with multiple components and local weather conditions.

Risk contours in plant operations require accurate modelling of simulated scenarios. Two types of simulation tools for far field effects calculation are empirical tools and Computational Fluid Dynamics (CFD) tools. Empirical tools use simplified physical models to replicate experimental conditions, while CFD tools aim to simulate release physics but integrate simplified models for faster computation. Both tools can yield similar outcomes for flammability or toxicity in scenarios with open spaces and minimal obstructions. However, for facilities with complex terrain, large buildings, intricate diffuse releases, congested areas, or unique scenarios, CFD tools are better suited for dispersion modelling. Empirical tools can be non-conservative in these cases, as they may not accurately represent physics in certain directions. The choice of modelling tool for the far field can significantly impact risk contours as shown in Figure 2.2, necessitating clear documentation in the risk analysis process.

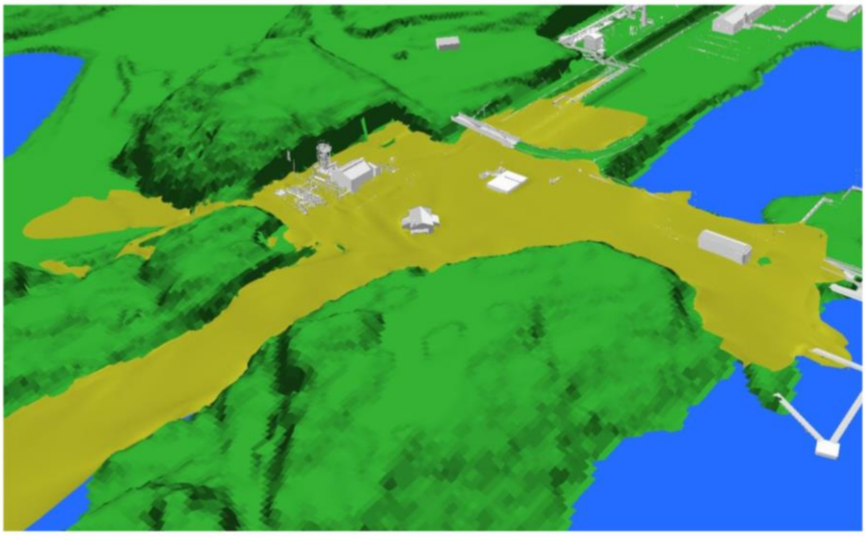


***Figure 2.2 Illustration of how the selection of frequency model affects risk contour (Vysus, 2021)***

Figure 2.3 shows two scenarios of a leak, one with a non-obstructed release and the other with a 3x3 meter obstruction. The illustration demonstrates that a leak's dispersion pattern and field can change significantly when encountering an obstacle. Turbulent fluctuations and wind field changes can cause real cloud field fluctuations, and CFD can model these fluctuations but requires complex simulations.

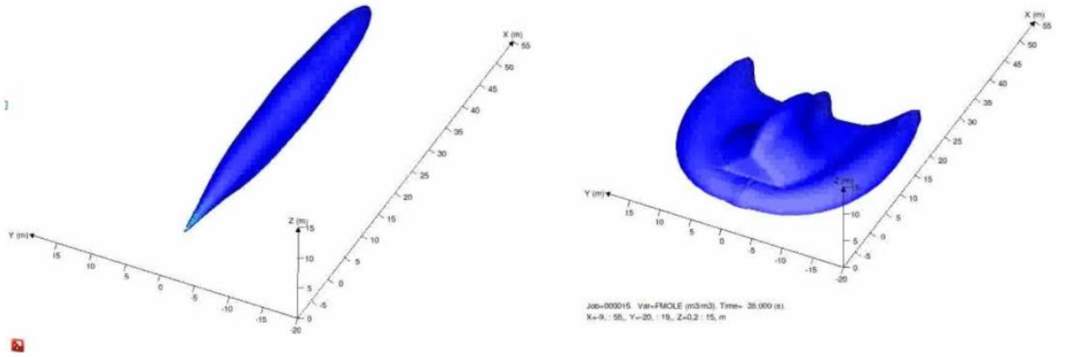


***Figure 2.3 non-obstructed release (Vysus, 2021)***

## Ignition Analysis

Ignition involves the release of flammable gas through discharge or vapor evaporation, leading to a fire. The likelihood of ignition is determined by the probability of a flammable gas cloud encountering an ignition source and the likelihood of ignition upon such exposure, known as ignition intensity. Ignition can occur immediately after the release, resulting in a fire, or after a delay, leading to an explosion or flashfire. Models that evaluate probability handle the relationship between immediate and delayed ignition in various ways, influencing the overall likelihood of delayed ignition incidents. Different types of ignition sources exist, both inside and outside the plant. For land use planning, the total ignition probability is set at 1.0, but separate evaluations of ignition sources are necessary for risk contours not intended for land use planning. Four primary ignition models are used to address this issue: RIVM, OGP, MISOF, and HyRAM. These models differ in how they assess the likelihood of exposure to ignition sources and ignition intensity, requiring varying levels of information and calling for either simplified or comprehensive analysis.

- **Hydrogen Ignition Model:** Hydrogen is highly flammable and requires special models for ignition due to its flammability range. The Sandia National Laboratories recommend the HyRAM model, which states that 2/3 of the ignition probability is immediate and 1/3 is delayed. However, it lacks refinement for leaks above 6.25 kg/s. A new model, based on DNV, improves ignition modelling for various leak rates and considers higher ignition probabilities for large leaks. The HYEX model, an adjusted HyRAM model, is recommended for hydrogen leaks due to no recent studies suggesting adjustments. The HYEX model is also recommended for tank rupture and liquid hydrogen leakage. However, there is uncertainty about delayed ignition and explosion calculations in tank ruptures. The model may be suitable for jet leaks, but adjustments may become necessary as more experience is gained with LH2 emissions and ignition. Early ignition accounts for 2/3 of the total ignition probability, while delayed ignition is a function of room volume.

### Explosion Analysis

Explosions from gas, liquid, and dust cause rapid pressure build-up and detonations due to high equipment density and long flame paths. The size of the flammable cloud influences societal risk contours. Controlling cloud size during ignition is crucial for assessing strong explosions. A range of leak rates is recommended for petroleum industry process plants, with smaller releases needed for inside buildings or process equipment.

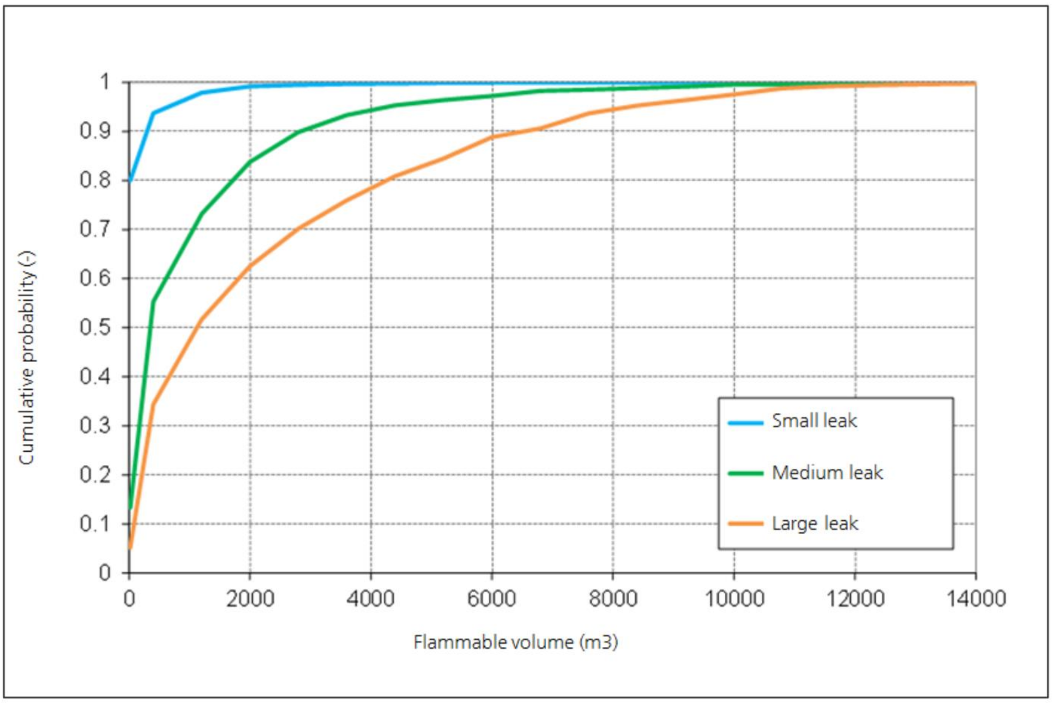


***Figure 2.4 Cumulative probability distribution of flammable cloud size (Example) (Vysus, 2021)***

Within Figure 2.4, we observe an illustrative cumulative probability distribution depicting flammable cloud size concerning different leak sizes. Notably, the figure 2.4 indicates that there is a 78% likelihood that a substantial leak will yield a flammable cloud size of 4,000 cubic meters or smaller. Additionally, there is a 90% probability associated with achieving a cloud size of 6,500 cubic meters or less.

The relationship between the size of ignited clouds and their frequency of occurrence can be established by combining data regarding flammable cloud sizes (as shown in Figure 2.4) and information about ignition sources (as depicted in Figure 2.5). The choice of an explosion model should be made in conjunction with the selection of an ignition probability model.

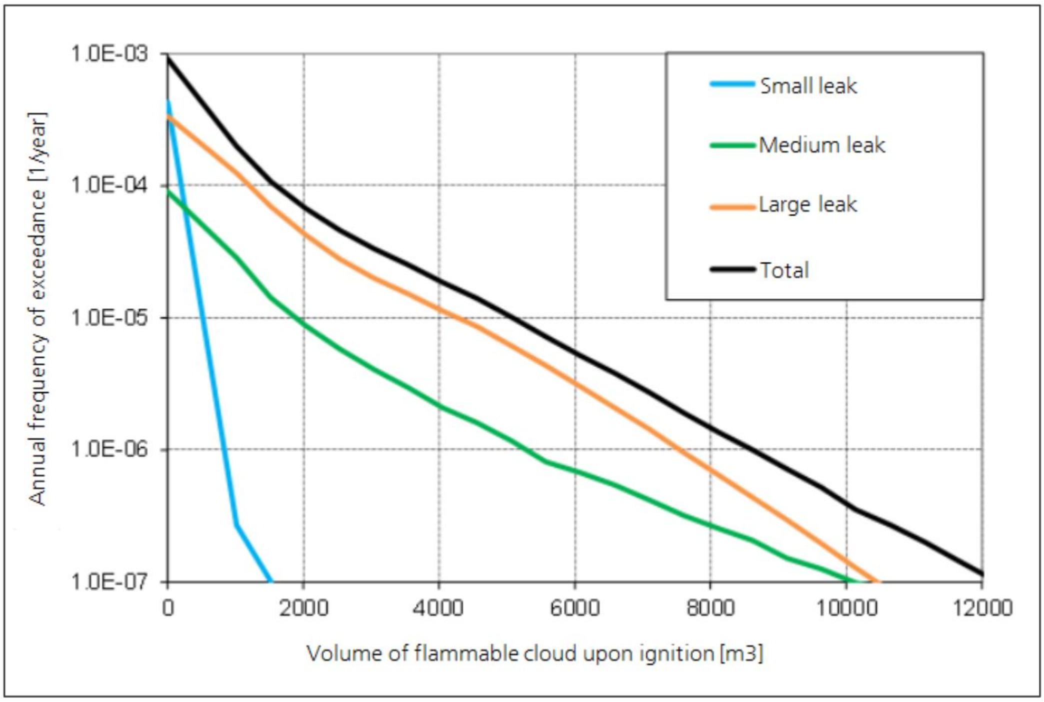


***Figure 2.5 Example of ignited cloud size exceedance frequency graph (Vysus, 2021)***

In Figure 2.5, we can observe an exemplar graph representing the frequency of exceeding ignited cloud sizes based on various leak sizes. Specifically, the figure 2.5 provides data indicating that the overall frequency of igniting a cloud equal to or larger than 5,000 cubic meters is 1E-5 per year. Additionally, the total frequency associated with ignited releases stands at 1E-3 per year.

The risk level outside a flammable cloud can be determined by estimating source overpressure within the cloud using simpler models or the multi-energy method. The recommended standard is NORSOK Z-013, which requires computational fluid dynamics simulations for gas dispersion and explosion overpressure. A good 3D geometry model is essential for calculating explosion overpressure. The efficiency factor, which indicates the proportion of combustion energy contributing to an ideal pressure wave, is crucial.

### Fire Analysis

The choice of scenarios significantly impacts the size of risk contours in fire simulation. The determination of combustion energy is typically established during scenario definition, and the results are less reliant on the simulation tool compared to dispersion modelling. It's important to categorize fires into three types, and all of these fire types must be considered in the risk analysis.

- **Flash Fires:** Flash fires involve the combustion of flammable gas, liquid droplets, or dust in air, causing large amounts of material to be burned quickly. The combustion occurs in flammable concentrations, but temperature rise can push the unburned cloud outwards. Lethal heat intensity extends beyond the flammable cloud, and consequences can occur outside the original flammable cloud. High equipment density accelerates combustion and pressure build-up, potentially leading to explosions or detonation. Flash fires have short durations and can cause personnel injury but require accurate models of the flammable cloud.

- **Diffuse Fires:** A liquid leak within a bund can ignite flammable gas, primarily influenced by gas availability and the space inside. Geometric factors like bund area are less crucial. Diffuse fires last long and emit heat, while pool fires produce smoke, reducing radiation, though strong winds can counteract this effect.
- **Jet Fires:** High-pressure gas or liquid releases create a high-pressure jet or spray, causing intense burning and heat emission. Jet fires can last for extended periods, with little difference in heat loads between gas jet fires and spray fires.

Fire calculations depend on the selection of simulation tools, but if obstacles significantly affect the characteristics and consequences of a fire, CFD should be considered. Hydrocarbons have higher combustion energy, resulting in a higher fire risk. Smoke from the fire must also be considered, especially when toxic gases are generated.

### BLEVE and other Events

A Boiling Liquid Expanding Vapor Explosion (BLEVE) occurs when a pressure vessel containing a fluid above its boiling point temperature ruptures, causing various scenarios such as substantial heat, projectiles, and overpressure waves. BLEVEs can occur due to weakened or unaffected tanks, exposure to heat, or failure without an external heat source. The explosion can be categorized as physical if mechanical, or chemical if a chemical reaction contributes to the consequence severity.

Pressure waves can be generated due to pressurized gas expansion, which can generate a primary pressure wave in the environment. This wave is crucial in risk assessments when conditions apply. In a "cold BLEVE," when the liquid temperature exceeds its boiling point but isn't superheated, the liquid boils upon rupture. However, this boiling isn't rapid enough to generate a strong pressure wave, and a fireball may form if the liquid is flammable.

In a BLEVE event, the tank rupture can propel fragments of the tank shell as projectiles, posing risks. For tanks with mixtures lacking a clear boiling point, estimating the liquid that atomizes is crucial, impacting fire and safety assessments. Comprehensive risk management during BLEVE scenarios is essential.

Low-temperature liquid tanks can experience layer splitting due to density differences, leading to increased evaporation and over-pressurization risk. Roll-over risk is a concern, especially in near-atmospheric pressure tanks. Operational control measures are crucial for managing these risks. Boil-over in oil storage tanks can cause water to boil and expand, increasing fire intensity and hazard distances.

### Establishment of Risk Contours

To generate accurate risk contours for a plant, it is essential to consider a sufficient variety of scenarios. Symmetry considerations and simplified physical adjustments can reduce the number of necessary simulations, facilitating a more extensive evaluation. The choice between empirical tools and computational fluid dynamics (CFD) tools for simulating scenarios depends on the required physical accuracy. Even if the leak frequency distribution is representative, ensuring a sufficient number of incidents is crucial to minimize uncertainty in the risk contours.

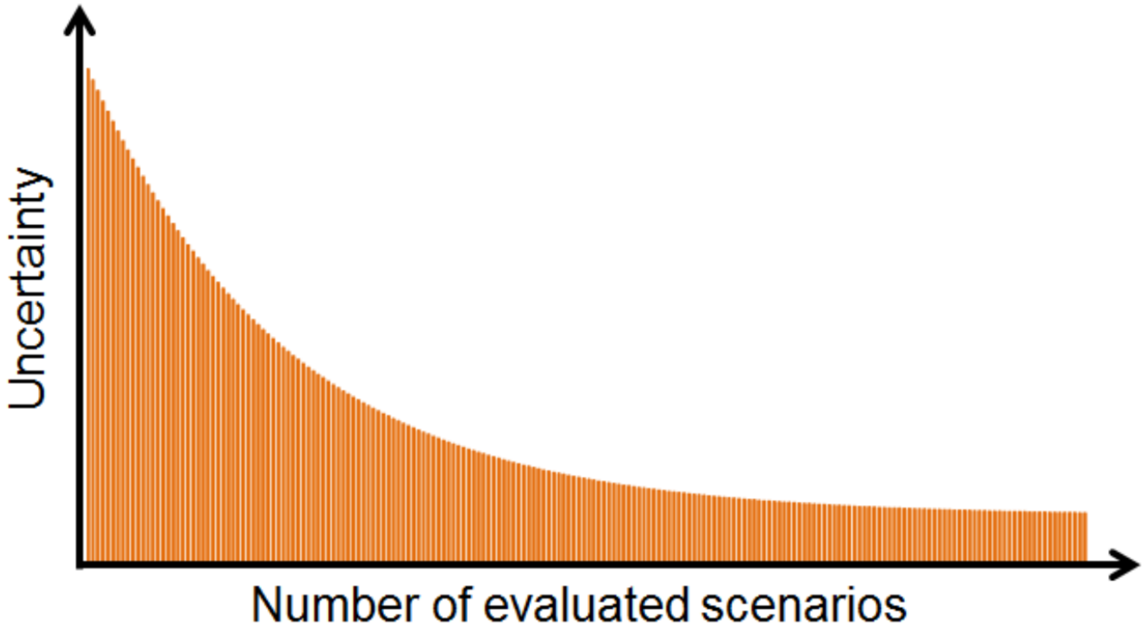


***Figure 2.6 Uncertainty and evaluated scenarios (Vysus, 2021)***

To establish accurate risk contours, facilities must consider various scenarios and calculate calculations for impact assessments as done in Figure 2.6 above. To achieve unbiased risk contours, three steps are recommended: run sufficient simulations to capture main physics in all relevant scenarios, use simulated scenarios to estimate similar scenarios, and smooth the result field if irregularities persist. Factors affecting risk contours include the number of simulations, interpolation of simulated scenarios, number of leak points, simulated rates, smoothing of the risk contours, and refining in critical areas.

### Describing Uncertainties

Risk analysis should consider factors that significantly affect risk contours, such as frequency evaluation, physical modelling, and modelling of possible outcomes. These factors should be assessed to ensure unbiased risk estimates. Determining the frequency of the top event in risk assessments involves careful consideration of various factors. It starts with the use of precise physical models that accurately represent the underlying physics of potential scenarios, particularly focusing on mechanisms to reduce the occurrence of leaks. Uncertainties related to probit functions and threshold values must be thoroughly discussed to assess their potential impact on risk assessments. The number of scenarios considered should be based on the best estimate and should take into account facility-specific attributes. Sensitivity analyses play a crucial role in identifying key parameters or assumptions that can significantly affect risk contours. Additionally, any special assessments that introduce uncertainty into risk contours should be addressed comprehensively to ensure a robust and reliable risk assessment process.

### 2.2.2. Vulnerability Criteria

#### Vulnerability Criteria’s Importance for Risk Contours

To create a fatality risk contour, a model that encompasses all possible events and the corresponding exposure levels such as toxic substance concentration, flammability, heat load, and explosion load needs to be developed. The selected thresholds for fatality levels significantly influence the dimensions of the risk contours. As the distance from the leakage point increases, the concentration of toxic substances diminishes, thereby affecting the extent of the risk contours.

Figure 2.7 provides a visual representation of how the selection of vulnerability criteria, specifically for toxicity assessment, can significantly influence the risk contours for a given event. Within this context, it's essential to note that the concentration of the toxic substance diminishes as one moves farther away from the point of leakage.

What stands out in this illustration is that when the criterion level for fatality is established at a lower concentration, as indicated by the orange curve, or at a slightly higher concentration, as depicted by the green curve, distinct risk contours emerge for the same scenario simulation. This underscores the pivotal role that the choice of vulnerability criteria plays in shaping the risk assessment outcomes.

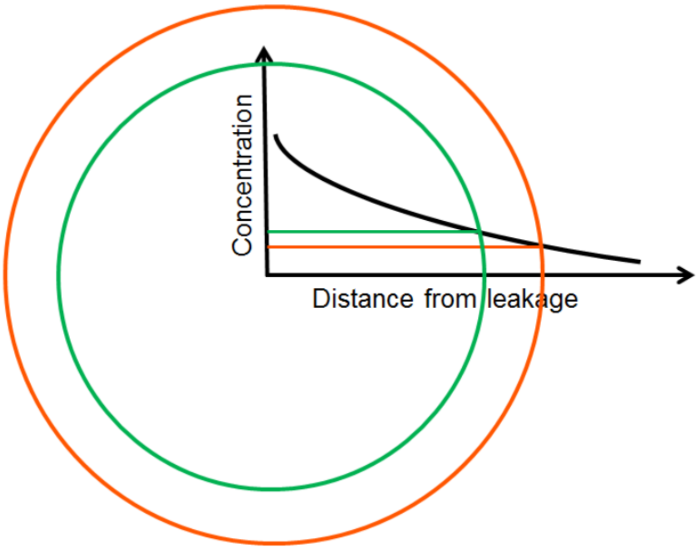


***Figure 2.7 Effect of vulnerability criterion for toxicity on risk contours (Vysus, 2021)***

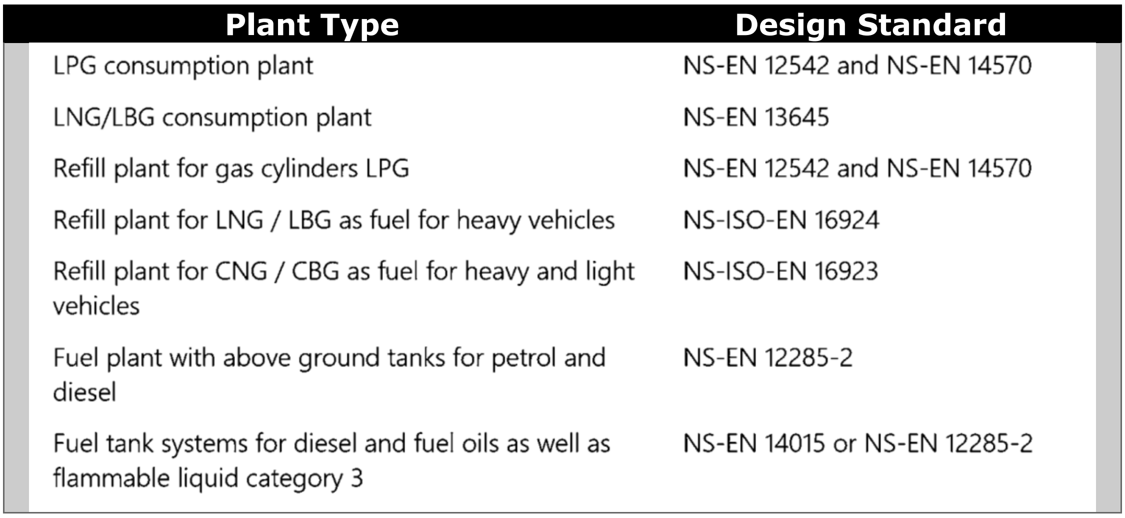
#### Vulnerability Criteria Recommendation

Probit functions are advised for calculating risk contours, as they determine the maximum exposure time corresponding to various probabilities of fatality. In the absence of a probit function, threshold values can be employed to estimate consequences. For the most objective risk contours, it is recommended to use a threshold value that represents 50% lethality.

### 2.2.3. Simplified Methodology

Certain plant types may require a simplified safety distance calculation method, as per guidelines for hazardous substance registration. These guidelines define plant units as assemblies of tanks, pipes, and equipment, with reference to relevant standards for each plant type (see Table 2). Further guidelines are required before implementation.

*Table 2. Relevant Design Standards (Vysus, 2021)*



| Plant Type | Design Standard |
|---|---|
| LPG consumption plant | NS-EN 12542 and NS-EN 14570 |
| LNG/LBG consumption plant | NS-EN 13645 |
| Refill plant for gas cylinders LPG | NS-EN 12542 and NS-EN 14570 |
| Refill plant for LNG / LBG as fuel for heavy vehicles | NS-ISO-EN 16924 |
| Refill plant for CNG / CBG as fuel for heavy and light vehicles | NS-ISO-EN 16923 |
| Fuel plant with above ground tanks for petrol and diesel | NS-EN 12285-2 |
| Fuel tank systems for diesel and fuel oils as well as flammable liquid category 3 | NS-EN 14015 or NS-EN 12285-2 |

### 2.2.4. Presentation of Results

#### Communication of Small Frequencies

Risk analyses offer valuable insights into the interpretation of risk outcomes and enable the comparison of a facility's calculated risk level with everyday societal hazards. One approach to gain perspective is by contrasting individual risk values in the vicinity of the facility with common fatality rates, as exemplified in Figure 2.9. For instance, in the Norwegian context, the facility's presence signifies an incremental risk of under one percent for public members and one in a million for areas falling outside the consideration zones.

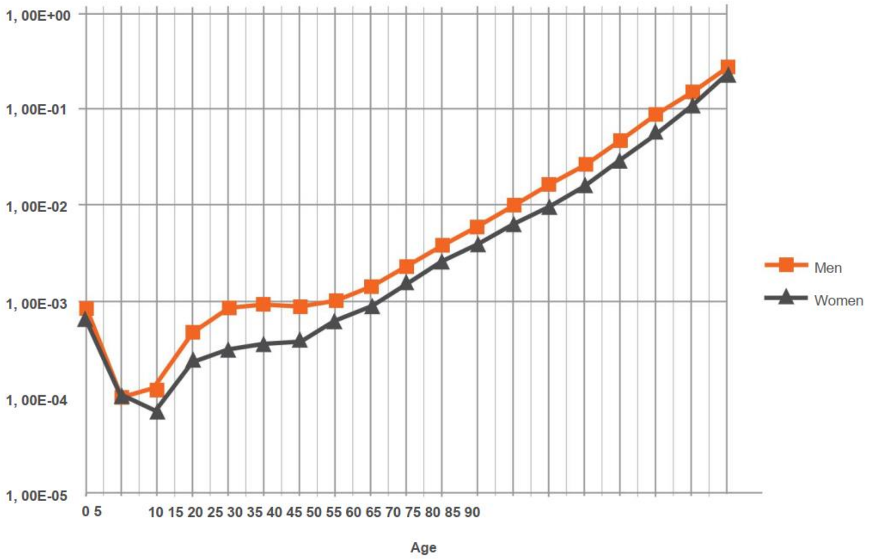


***Figure 2.8 Fatality rates according to age in Norway, (2006-2010) 5-year groups (Vysus, 2021)***

### Results

The primary results should encompass key elements such as the frequency distribution of top events, ignition probabilities, individual risk contours, and illustrations of significant events pertinent to external emergency preparedness. Intermediate results serve as valuable tools for conveying insights into risk factors and preparedness strategies, including risk contours related to exposure to flammable or toxic substances, fire loads, and explosion loads. Risk contours should be plotted on maps or photos for clarity as shown in figure 2. 10 and eliminate potential errors associated with manual reproduction. In the analysis of future facilities, it is advisable to superimpose risk contours onto the existing local development plan, spatial plan, or planning permission map, especially when considering expansions or substantial alterations to existing facilities. This practice should also extend to affected development plans in such cases.

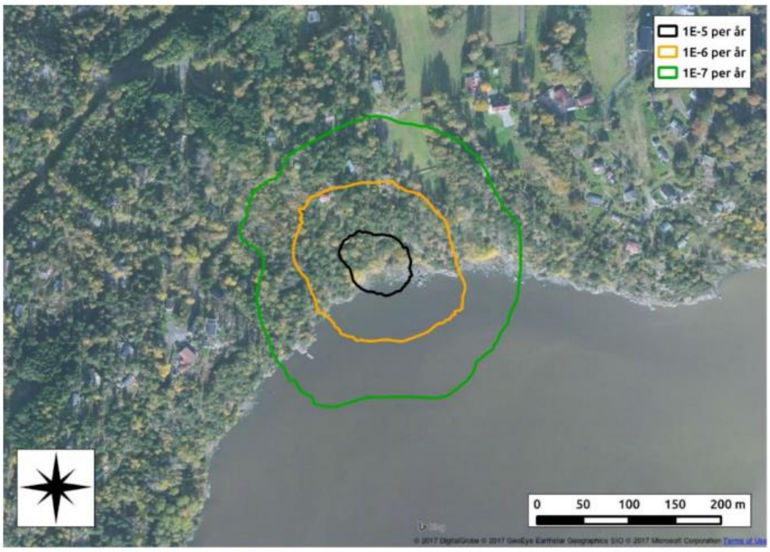


***Figure 2.9 Risk contours (aerial image) with randomly selected location (Vysus, 2021)***

### Application of consideration zones above the ground

Risk contours can be displayed either as a maximum projection or as varying with elevation above ground level. Projected representations offer a single diagram that includes all iso-contours at their maximum extent. These contours can be plotted at different elevations or projected onto the ground. Projected risk contours are generally recommended for consideration zones, as they provide consistent consideration zones for both high-rise buildings and detached houses. However, significant differences between ground-level and high-elevation risk contours should be addressed in the risk analysis.

An alternative to using a projected representation is to plot risk contours at various elevations. For example, as shown in Figure 2.11, the exposure to flammable gas varies with elevation. To capture this elevation effect in a two-dimensional (2D) representation, risk contours can be generated at multiple elevations. If this detailed level of information is unnecessary, the farthest point in the z-direction can be projected onto the ground to simplify the illustration.

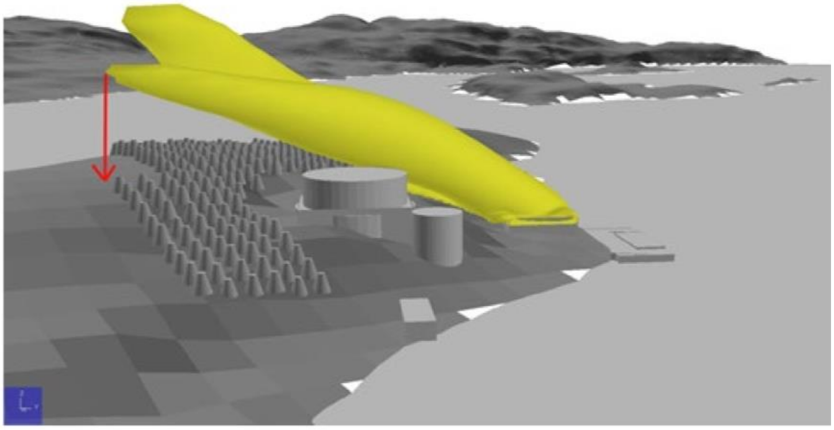


***Figure 2.10 Example of varying flammable gas exposure with variation in elevation (Vysus, 2021)***

The theme report defines consideration zones for land planning, emphasizing that risk levels are geographical and not individual, and occupancy factors cannot reduce risk levels. However, exposure time can be considered for specific group risk calculations.

## 2.2.5. Scenarios for Emergency Preparedness

Risk contours represent the cumulative risk exposure for third parties, considering all potential scenarios. Nevertheless, risk analysis permits the identification of contingency scenarios that align with calculated risk contours. It is advisable to present illustrative scenarios for emergency situations corresponding to risk contours of 1E-5, 1E-6, and 1E-7 per year. In particular, worst-case scenarios can be visually depicted through exposure area plots.

## 2.3. Summary

The study provides a detailed examination of regulatory procedures for hydrogen processing facilities, emphasizing the use of Quantitative Risk Analysis (QRA) to identify and assess potential risks. It highlights the necessity for specialized handling and storage practices for hydrogen and advocates for a standardized, systematic approach to QRA to ensure safety and responsible management. The study recommends that stakeholders in the hydrogen sector become proficient in these regulatory procedures and employ QRA methodologies to evaluate risks comprehensively. This approach will aid in understanding potential hazards and implementing effective risk mitigation strategies. The adoption of the Report Guidelines for Quantitative Risk Analysis of Facilities Handling Hazardous Substances is recommended to ensure consistency and accuracy in risk assessments. By following these guidelines, stakeholders can enhance safety and contribute to the sustainable growth of the hydrogen industry. Future analyses should focus on the unique properties of hydrogen to provide further insights and improve safety in hydrogen storage and operations.

# 3. Methodology

This chapter provides a brief introduction to HyRAM and highlights some of its key features. It also outlines the quantitative risk analysis (QRA) approach. Finally, three different case studies are presented, demonstrating the application of QRA using the HyRAM software.

## 3.1. HyRAM+ Software

HyRAM+ is a software toolkit designed to evaluate the safety of facilities handling hydrogen and other fuels across various applications, including refuelling stations. It employs both deterministic and probabilistic models to analyse and assess accident scenarios, predict physical outcomes, and evaluate other potential dangers related to fuel. Version 5.0 of HyRAM+ incorporates features from earlier versions, such as failure probabilities for equipment in both gaseous and liquid phases, and probabilistic models for assessing the effects of heat flux on humans and other facilities (Ehrhart & Hecht, 2022). The software has been validated through computational and experimental methods, covering various aspects of fuel releases. Advanced features enable it to manage cryogenic fluids and blended mixtures, add two additional components for diverse applications, customize risk analysis sections, and account for unconfined overpressure and impulse behaviour in delayed ignition assessments. HyRAM+ serves as a practical platform using a standardized framework for conducting hydrogen Quantitative Risk Assessment (QRA) to ensure reliable and progressive results. It is structured in a modular format, allowing updates based on advancements in scientific knowledge and engineering principles related to hydrogen systems (Groth et al., 2017) .

## 3.2. Quantitative Risk Analysis (QRA) and Risk Metrices

Quantitative Risk Assessment (QRA) is a structured method used to calculate and evaluate the probabilities associated with various decisions across different fields. It aids in estimating potential outcomes and the likelihood of fatalities in the event of multiple release scenarios and varying frequencies (Ehrhart & Hecht, 2022).

### 3.2.1. Risk

Risk is defined by a series of hazard exposure scenarios ($i$), the resulting consequences ($c_i$) for each scenario, and the probability ($p_i$) of these consequences occurring (Ehrhart & Hecht, 2022) . A general equation for evaluating risk is show below:

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

### 3.2.2. Risk Metrices Calculations

**Potential Loss of Life (PLL)**

The expected number of fatalities per system-year:

$$\text{PLL} = \sum_n (f_n \times c_n) \text{ (Ehrhart \& Hecht, 2022)}$$

where *n* is one of the potential safety-significant events, *fn* is the frequency of that accident event *n*, *cn* is the forecasted number of fatalities for accident event *n*.

### Fatal Accident Rate (FAR)

The expected number of fatalities in a group, per 100 million exposed hours:

$$\text{FAR} = \frac{\text{PLL} \times 10^8}{\text{Exposed hours}} = \frac{\text{PLL} \times 10^8}{N_{pop} \times 8760} \quad \text{(Ehrhart \& Hecht, 2022)}$$

$N_{pop}$ is the average count of occupants within the facility and dividing by 8760 converts from years to hours.

### Average Individual Risk (AIR)

The average number of fatalities per exposed individual. It depends on how many hours the average person spends in the facility.

$$\text{AIR} = H \times \text{FAR} \times 10^{-8} \text{ (Ehrhart \& Hecht, 2022)}$$

where *H* is the number of hours the occupant spends in the facility per year.

## 3.3. Approach

The risk assessment for a hydrogen refuelling station (HRS) is conducted using the aforementioned HyRAM+ software across various systems. Initially, a dispenser example from a Sandia Energy report is used to understand the software's functionality and limitations, followed by an analysis of a more complex infrastructure. Finally, an alternative system is examined, replacing the compressor with a pump and utilizing liquid in the tanks. User-dependent inputs for the QRA section are detailed and discussed in the methodology chapter, while inputs for physics and accumulation will be presented and analysed in the subsequent chapter, which covers results and discussion.

## 3.4. Case Studies Description

Hydrogen refuelling stations are a crucial component of the infrastructure needed for wider adoption of hydrogen fuel cell vehicles. However, ensuring their safety is paramount. Quantitative risk analysis (QRA) plays a vital role in achieving this goal by systematically identifying potential hazards, assessing their likelihood of occurrence, and evaluating their consequences. This thesis delves into the application of HyRAM+ software, a specialized tool for hydrogen system risk assessment, to analyse two case studies of hydrogen refuelling stations. The first case study employs a simplified system with mostly default values and a limited number of components, reflecting a baseline scenario. This allows for a clear understanding of the software's functionality and the fundamental risk factors associated with hydrogen refuelling. The second case study builds upon the first by incorporating modifications to existing component values and introducing additional elements into the system. This complexity mirrors a more realistic station design and enables the exploration of how these changes influence the overall risk profile. Finally, in the third case study, the scenario is the opposite of the second case study: there is a liquid hydrogen supply, and the compressor is replaced with a pump. This setup is analysed to examine this aspect of HyRAM+ as well. By comparing the results of these case studies, this thesis aims to not only evaluate the effectiveness of HyRAM+ as a QRA tool for hydrogen refuelling stations but also gain valuable insights into the impact of design choices on potential safety hazards. The accompanying Process & Instrumentation Diagrams (P&ID) developed for each case study provide a visual representation of the system layout and component interconnections, facilitating a clear understanding of the modelled scenarios.

### 3.4.1. Case Study 1: Model Case Study for Dispenser

Setup and specifications for HRS:

**Dispenser:**

- Operates at 35 MPa (5000 psi) and 15°C.
- Functions for up to 5 minutes per fuelling event.
- Made of 3/8" OD, 0.065" wall, ASTM A269 seamless 316 stainless steel tubing.

**Facility:**

- Freestanding warehouse, 100m x 100m with 7.62m ceiling.
- Contains a single dispenser on the ground floor, cantered along a wall.
- No piloted ignition sources near the dispenser.
- Dispenser has protective casing, curb, and guard posts.
- Hydrogen piping: 3/8" OD, 0.065" wall, ASTM A269 seamless 316 stainless steel tubing, runs 20m inside the building.

**Personnel:**

- 50 employees working at any given time (2000 hours/year each).
- Randomly distributed throughout the warehouse.
- Trained on dispenser operation.
- These details will be used to assess potential hazards, likelihood of occurrence, and consequences in the QRA for a simplified case study.

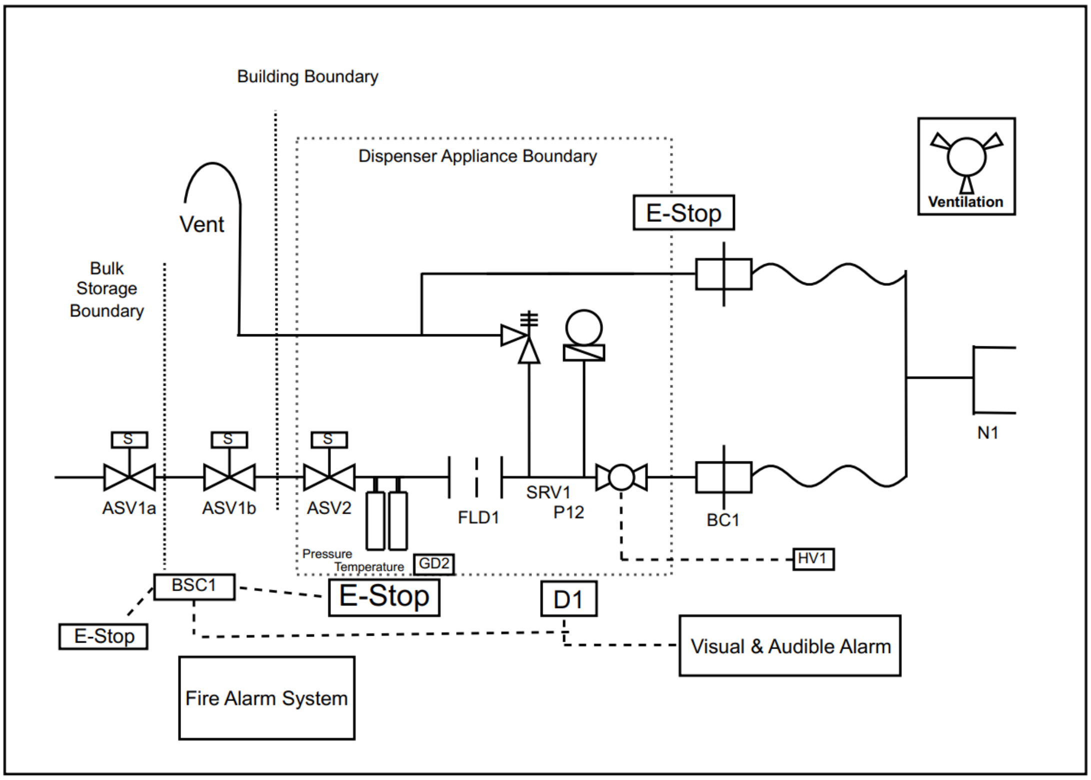
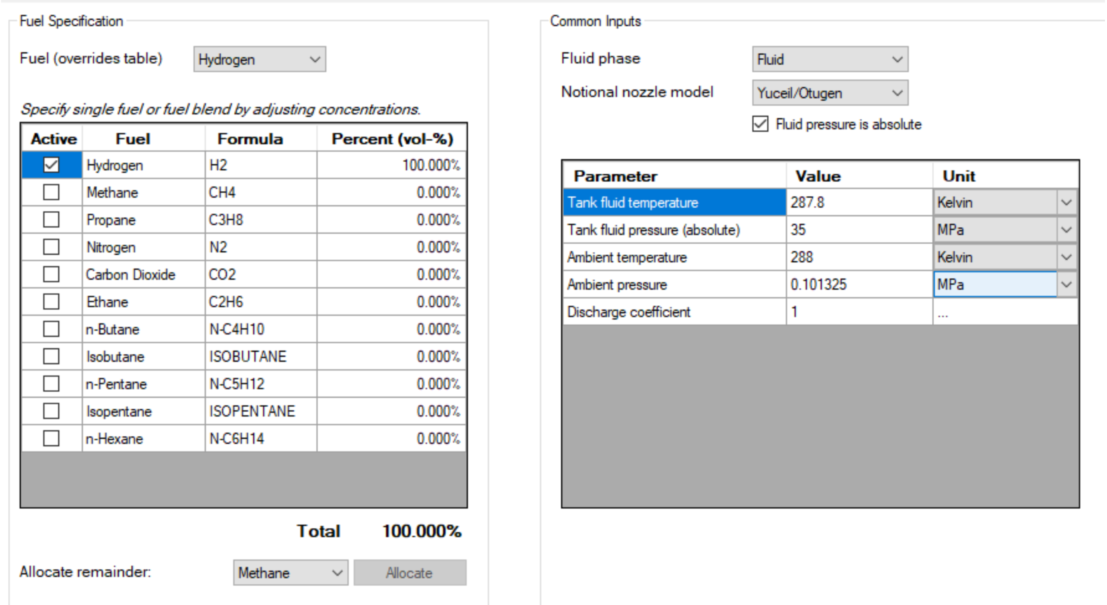


*Figure 3.1 P&ID of general dispenser used in model case study (Feliciano et al., 2019)*

## System State:

To conduct QRA in HyRAM+, the first step is to define the system state of the system being analysed. This involves specifying the fuel, which in this case is hydrogen, along with other relevant parameters as depicted in the image.


Fuel Specification

Fuel (overrides table): Hydrogen

*Specify single fuel or fuel blend by adjusting concentrations.*

| Active | Fuel | Formula | Percent (vol-%) |
|---|---|---|---|
| ☑ | Hydrogen | H2 | 100.000% |
| ☐ | Methane | CH4 | 0.000% |
| ☐ | Propane | C3H8 | 0.000% |
| ☐ | Nitrogen | N2 | 0.000% |
| ☐ | Carbon Dioxide | CO2 | 0.000% |
| ☐ | Ethane | C2H6 | 0.000% |
| ☐ | n-Butane | N-C4H10 | 0.000% |
| ☐ | Isobutane | ISOBUTANE | 0.000% |
| ☐ | n-Pentane | N-C5H12 | 0.000% |
| ☐ | Isopentane | ISOPENTANE | 0.000% |
| ☐ | n-Hexane | N-C6H14 | 0.000% |

**Total** **100.000%**

Allocate remainder: Methane

Common Inputs

Fluid phase: Fluid

Notional nozzle model: Yuceil/Otugen

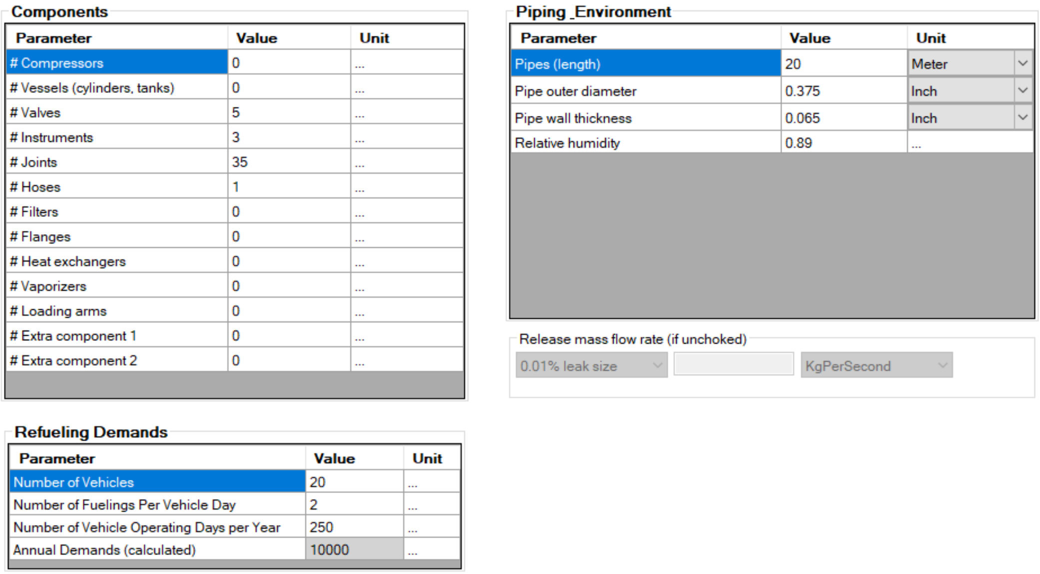
☑ Fluid pressure is absolute

| Parameter | Value | Unit |
|---|---|---|
| Tank fluid temperature | 287.8 | Kelvin |
| Tank fluid pressure (absolute) | 35 | MPa |
| Ambient temperature | 288 | Kelvin |
| Ambient pressure | 0.101325 | MPa |
| Discharge coefficient | 1 | ... |

*Figure 3.2 System State for Model Case Study*

## System Description

It's also crucial to specify the types and quantities of components within the system under examination. In this dispenser model, there are no compressors or vessels included. The dispenser system comprises only 5 valves, 3 instruments, 35 joints, and 1 hose with pipes totalling 30 meters in length. Refuelling demand is estimated based on 20 vehicles requiring 2 refuelling per vehicle per day, over 250 operating days per year. The system automatically calculates the annual demand, shown in the figure below as 10,000. The estimated occupants are 9, and the facility dimensions default to 20 meters in length and 12 meters in width.



**Components**

| Parameter | Value | Unit |
|---|---|---|
| # Compressors | 0 | ... |
| # Vessels (cylinders, tanks) | 0 | ... |
| # Valves | 5 | ... |
| # Instruments | 3 | ... |
| # Joints | 35 | ... |
| # Hoses | 1 | ... |
| # Filters | 0 | ... |
| # Flanges | 0 | ... |
| # Heat exchangers | 0 | ... |
| # Vaporizers | 0 | ... |
| # Loading arms | 0 | ... |
| # Extra component 1 | 0 | ... |
| # Extra component 2 | 0 | ... |

**Piping_Environment**

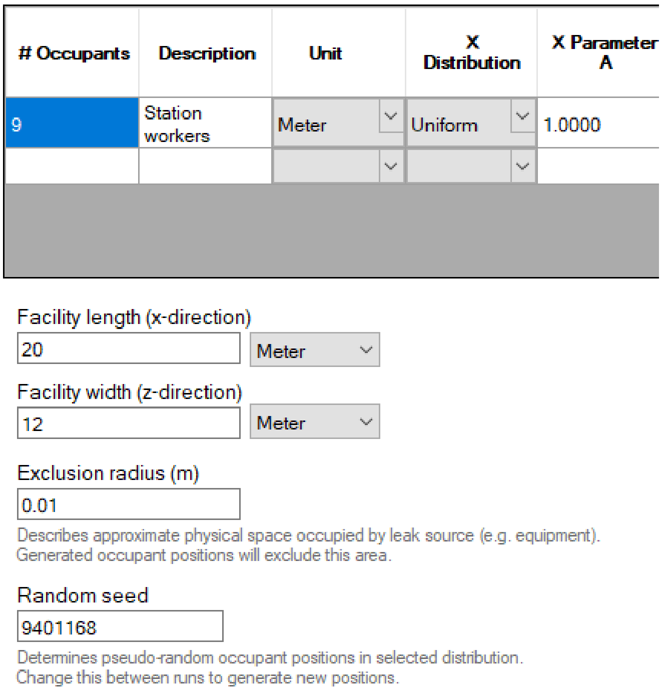
| Parameter | Value | Unit |
|---|---|---|
| Pipes (length) | 20 | Meter |
| Pipe outer diameter | 0.375 | Inch |
| Pipe wall thickness | 0.065 | Inch |
| Relative humidity | 0.89 | ... |

Release mass flow rate (if unchoked)
0.01% leak size | | KgPerSecond

**Refueling Demands**

| Parameter | Value | Unit |
|---|---|---|
| Number of Vehicles | 20 | ... |
| Number of Fuelings Per Vehicle Day | 2 | ... |
| Number of Vehicle Operating Days per Year | 250 | ... |
| Annual Demands (calculated) | 10000 | ... |

*Figure 3.3 System Description of Model Case Study*



| # Occupants | Description | Unit | X Distribution | X Parameter A |
|---|---|---|---|---|
| 9 | Station workers | Meter | Uniform | 1.0000 |
| | | | | |

Facility length (x-direction)
20 Meter

Facility width (z-direction)
12 Meter

Exclusion radius (m)
0.01
Describes approximate physical space occupied by leak source (e.g. equipment).
Generated occupant positions will exclude this area.

Random seed
9401168
Determines pseudo-random occupant positions in selected distribution.
Change this between runs to generate new positions.

*Figure 3.4 Facility Parameters for Model Case Study*

### 3.4.2. Case Study 2: Hydrogen Refuelling Station (HRS)

The case study in this section focuses on an entire hydrogen refuelling station. Since it is a refuelling station, it includes more processing sections and additional components beyond just the dispenser. This means that different inputs will be required for designing the system and describing its components compared to the model case study, leading to different results. The figures below (3.6 and 3.7) provide a systematic diagram of the HRS, detailing the components of a hydrogen refuelling station, as well as the P&ID of a hydrogen station. Importantly, the parameters for system states will remain the same as in the model case study.

*Figure 3.5 Schematic Diagram of HRS with Gas (Riedl, 2020)*

It is significant to enlist the main components of a hydrogen refuelling station (HRS) and explain their functions to have better understating of system.

**Hydrogen Supply Terminal:** The main goal of hydrogen gas storage at refuelling stations is to guarantee a consistent and reliable supply of hydrogen. This storage system enables hydrogen refuelling stations (HRS) to accumulate and store hydrogen during periods of low demand, ensuring it is readily available for dispensing when vehicles need refuelling. This approach helps maintain a balance between hydrogen supply and demand (Tarhan & Çil, 2021).

**Compression Unit:** The main function of the compressor is to increase the pressure of hydrogen gas from the storage tanks to a suitable level for vehicle refuelling. Hydrogen is usually stored at high pressures, often up to 700 bar, to maximize storage capacity and extend the driving range of fuel cell vehicles. To ensure vehicles receive an adequate fuel supply quickly, the compressor draws hydrogen from the storage tanks and compresses it to the necessary pressure (Lototskyy et al., 2014).

**Buffer Storage:** This storage system is designed to keep hydrogen at high pressures, typically ranging from 350 to 700 bar. It acts as a buffer between the hydrogen storage units and the dispenser, guaranteeing a consistent and controlled flow of hydrogen during refuelling operations (Sadi & Deymi-Dashtebayaz, 2019) .

The buffer storage system acts like a surge protector for a hydrogen refuelling station. During busy times, it keeps pressure steady so cars can refuel quickly without affecting the station's performance. This system also helps the compressor run smoothly by reducing on-and-off cycles. By maintaining a constant flow, the compressor lasts longer, and the station can refuel more vehicles overall. While the main storage holds the bulk of the hydrogen, the buffer handles the ups and downs in demand, guaranteeing a dependable supply for refuelling.

**Refrigeration Unit:** The basic function of the refrigeration system is to cool the hydrogen as a precautionary measure to safeguard the integrity of the vehicles' tanks (Jouybari et al., 2022). The precise cooling temperature of hydrogen gas is dependent on various factors, including the fuel cell vehicle requirements and dispenser technology. The refrigeration system's general goal is to cool the hydrogen to between -40 and -20°C. It is important to cool hydrogen to very low temperatures for a number of reasons. First, it increases the gas density of hydrogen, which allows for the storage of more hydrogen in a given volume.

**Dispenser Unit:** The dispenser's primary job is to deliver a regulated hydrogen flow by moving hydrogen fuel from the storage system to fuel cell vehicles. It is crucial for controlling the pressure at which hydrogen is dispensed, making sure that the vehicle's fuel cell system requires that the hydrogen be supplied at the proper pressure for effective fueling (Agll et al., 2016).

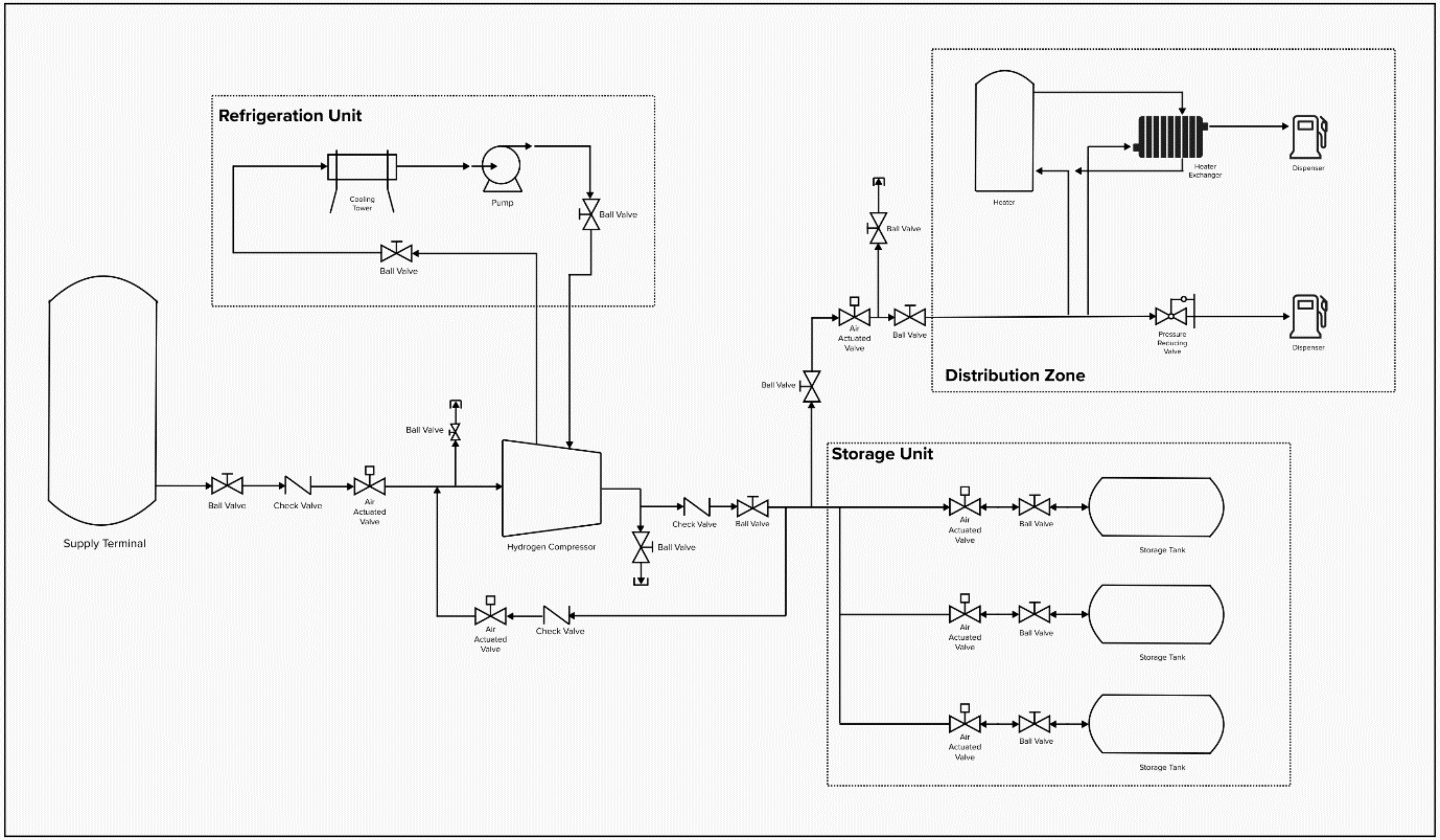
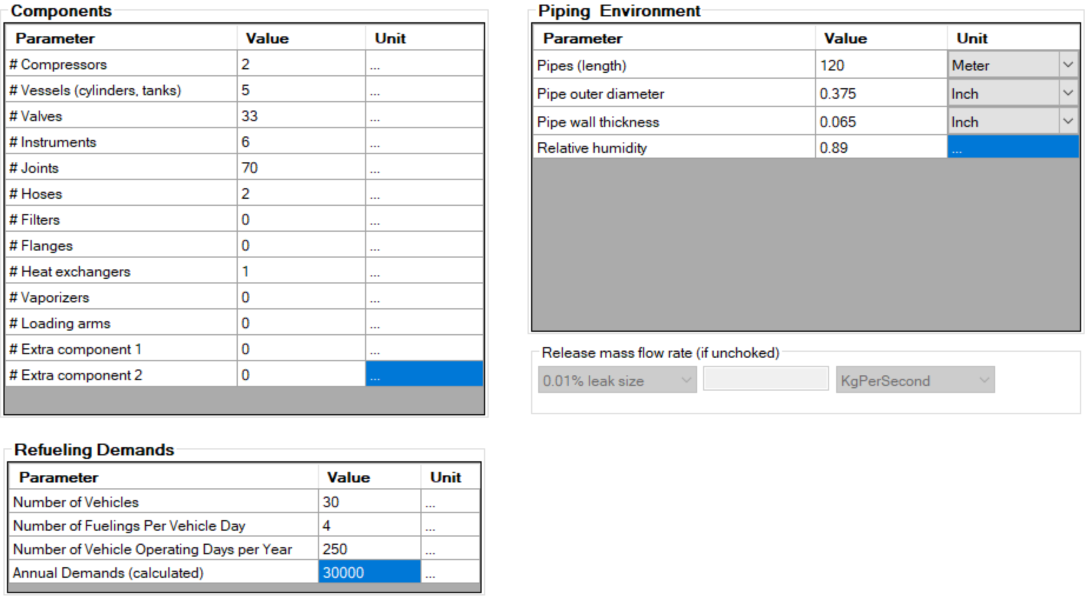


*Figure 3.6 P&ID for HRS with Gas*

## System Description:

The HRS system comprises five distinct sections: the supply terminal, hydrogen compressor, refrigeration unit, storage unit, and distribution unit. Initially, the supply terminal feeds the compressing section. Adjacent to it, a refrigeration unit houses a compressor with a pump and a cooling tower. A buffer storage unit is installed before the distribution of compressed hydrogen. The distribution unit includes a heat exchanger and two dispensers. This complex HRS system incorporates additional components, such as one compressor, one pump, five vessels, 33 valves, six instruments, and two hoses. The system features 70 joints and a total pipe length of 120 meters.



**Components**

| Parameter | Value | Unit |
|---|---|---|
| # Compressors | 2 | ... |
| # Vessels (cylinders, tanks) | 5 | ... |
| # Valves | 33 | ... |
| # Instruments | 6 | ... |
| # Joints | 70 | ... |
| # Hoses | 2 | ... |
| # Filters | 0 | ... |
| # Flanges | 0 | ... |
| # Heat exchangers | 1 | ... |
| # Vaporizers | 0 | ... |
| # Loading arms | 0 | ... |
| # Extra component 1 | 0 | ... |
| # Extra component 2 | 0 | ... |

**Piping Environment**

| Parameter | Value | Unit |
|---|---|---|
| Pipes (length) | 120 | Meter |
| Pipe outer diameter | 0.375 | Inch |
| Pipe wall thickness | 0.065 | Inch |
| Relative humidity | 0.89 | ... |

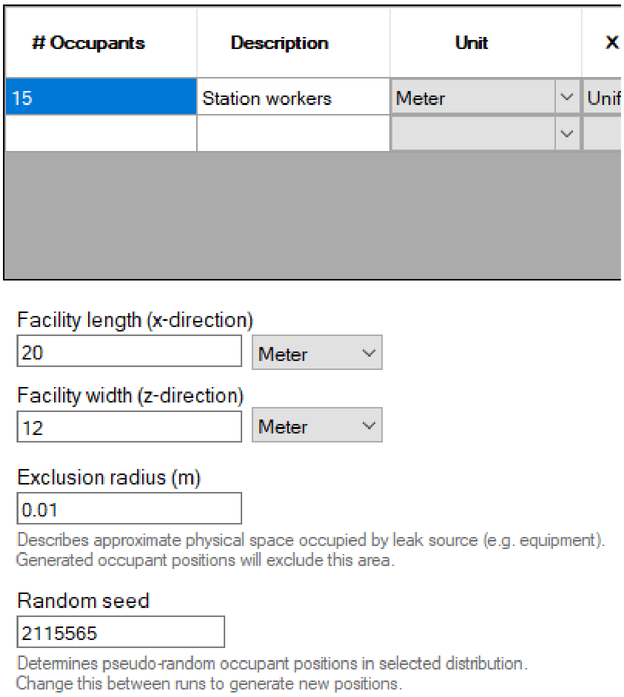
Release mass flow rate (if unchoked)

**Refueling Demands**

| Parameter | Value | Unit |
|---|---|---|
| Number of Vehicles | 30 | ... |
| Number of Fuelings Per Vehicle Day | 4 | ... |
| Number of Vehicle Operating Days per Year | 250 | ... |
| Annual Demands (calculated) | 30000 | ... |

***Figure 3.7 System Description for HRS with Gas***

To calculate refuelling demand, the system considers 30 vehicles, each refuelling four times per day over 250 operating days per year, resulting in an annual demand of 30,000 refuelling. In the HyRAM+ software, pumps and compressors are categorized under the same component type. For the entire HRS system, the facility occupancy is set at 15, with the length and width of the facility matching those in the model case study.



| # Occupants | Description | Unit | X |
|---|---|---|---|
| 15 | Station workers | Meter | Unif |
| | | | |

Facility length (x-direction)
20 Meter

Facility width (z-direction)
12 Meter

Exclusion radius (m)
0.01
Describes approximate physical space occupied by leak source (e.g. equipment).
Generated occupant positions will exclude this area.

Random seed
2115565
Determines pseudo-random occupant positions in selected distribution.
Change this between runs to generate new positions.

*Figure 3.8 Facility Parameters for HRS with Gas*

### 3.4.3. Case Study 3: Hydrogen Refuelling Station (HRS) with liquid hydrogen in Tanks

In this analysis, another HRS system is considered, featuring liquid hydrogen in the supply tanks and gaseous hydrogen in the dispensers, making it an inverse scenario in terms of fluid states compared to previous case studies. Here, the compressor is replaced with a pump, eliminating the need for a refrigeration unit. Instead, a heat exchanger is employed to raise the temperature of the liquid hydrogen after pumping and before reaching the dispensers. The figures (3.10 & 3.11) below illustrate the schematic diagram and P&ID for the HRS under discussion.

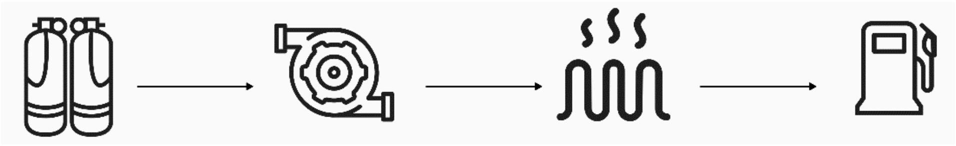


*Figure 3.9 Schematic Diagram for HRS with Liquid hydrogen in tanks*

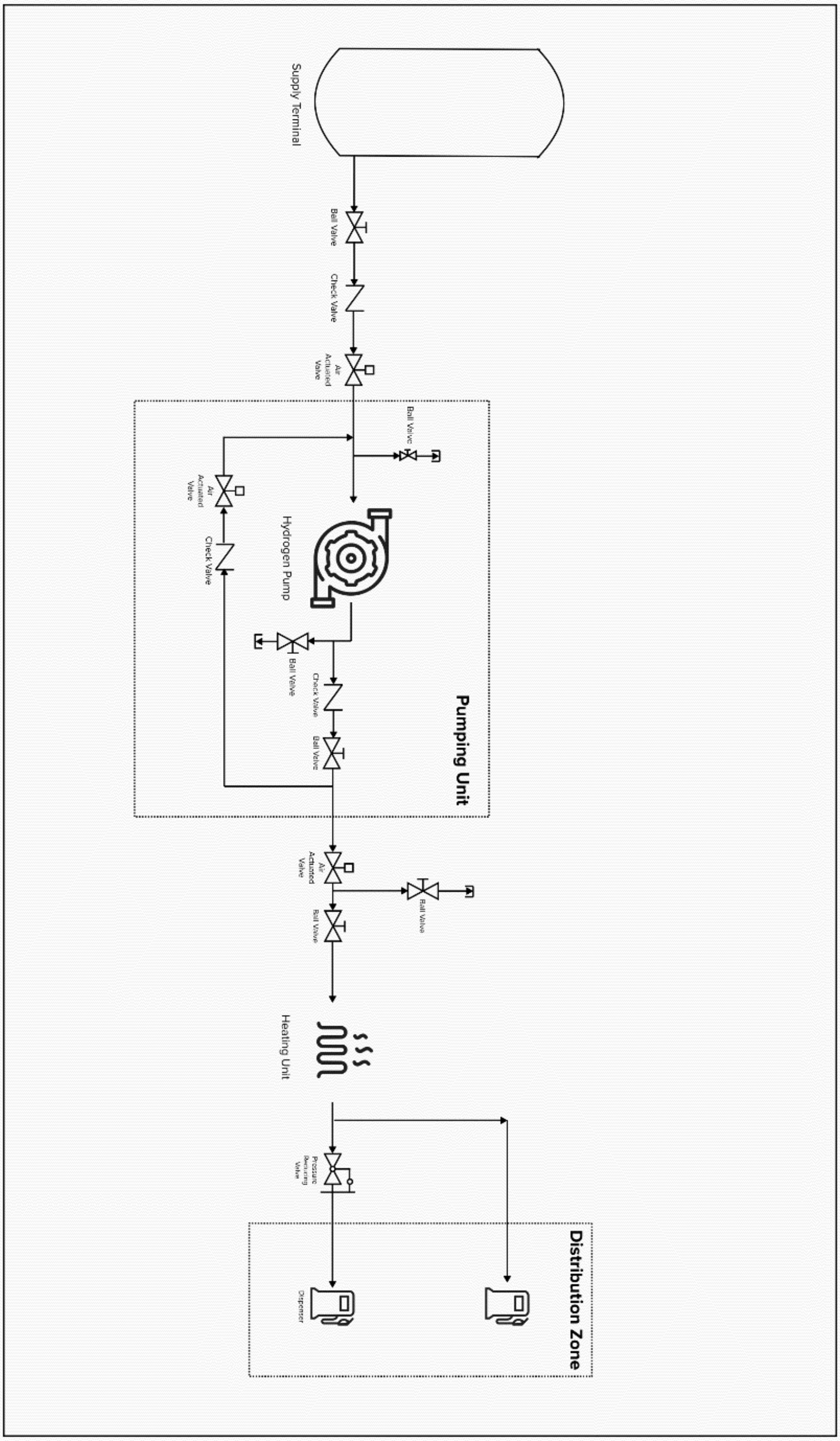
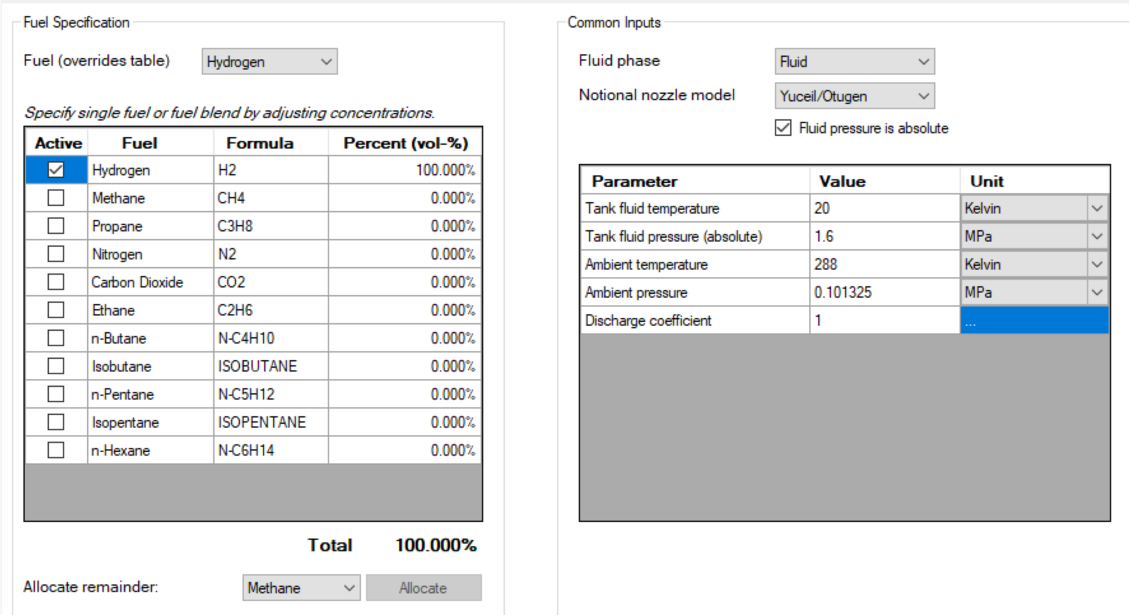


*Figure 3.10 P&ID of HRS with Liquid hydrogen in tanks*

## System State

When defining the system state for this type of HRS, it is necessary to adjust the inputs for the fluid's physical properties within the software. The tank fluid temperature is set to 20 Kelvin, the tank fluid pressure to 1.6-2 MPa (Robert, 2020) , the ambient temperature to 288 Kelvin, and the ambient pressure to 0.101325 MPa. Under these physical conditions, the hydrogen remains in a liquid state within the supply tanks.



Fuel Specification

Fuel (overrides table): Hydrogen

*Specify single fuel or fuel blend by adjusting concentrations.*

| Active | Fuel | Formula | Percent (vol-%) |
|---|---|---|---|
| ☑ | Hydrogen | H2 | 100.000% |
| ☐ | Methane | CH4 | 0.000% |
| ☐ | Propane | C3H8 | 0.000% |
| ☐ | Nitrogen | N2 | 0.000% |
| ☐ | Carbon Dioxide | CO2 | 0.000% |
| ☐ | Ethane | C2H6 | 0.000% |
| ☐ | n-Butane | N-C4H10 | 0.000% |
| ☐ | Isobutane | ISOBUTANE | 0.000% |
| ☐ | n-Pentane | N-C5H12 | 0.000% |
| ☐ | Isopentane | ISOPENTANE | 0.000% |
| ☐ | n-Hexane | N-C6H14 | 0.000% |

**Total** **100.000%**

Allocate remainder: Methane

Common Inputs

Fluid phase: Fluid

Notional nozzle model: Yuceil/Otugen

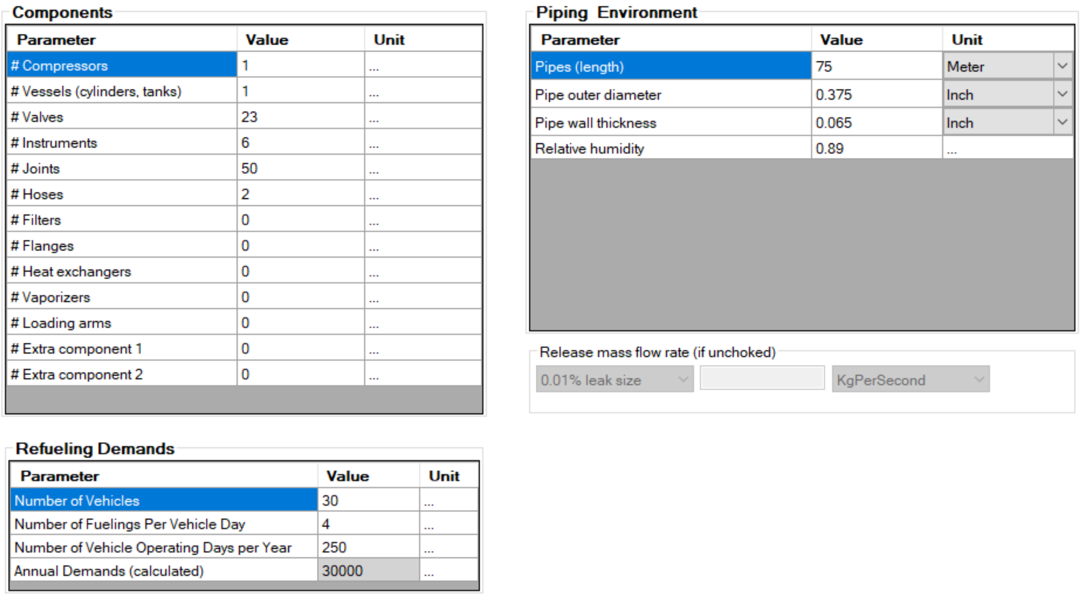
☑ Fluid pressure is absolute

| Parameter | Value | Unit |
|---|---|---|
| Tank fluid temperature | 20 | Kelvin |
| Tank fluid pressure (absolute) | 1.6 | MPa |
| Ambient temperature | 288 | Kelvin |
| Ambient pressure | 0.101325 | MPa |
| Discharge coefficient | 1 | ... |

*Figure 3.11 System State of HRS with Liquid hydrogen*

## System Description:

This HRS system consists of only four units, resulting in fewer components, joints, and shorter pipe lengths compared to the HRS in the previous case study. Specifically, it includes 1 pump, 1 vessel, 23 valves, 6 instruments, and 2 hoses. The pipe length totals 75 meters with 50 joints. In the HyRAM+ software, compressors and pumps are categorized together, so the compressor section shows "1". The number of occupants is the same as in the previous study, i.e., 15, and the facility dimensions are also identical, with a length of 20 meters and a width of 12 meters.



**Components**

| Parameter | Value | Unit |
|---|---|---|
| # Compressors | 1 | ... |
| # Vessels (cylinders, tanks) | 1 | ... |
| # Valves | 23 | ... |
| # Instruments | 6 | ... |
| # Joints | 50 | ... |
| # Hoses | 2 | ... |
| # Filters | 0 | ... |
| # Flanges | 0 | ... |
| # Heat exchangers | 0 | ... |
| # Vaporizers | 0 | ... |
| # Loading arms | 0 | ... |
| # Extra component 1 | 0 | ... |
| # Extra component 2 | 0 | ... |

**Piping Environment**

| Parameter | Value | Unit |
|---|---|---|
| Pipes (length) | 75 | Meter |
| Pipe outer diameter | 0.375 | Inch |
| Pipe wall thickness | 0.065 | Inch |
| Relative humidity | 0.89 | ... |

Release mass flow rate (if unchoked)

0.01% leak size

KgPerSecond

**Refueling Demands**

| Parameter | Value | Unit |
|---|---|---|
| Number of Vehicles | 30 | ... |
| Number of Fuelings Per Vehicle Day | 4 | ... |
| Number of Vehicle Operating Days per Year | 250 | ... |
| Annual Demands (calculated) | 30000 | ... |

***Figure 3.12 System Description of HRS with Liquid Hydrogen***

# 4. Results and Discussion

In this chapter, QRA outputs generated by HyRAM are presented and discussed. Results for all the parameters of QRA given by HyRAM are analysed for each case study separately. In the Physics model from the software is presented to show the fuel release behaviour.

## 4.1. Quantitative Risk Analysis (QRA) Outputs

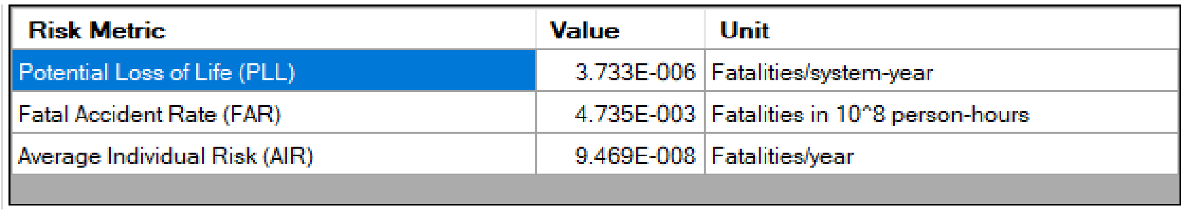
The Quantitative Risk Assessment (QRA) outputs generated by HyRAM+ for all the three case studies are presented and discussed below. These results are based on the system specified for analysis, inputs in system states and system descriptions.

### 4.1.1. Risk Metrices

The terms and equations involved in risk metrics already has been discussed in methodology chapter. HyRAM+ also calculates the values for these risk metrics. Risk metrics for each case is shown in the figure below.

**Case Study 1: Model Case Study (Dispenser)**

Potential Loss of Life (PLL) for dispenser 3.733E-006 fatalities per system year. The value for Fatal Accidental Rate (FAR) is 4.735E-003 fatalities in $10^8$ person hours, and Average Individual Risk (AIR) is 9.469E-008 fatalities per year.

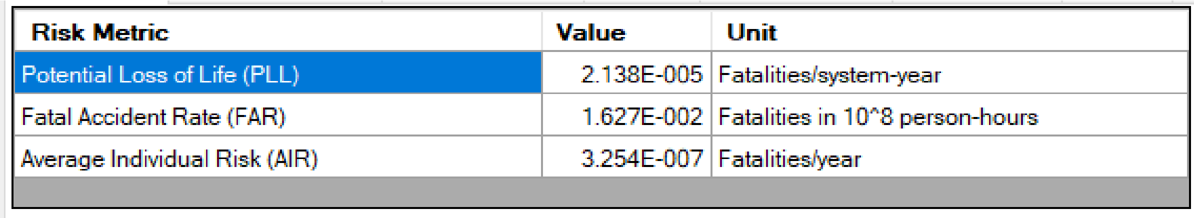


| Risk Metric | Value | Unit |
|---|---|---|
| Potential Loss of Life (PLL) | 3.733E-006 | Fatalities/system-year |
| Fatal Accident Rate (FAR) | 4.735E-003 | Fatalities in 10^8 person-hours |
| Average Individual Risk (AIR) | 9.469E-008 | Fatalities/year |

*Figure 4.1 Risk Metrics for Dispenser*

**Case Study 2: Hydrogen Refuelling Station (HRS)**

Similarly for HRS, Potential Loss of Life (PLL) is 2.138E-005 fatalities per system year. Whereas Fatal Accidental Rate (FAR) is 1.627E-002 fatalities in 108 person hours, and Average Individual Risk (AIR) is 3.254E-007 fatalities per year.

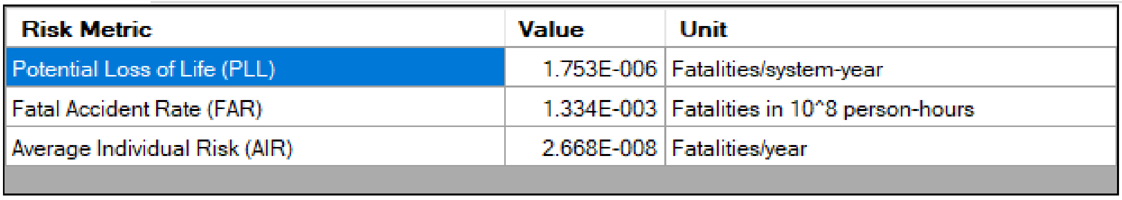


| Risk Metric | Value | Unit |
|---|---|---|
| Potential Loss of Life (PLL) | 2.138E-005 | Fatalities/system-year |
| Fatal Accident Rate (FAR) | 1.627E-002 | Fatalities in 10^8 person-hours |
| Average Individual Risk (AIR) | 3.254E-007 | Fatalities/year |

*Figure 4.2 Risk Metrics of Hydrogen Refuelling Station (HRS)*

### Case Study 3: Hydrogen Refuelling Station (HRS) with hydrogen in liquid phase

In case of HRS when hydrogen is in liquid phase, the calculated Potential Loss of Life (PLL) by HyRAM is 1.753E-006 fatalities per system year. Also, the Fatal Accidental Rate (FAR) is 1.334E-003 fatalities in 108 person hours, and Average Individual Risk (AIR) is 2.668E-008 fatalities per year.



| Risk Metric | Value | Unit |
|---|---|---|
| Potential Loss of Life (PLL) | 1.753E-006 | Fatalities/system-year |
| Fatal Accident Rate (FAR) | 1.334E-003 | Fatalities in 10^8 person-hours |
| Average Individual Risk (AIR) | 2.668E-008 | Fatalities/year |

***Figure 4.3 Risk Metrics of Hydrogen Refuelling Station (HRS) with hydrogen in liquid phase***

## 4.1.2. Thermal Effects

The graphs below show the visual representation of the calculated radiative heat flux that will be experienced by the occupants within the HRS facility. There are different plots for different leak sizes varying from 0.01%, 0.1%, 1%, 10%, 100%. The blue square located in the corner of the facility plot indicates the specific spot where a fuel leak has occurred. On the other hand, the blue line positioned at the bottom of the plot, specifically along the x-axis, illustrates the direction in which the leak is moving. The dot in the graph shows the coordinate location of the occupants of the facility and the Radiative Heat Flux (kW/m2) that would be observed by the occupants according to their location in the facility is represented by the colour. Similarly, Peak Over Pressure (in kPa) and Impulse (in kPa*s) are shown in the plots that would be experienced by the occupants. Peak Over Pressure and Impulse are not discussed further in this study but the results can be seen in the Appendix.

### Case Study 1: Model Case Study

In the event of a dispenser leak with 9 occupants in the facility, the figure below illustrates that for smaller leak sizes, the radiative heat flux experienced by the occupants facing the leak is lower compared to others. However, with larger leak sizes, the occupants in the direction of the leak are more significantly affected.

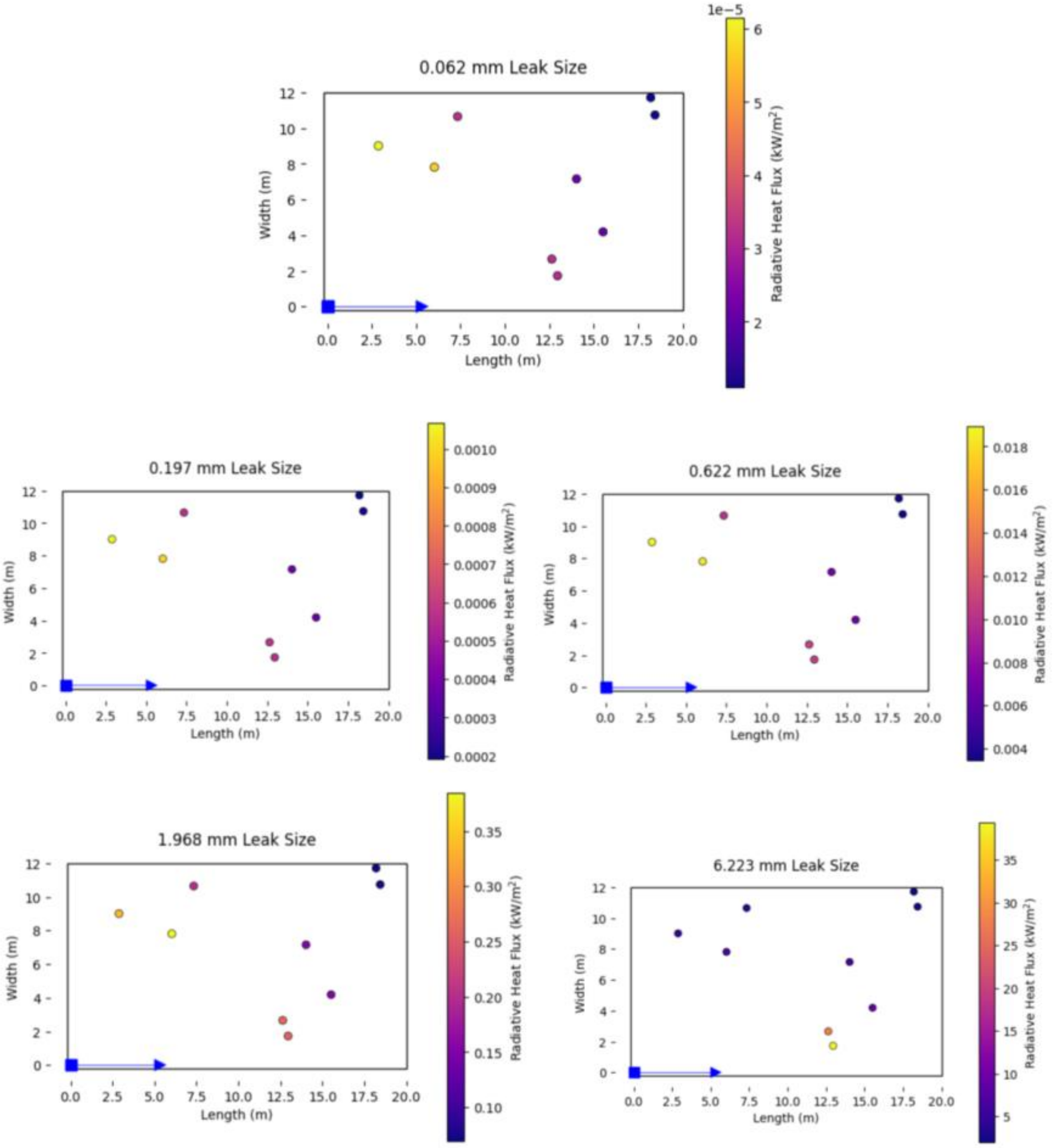


*Figure 4.4 Thermal Effects Plots for Dispenser*

## Case Study 2: Hydrogen Refuelling Station (HRS)

In the case of a hydrogen refuelling station (HRS) with 15 occupants, the pattern remains consistent with the previous scenario. As the leak size increases, the occupants in the direction of the leak are more significantly affected.

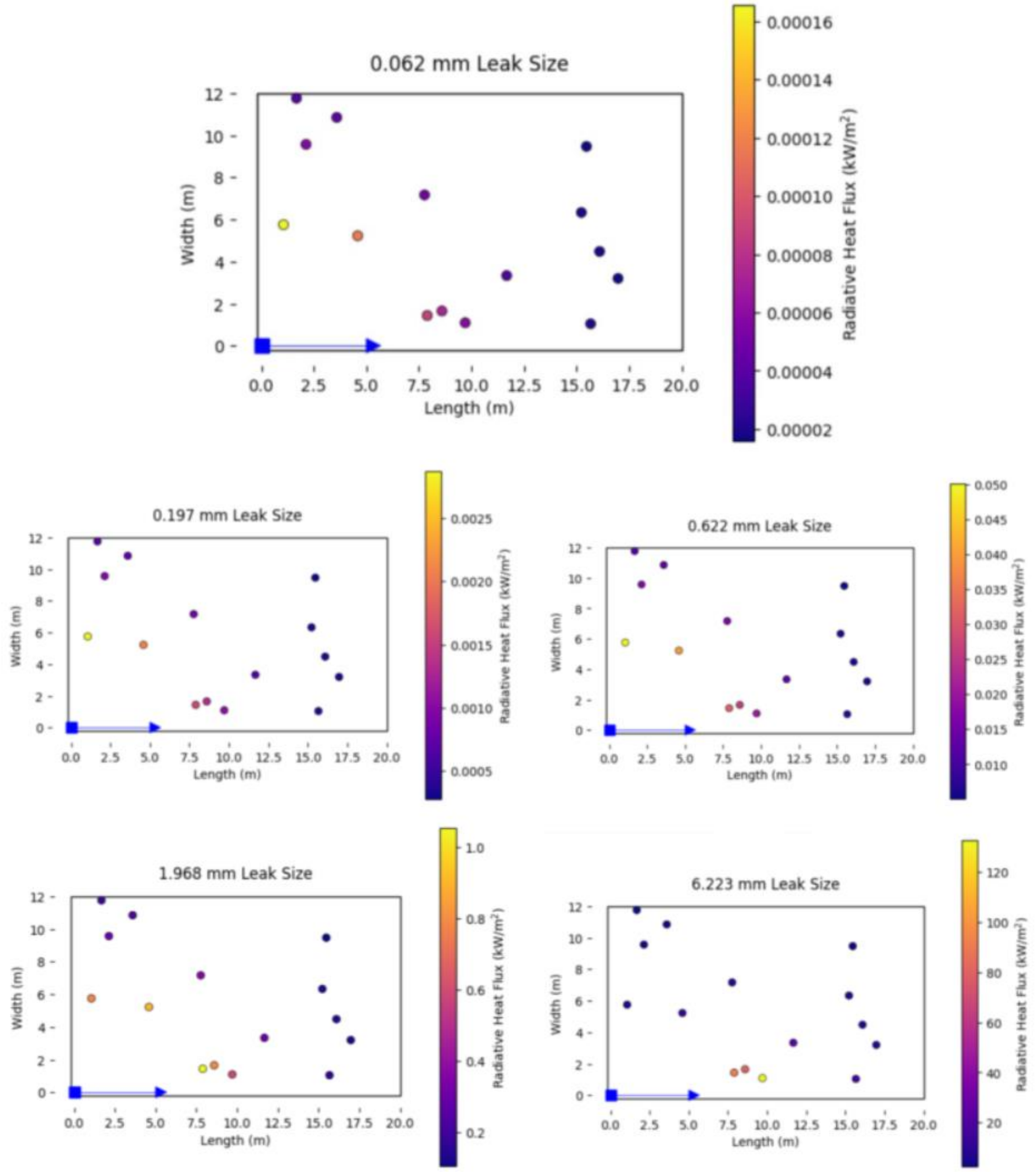


*Figure 4.5 Thermal Effects Plots for HRS*

### Case Study 3: Hydrogen Refuelling Station (HRS) with hydrogen in liquid phase

For a hydrogen refuelling station with liquid hydrogen in tanks and 15 occupants in the facility, no significant change is observed as the leak size increases. The occupants closest to the leak experience the highest heat flux.

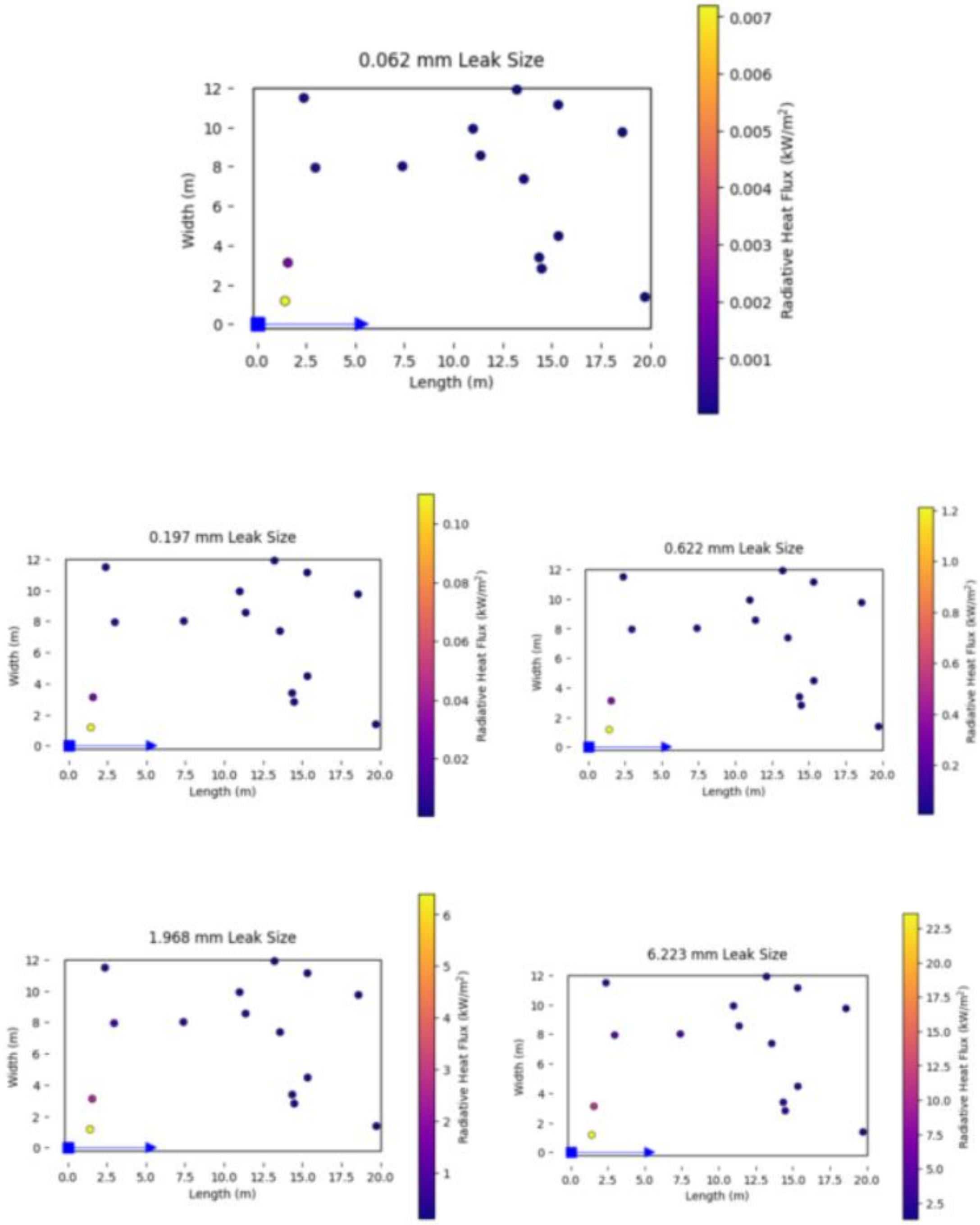


*Figure 4.6 Thermal Effects for HRS with liquid hydrogen in Tanks*

## 4.2. Physical Phenomenon Evaluation

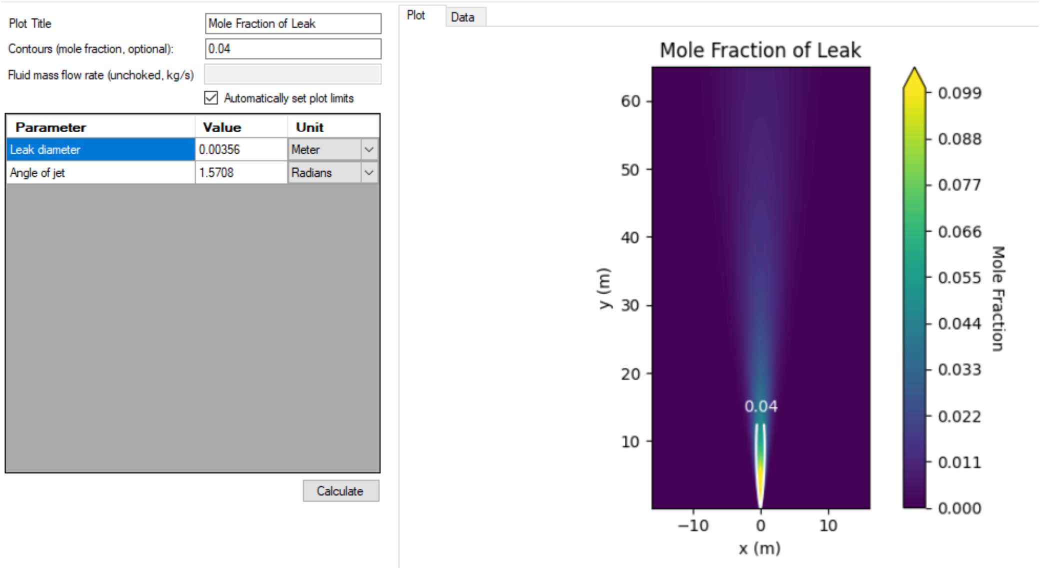
In this section, physics models are explained from HyRAM+. Some physics models require some extra information to calculate different parameters. Therefore, there are some input windows included in this section.

### 4.2.1. Plume Dispersion

To obtain the plot for plume and calculate mass flow rate (kg/s), it is required to input the value for contour, leak diameter and angle of jets. The data for distance to hazard can also be calculated using these values.

## Case Study 1: Model Case Study

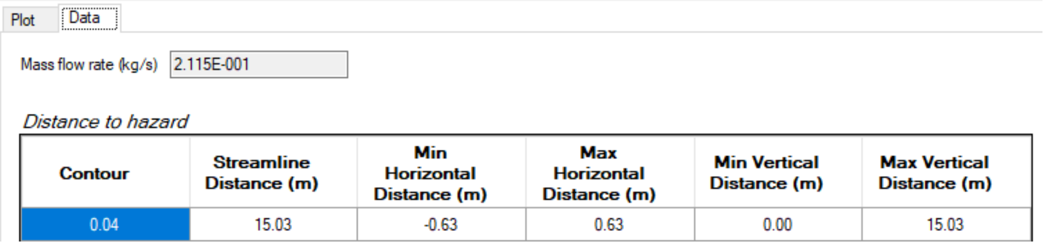
For dispenser, the calculated mass flow rate is 2.115E-001.



Plot Title: Mole Fraction of Leak
Contours (mole fraction, optional): 0.04
Fluid mass flow rate (unchoked, kg/s):
☑ Automatically set plot limits

| Parameter | Value | Unit |
|---|---|---|
| Leak diameter | 0.00356 | Meter |
| Angle of jet | 1.5708 | Radians |

*Figure 4.7 Plume Dispersion Input and Output Plot*



Mass flow rate (kg/s) 2.115E-001

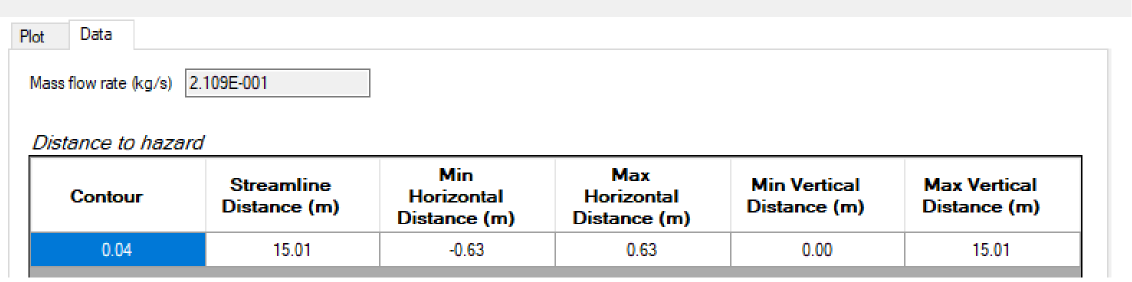
*Distance to hazard*

| Contour | Streamline Distance (m) | Min Horizontal Distance (m) | Max Horizontal Distance (m) | Min Vertical Distance (m) | Max Vertical Distance (m) |
|---|---|---|---|---|---|
| 0.04 | 15.03 | -0.63 | 0.63 | 0.00 | 15.03 |

*Figure 4.8 Mass Flow Rate and Distance to Hazard Data for Dispenser*

## Case Study 2: Hydrogen Refuelling Station (HRS)

For hydrogen refuelling station, the calculated mass flow rate is 2.109E-001.



Mass flow rate (kg/s) 2.109E-001

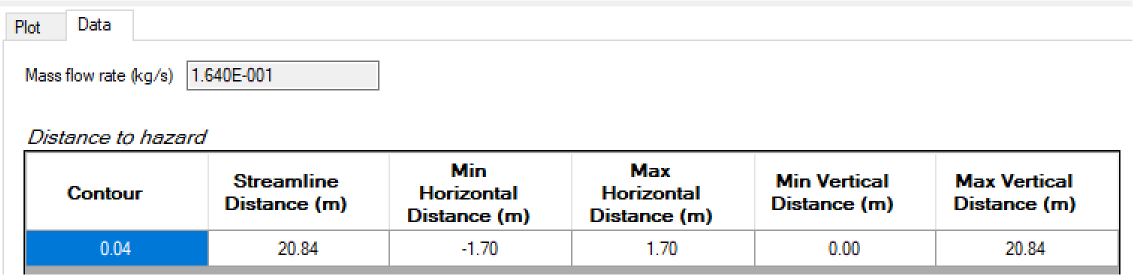
*Distance to hazard*

| Contour | Streamline Distance (m) | Min Horizontal Distance (m) | Max Horizontal Distance (m) | Min Vertical Distance (m) | Max Vertical Distance (m) |
|---|---|---|---|---|---|
| 0.04 | 15.01 | -0.63 | 0.63 | 0.00 | 15.01 |

***Figure 4.9 Mass Flow Rate and Distance to Hazard Data for HRS***

### Case Study 3: Hydrogen Refuelling Station (HRS) with hydrogen in liquid phase

For hydrogen refuelling station with liquid hydrogen in tanks, the calculated mass flow rate is 1.640E-001.



Mass flow rate (kg/s) 1.640E-001

*Distance to hazard*

| Contour | Streamline Distance (m) | Min Horizontal Distance (m) | Max Horizontal Distance (m) | Min Vertical Distance (m) | Max Vertical Distance (m) |
|---|---|---|---|---|---|
| 0.04 | 20.84 | -1.70 | 1.70 | 0.00 | 20.84 |

***Figure 4.10 Mass Flow Rate and Distance to Hazard Data for HRS with liquid hydrogen***

## 4.2.2. Accumulation

- **Indoor Release Parameters:** In order to calculate indoor release accumulation, HyRAM+ requires inputs including leak diameter, release height, enclosure height, floor/ceiling area. For a better understanding, this window also includes a general figure that explains a better visual aspect and helps to analyse the parameters. The results are presented in the form of pressure, flammable mass, layer and trajectory plots by HyRAM.

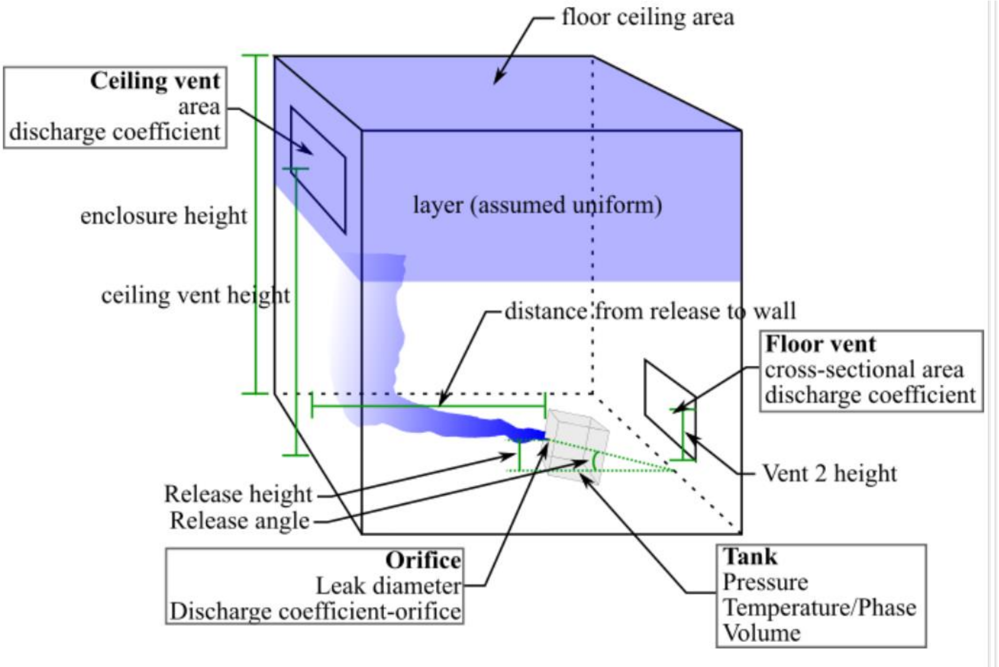
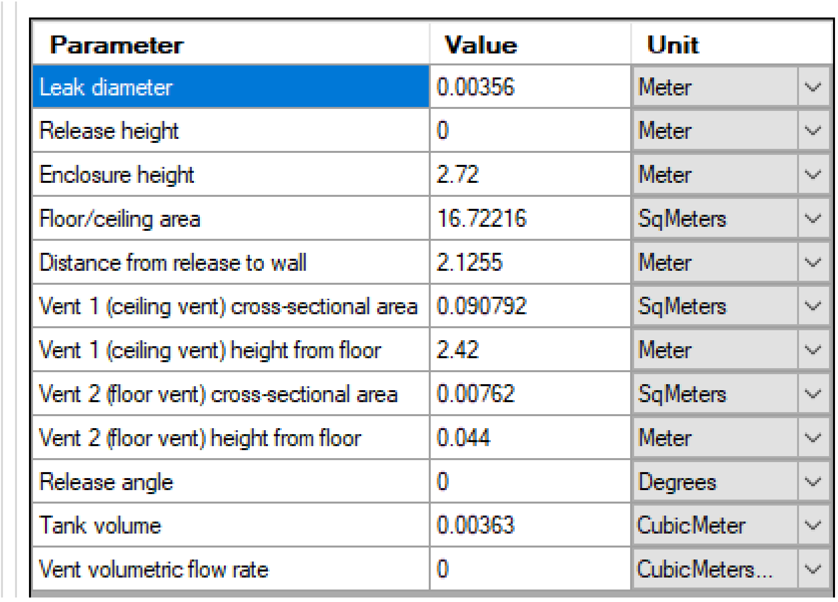


***Figure 4.11 General Sketch for Indoor Accumulation given in HyRAM Software***

The Layer line in the Overpressure graph shows the overpressure resulting from the igniting of the accumulated layer. The combined plot line shows the overpressure resulting from a combustion of the layer and the gas plume. The flammable Mass Plot displays the mass of hydrogen that is present in a concentration and capable of ignite over the specific time period. This surrounds both the accumulated layer and the plume in case of a leak. Additionally, the overall flammable mass, which includes the flammable masses from both the layer and the plume, is also shown. Overpressure output shows Layer plot depending on the default input values. The Trajectory map explains the paths followed by the hydrogen leak jet plume as it travels with respect to time. In colour scheme, the dark blue colour represents the initial stages of the blowdown, while yellow shows the later stages of the blowdown event. The mass flow rate plot illustrates the mass flow plot tab using the default inputs.

### Case Study 1: Model Case Study

As shown in figure, leak diameter is 0.00356 meters, enclosure height is 2.72 m, ceiling is 16.72216 $m^2$ and distance from release to wall is 2.1255 m. Tank volume is taken as 0.00363 $m^3$. All these values are by default.



| Parameter | Value | Unit |
|---|---|---|
| Leak diameter | 0.00356 | Meter |
| Release height | 0 | Meter |
| Enclosure height | 2.72 | Meter |
| Floor/ceiling area | 16.72216 | SqMeters |
| Distance from release to wall | 2.1255 | Meter |
| Vent 1 (ceiling vent) cross-sectional area | 0.090792 | SqMeters |
| Vent 1 (ceiling vent) height from floor | 2.42 | Meter |
| Vent 2 (floor vent) cross-sectional area | 0.00762 | SqMeters |
| Vent 2 (floor vent) height from floor | 0.044 | Meter |
| Release angle | 0 | Degrees |
| Tank volume | 0.00363 | CubicMeter |
| Vent volumetric flow rate | 0 | CubicMeters... |

***Figure 4.12 Input Parameters for Indoor Accumulation for Dispenser***

Figure shows the plots for over pressure, flammable mass for hydrogen, layer thickness from ceiling and percentage of fuel in the layer, and release path trajectory over time in case dispenser.

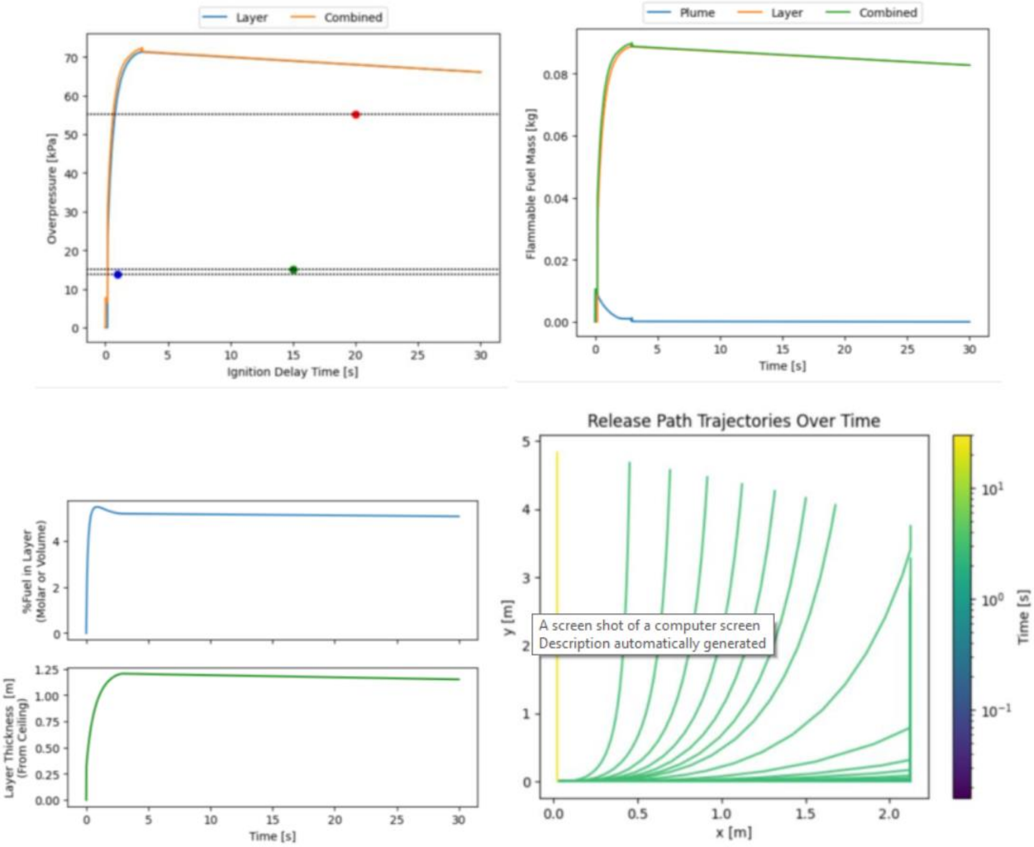
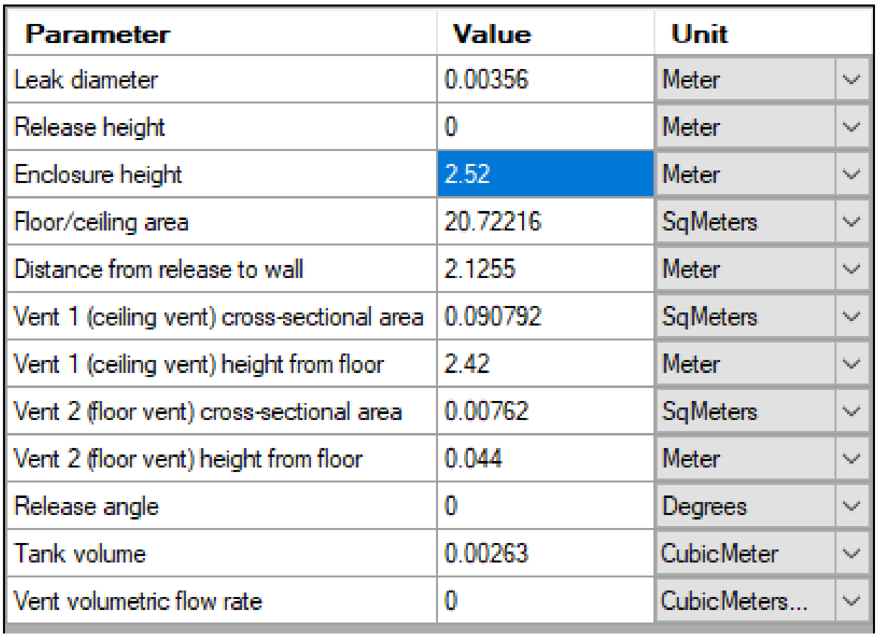


***Figure 4.13 Accumulation Plots for Dispenser***

## Case Study 2: Hydrogen Refuelling Station (HRS)

For the Hydrogen Refueling Station (HRS), most input parameters remain the same, but four parameters have been updated. The enclosure height is now 2.52 m, and the ceiling area is 20.72216 $m^2$. Additionally, the tank volume has been adjusted to 0.00263 $m^3$ for this scenario.



| Parameter | Value | Unit |
|---|---|---|
| Leak diameter | 0.00356 | Meter |
| Release height | 0 | Meter |
| Enclosure height | 2.52 | Meter |
| Floor/ceiling area | 20.72216 | SqMeters |
| Distance from release to wall | 2.1255 | Meter |
| Vent 1 (ceiling vent) cross-sectional area | 0.090792 | SqMeters |
| Vent 1 (ceiling vent) height from floor | 2.42 | Meter |
| Vent 2 (floor vent) cross-sectional area | 0.00762 | SqMeters |
| Vent 2 (floor vent) height from floor | 0.044 | Meter |
| Release angle | 0 | Degrees |
| Tank volume | 0.00263 | CubicMeter |
| Vent volumetric flow rate | 0 | CubicMeters... |

***Figure 4.14 Input Parameters for Indoor Accumulation for HRS***

The plots for over pressure, flammable mass for hydrogen, layer thickness from ceiling and percentage of fuel in the layer, and release path trajectory over time in case dispenser for hydrogen refuelling station are shown in figure.

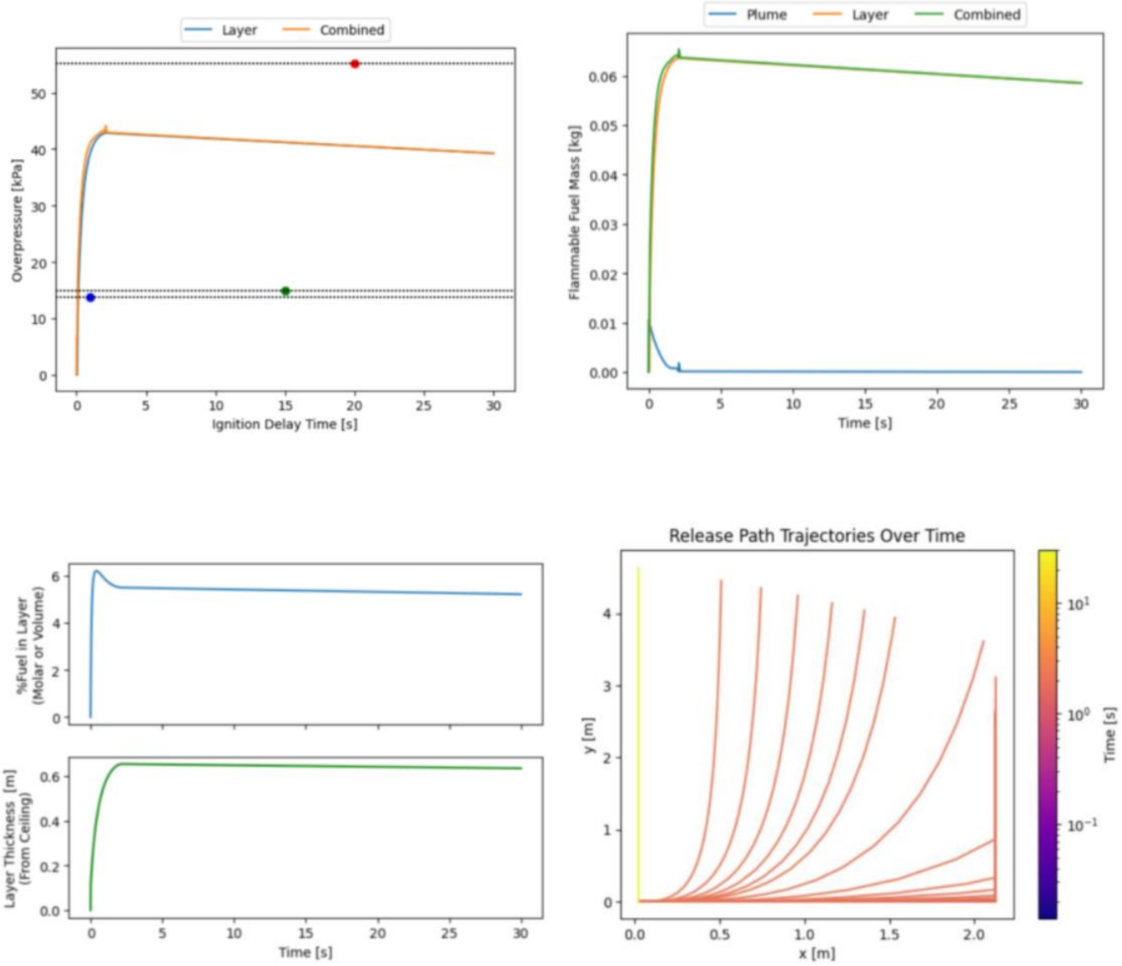


*Figure 4.15 Accumulation Output Plots for HRS*

## Case Study 3: Hydrogen Refuelling Station (HRS) with hydrogen in liquid phase

The indoor accumulation parameters are taken as same as case 2. But the accumulation plots can be seen in the figure below.

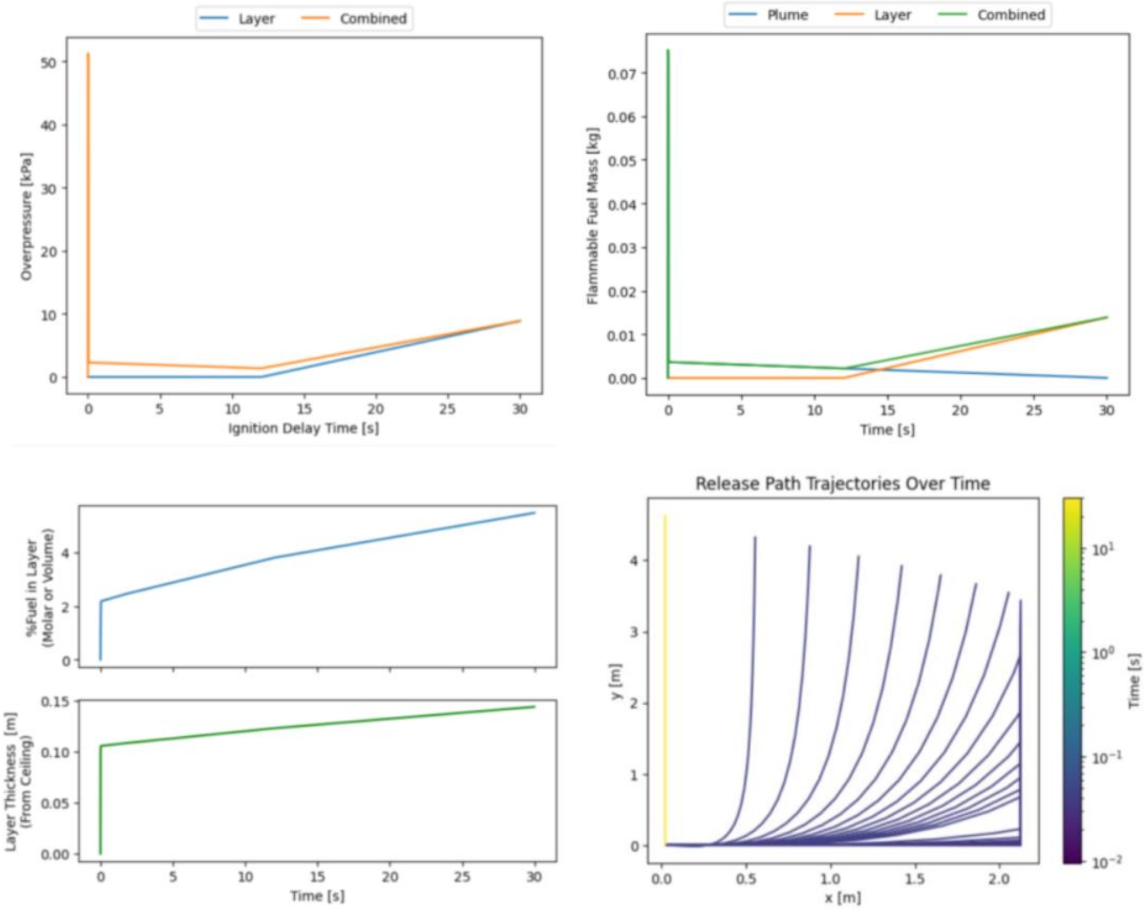


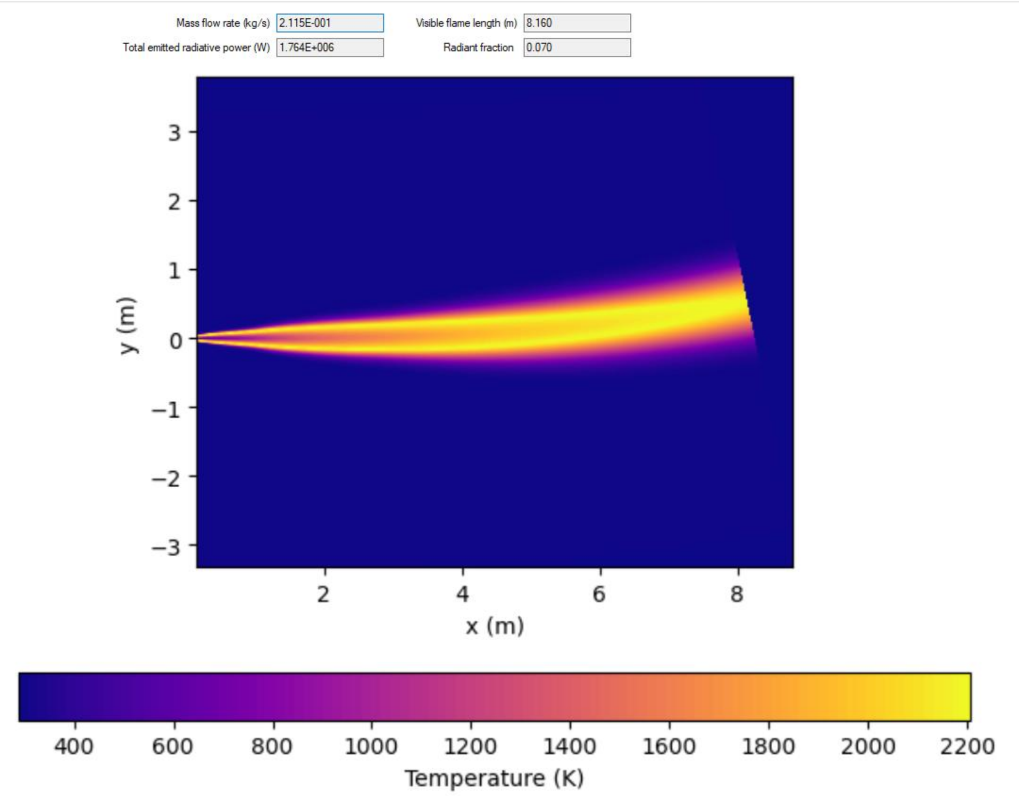
*Figure 4.16 Accumulation Plots for HRS with liquid hydrogen in tank*

### 4.2.3. Jet Flame Temperature and Trajectory

Here, HyRAM calculates and analyses the jet flame behaviour, along with temperature of the fuel, direction of jet and its leak size. As and additional input, leak diameter is required and it calculates mass flow rate, total entitled radiative power and also visible flame length.

#### Case Study 1: Model Case Study

For dispenser, the mass flow rate is 2.115E-001 (kg/s), total emitted radiative power is 1.764E+006 and the visible flame length is 8.16 m. The temperature for the jet can be analysed by comparing the colour of the jet flame with the colour scale under the plot as shown in figure below.



Mass flow rate (kg/s) 2.115E-001

Visible flame length (m) 8.160

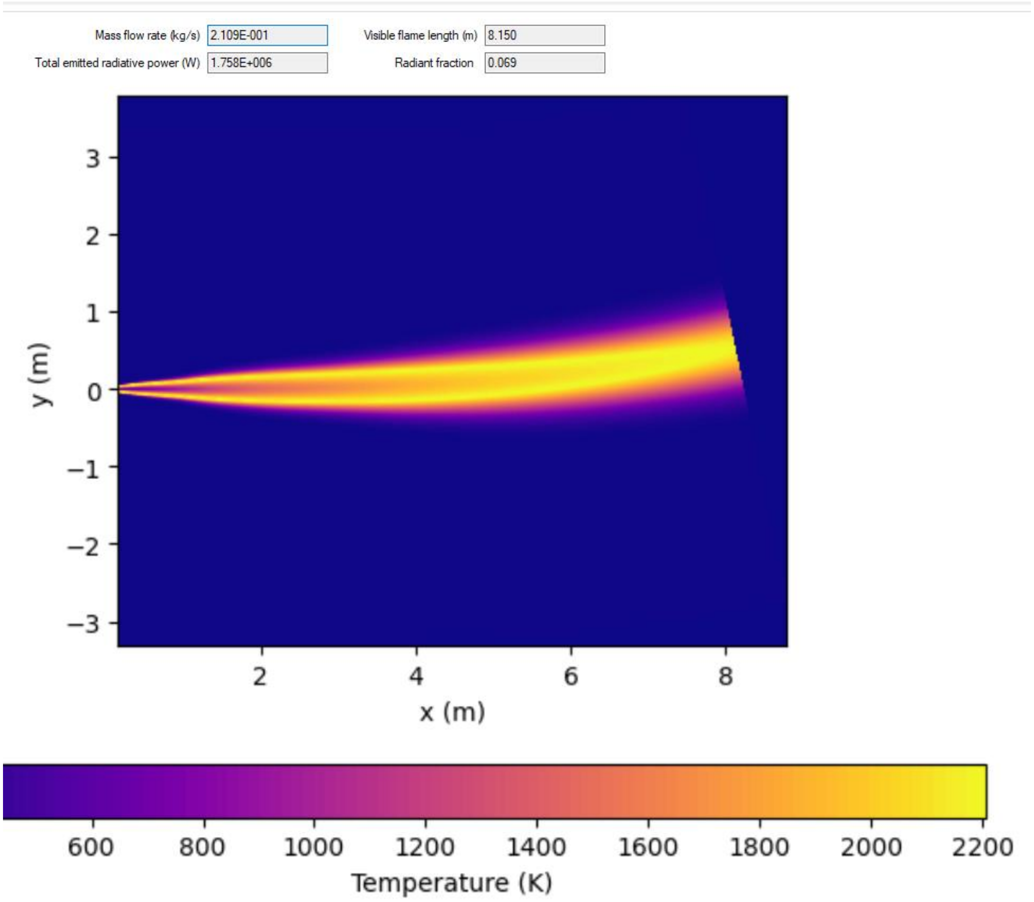
Total emitted radiative power (W) 1.764E+006

Radiant fraction 0.070

***Figure 4.17 Input window and jet flame temperature and trajectory plot for dispenser***

## Case Study 2: Hydrogen Refuelling Station (HRS)

For HRS, the mass flow rate is 2.109E-001 (kg/s), total emitted radiative power is 1.758E+006 and the visible flame length is 8.15 meter as mentioned in the figure.

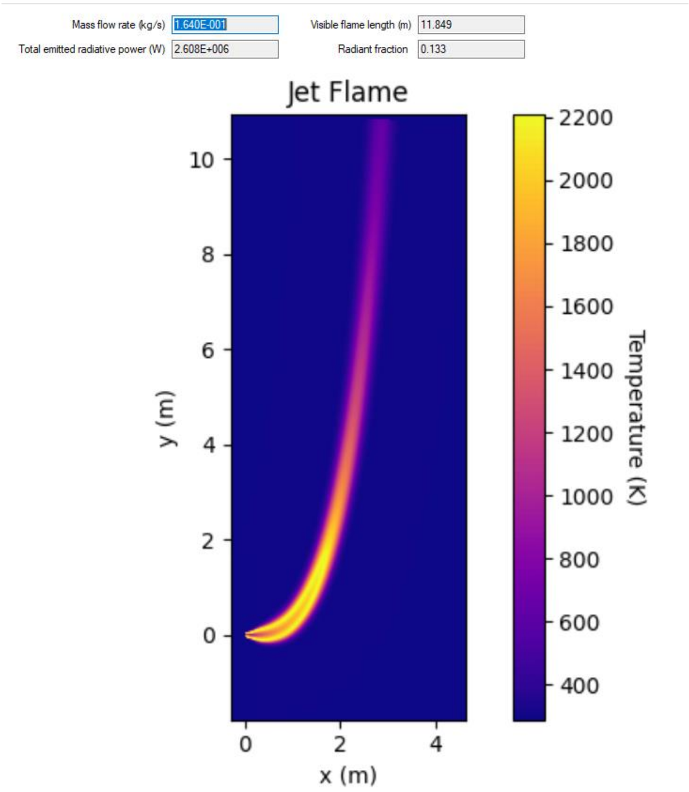


Mass flow rate (kg/s) 2.109E-001
Visible flame length (m) 8.150
Total emitted radiative power (W) 1.758E+006
Radiant fraction 0.069

***Figure 4.18 Jet flame temperature and trajectory plot for HRS***

## Case Study 3: Hydrogen Refuelling Station (HRS) with hydrogen in liquid phase

In case of HRS with liquid hydrogen in tanks, the mass flow rate is 1.640E-001 (kg/s), total emitted radiative power is 2.608E+006 and the visible flame length is 11.849 m. The values and the behaviour of the jet flame can be seen in the figure 4.19.



Mass flow rate (kg/s) 1.640E-001
Visible flame length (m) 11.849
Total emitted radiative power (W) 2.608E+006
Radiant fraction 0.133

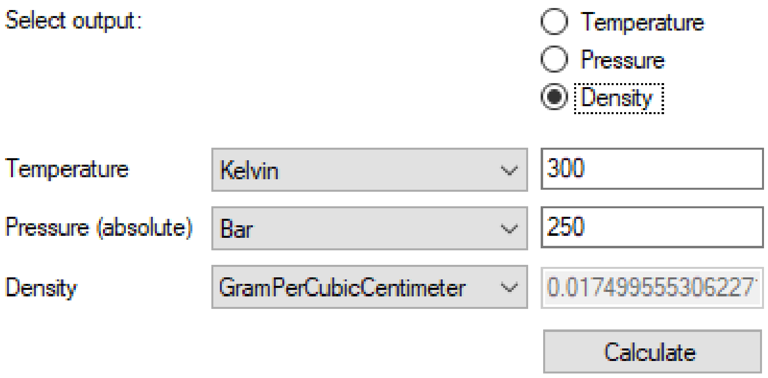
***Figure 4.19 Jet Flame Temperature and Trajectory Plot for HRS with liquid hydrogen in tanks***

### 4.2.4. Temperature, Pressure and Density

HyRAM also helps to calculate the required property if any of the two properties are given as input from temperature, pressure and density. Here density is calculated using the values of temperature, pressure.

**Case Study 1: Model Case Study**

In the case of dispenser, the density is calculated. It can be seen in the figure below, temperature is 300 K, pressure is 250 bar and HyRAM calculates the density as 0.01749 g/cm$^3$.



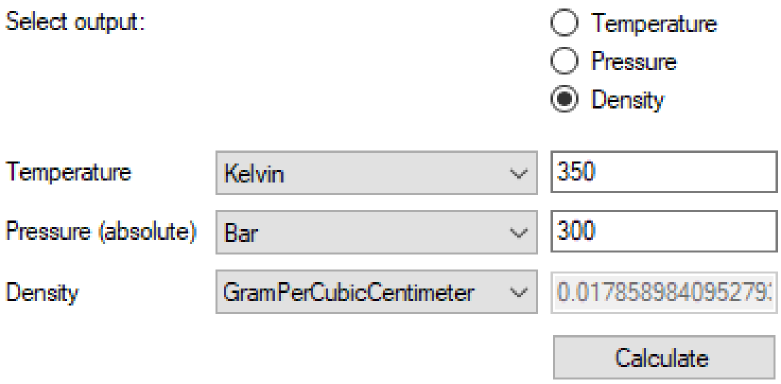
Select output:
○ Temperature
○ Pressure
● Density

Temperature Kelvin 300
Pressure (absolute) Bar 250
Density GramPerCubicCentimeter 0.017499555306227

***Figure 4.20 Density Calculated for Dispenser***

### Case Study 2: Hydrogen Refuelling Station (HRS)

For hydrogen refueling station HRS, temperature is 350 K, pressure is 300 bar density is 0.01785 g/cm$^3$.



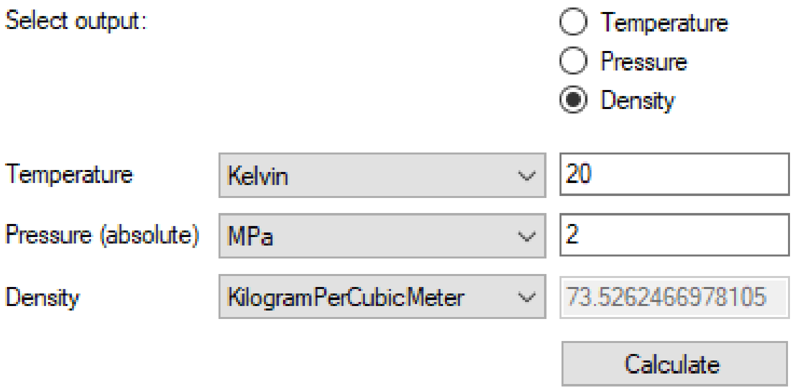
Select output:
○ Temperature
○ Pressure
● Density

Temperature: Kelvin 350
Pressure (absolute): Bar 300
Density: GramPerCubicCentimeter 0.017858984095279

*Figure 4.21 Density Calculated for HRS*

### Case Study 3: Hydrogen Refuelling Station (HRS) with hydrogen in liquid phase

Calculated density for HRS with liquid hydrogen in tanks is shown in the figure below. The temperature is 20 K, pressure is 2 bar and calculated density is 73.5262 g/cm$^3$.



Select output:
○ Temperature
○ Pressure
● Density

Temperature: Kelvin 20
Pressure (absolute): MPa 2
Density: KilogramPerCubicMeter 73.5262466978105

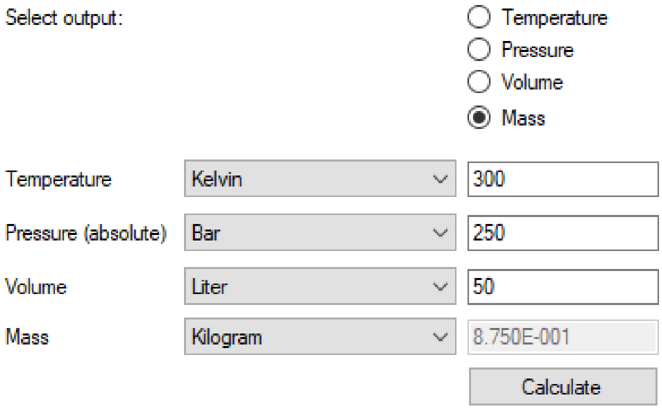
*Figure 4.22 Density Calculated for HRS with hydrogen in liquid phase*

## 4.2.5. Tank Mass Parameter

Similarly, the desired output can be selected according to the requirement. Temperature, pressure, and volume are given as input, and it calculates mass in the tank. The calculated masses for all the three cases are also shown in the figures below.

### Case Study 1: Model Case Study

For 300 K temperature, 250 bar pressure and 50 liters of hydrogen, the calculated mass in the tank is 8.750E-001 kg for dispenser.



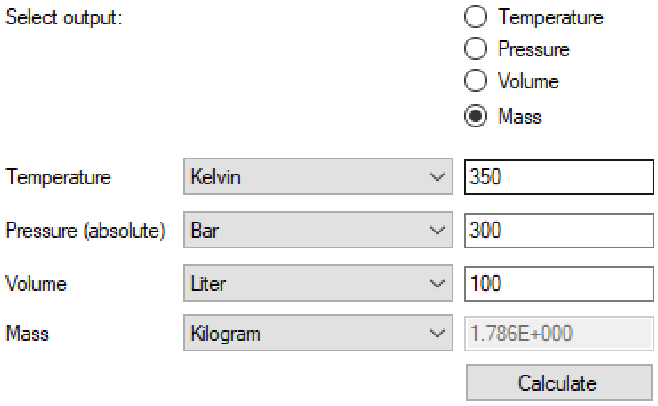
Select output:
○ Temperature
○ Pressure
○ Volume
● Mass

| | | |
|---|---|---|
| Temperature | Kelvin | 300 |
| Pressure (absolute) | Bar | 250 |
| Volume | Liter | 50 |
| Mass | Kilogram | 8.750E-001 |

***Figure 4.23 Tank Mass for Dispenser***

### Case Study 2: Hydrogen Refuelling Station (HRS)

In case of HRS, tank mass is 1.786 kg when temperature is 350 K, pressure 300 bar and hydrogen volume is 100 litres.



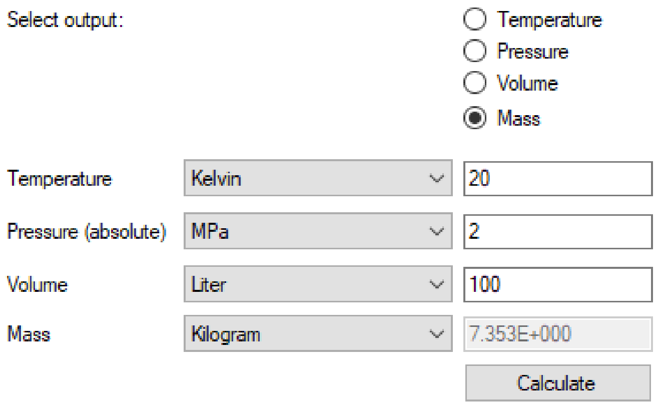
Select output:
○ Temperature
○ Pressure
○ Volume
● Mass

| | | |
|---|---|---|
| Temperature | Kelvin | 350 |
| Pressure (absolute) | Bar | 300 |
| Volume | Liter | 100 |
| Mass | Kilogram | 1.786E+000 |

***Figure 4.24 Tank Mass for HRS***

### Case Study 3: Hydrogen Refuelling Station (HRS) with hydrogen in liquid phase

For HRS with liquid in tanks, the mass is 7.353 kg when the hydrogen is in liquid phase in the tanks.


Select output:
○ Temperature
○ Pressure
○ Volume
● Mass

Temperature Kelvin 20
Pressure (absolute) MPa 2
Volume Liter 100
Mass Kilogram 7.353E+000

*Figure 4.25 Tank Mass for HRS with hydrogen in liquid phase*

### 4.2.6. Mass Flow Rate

Time to empty the tank can be calculated using HyRAM. For this, it is required to input the temperature, pressure, ambient pressure, volume, orifice diameter and discharge coefficient. Release type also has to be chosen.

#### Case Study 1: Model Case Study

In case of dispenser, it takes 4.815E+002 seconds to empty the tank. As shown in the figure 4.26 under.

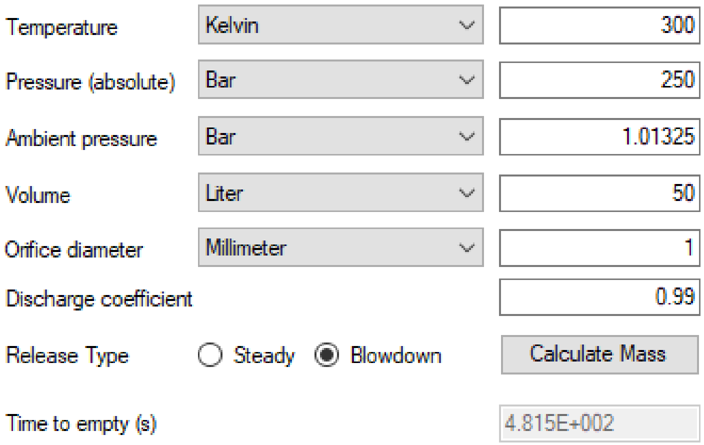
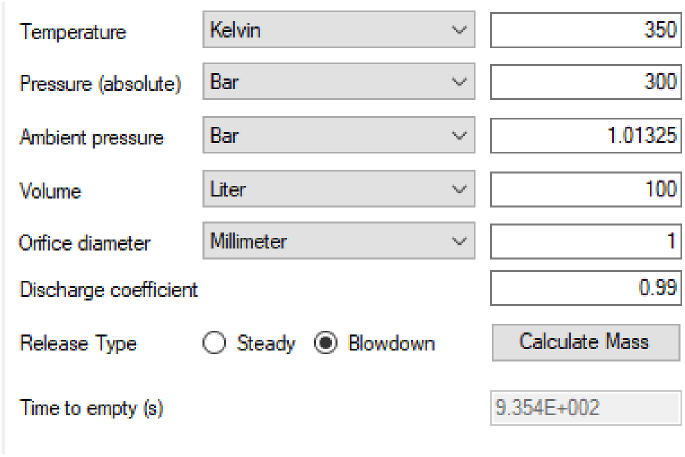

Temperature Kelvin 300
Pressure (absolute) Bar 250
Ambient pressure Bar 1.01325
Volume Liter 50
Orifice diameter Millimeter 1
Discharge coefficient 0.99
Release Type ○ Steady ● Blowdown
Time to empty (s) 4.815E+002

*Figure 4.26 Time to empty tank for dispenser*

#### Case Study 2: Hydrogen Refuelling Station (HRS)

It can be seen in the figure 4.27, the tank will be empty in 9.354E+002 when it is calculated for HRS.

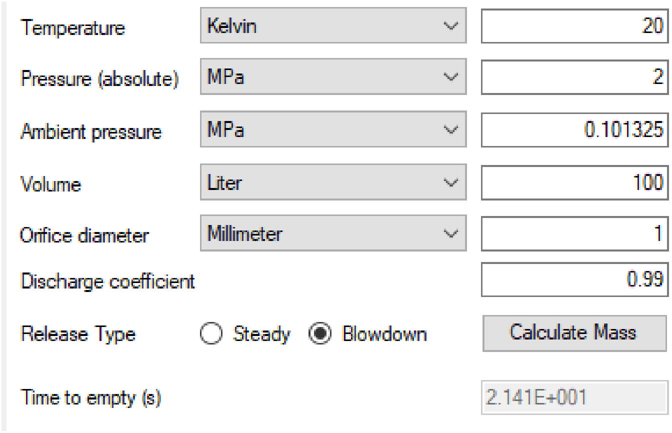


| | | |
|---|---|---|
| Temperature | Kelvin | 350 |
| Pressure (absolute) | Bar | 300 |
| Ambient pressure | Bar | 1.01325 |
| Volume | Liter | 100 |
| Orifice diameter | Millimeter | 1 |
| Discharge coefficient | | 0.99 |
| Release Type | ○ Steady ● Blowdown | |
| Time to empty (s) | | 9.354E+002 |

*Figure 4.27 Time to empty tank for HRS*

### Case Study 3: Hydrogen Refuelling Station (HRS) with Liquid hydrogen in tanks

Similarly, tank will be empty in 2.141E+001 when hydrogen is in liquid phase and shown in the figure 4.28.

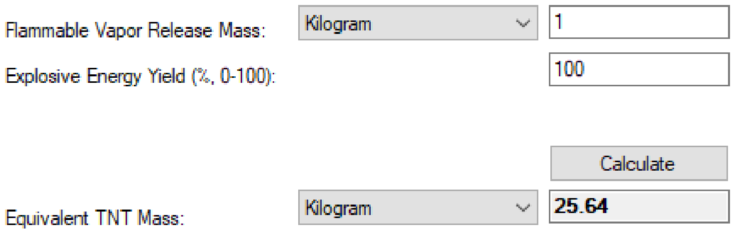


| | | |
|---|---|---|
| Temperature | Kelvin | 20 |
| Pressure (absolute) | MPa | 2 |
| Ambient pressure | MPa | 0.101325 |
| Volume | Liter | 100 |
| Orifice diameter | Millimeter | 1 |
| Discharge coefficient | | 0.99 |
| Release Type | ○ Steady ● Blowdown | |
| Time to empty (s) | | 2.141E+001 |

*Figure 4.28 Time to empty tank for HRS with hydrogen in liquid phase*

## 4.2.7. TNT Mass Equivalence

The energy yield from the combustion of a given quantity of hydrogen may be equated to the energy release from a TNT explosion. It can be seen in the Figure 4.29, HyRAM calculates as 1 kilogram of flammable vapor release mass is equivalent to 25.64 kilograms of TNT Mass when explosive energy yield is 100%.


Flammable Vapor Release Mass: Kilogram 1

Explosive Energy Yield (%, 0-100): 100

Equivalent TNT Mass: Kilogram 25.64

*Figure 4.29 Equivalent TNT Mass*

## 4.3. Discussion

In this section, the results obtained for the Quantitative Risk Analysis (QRA) using HyRAM+ software are discussed. The output values, along with plots, graphs, tables and other visuals are compared and analysed with respect the system and input parameters.

The calculated risk metrics, including Potential Loss of Life (PLL), Fatal Accidental Rate (FAR), and Average Individual Risk (AIR), offer valuable insights into the safety aspects of each system. The dispenser case study exhibited the lowest PLL of 3.733E-006 fatalities per system year, while the HRS had the highest PLL of 2.138E-005 fatalities per system year. These values provide a quantitative measure of the risk associated with each system and can aid in decision-making processes related to risk mitigation strategies. The thermal effects plots illustrate the radiative heat flux experienced by occupants within the facility for different leak sizes. As expected, larger leak sizes result in higher heat flux levels, particularly for occupants in the direction of the leak. This information is crucial for designing appropriate safety measures, such as evacuation procedures and personal protective equipment requirements.

The physics models for plume dispersion and indoor accumulation provide valuable insights into the behaviour of hydrogen leaks. The mass flow rate calculations and distance to hazard data aid in understanding the dispersion characteristics of hydrogen. Additionally, the indoor accumulation plots, including overpressure, flammable mass, layer thickness, and trajectory, offer a comprehensive understanding of the potential consequences of indoor hydrogen releases. The analysis of jet flame temperature, trajectory, and visible flame length is crucial for assessing the thermal hazards associated with hydrogen leaks. The results demonstrate the influence of leak size on these parameters, with larger leaks resulting in higher temperatures and longer visible flame lengths.

The chapter also presents results related to temperature, pressure, density, tank mass, mass flow rate, and TNT mass equivalence. These calculations provide valuable data for understanding the physical properties and behaviour of hydrogen under various conditions, which can inform the design and operation of hydrogen systems.

The results presented in this chapter offer a comprehensive quantitative risk assessment for each case mentioned earlier. The analysis covers a wide range of risk metrics, thermal effects, and physics models, providing valuable insights for enhancing the safety and reliability of hydrogen infrastructure.

# 5. Conclusion

The study provides a comprehensive examination of the methodologies and tools used to assess and mitigate risks associated with hydrogen facilities. The study is structured into four main chapters, each addressing different aspects of the risk analysis process. Here is a brief recap of the chapters.

It starts with discussing the importance of safety in hydrogen facilities and the role of Quantitative Risk Analysis (QRA) in ensuring this safety. It outlines the objectives of the study, which include evaluating the effectiveness of the HyRAM software in conducting QRA for hydrogen refuelling stations and understanding the impact of design choices on safety. The chapter details the tools and models used for risk assessment, including HyRAM software and PLOFAM models, and the steps required to create representative risk contours. The chapter presents three case studies of hydrogen refuelling stations, each with different configurations, providing practical insights into the application of HyRAM and the impact of different design choices on risk profiles. The final chapter discusses the QRA outputs, presenting risk metrics such as Potential Loss of Life, Fatal Accident Rate, Average Individual Risk, thermal effects, plume dispersion, and indoor accumulation of hydrogen leaks.

The risk assessment methodology presented provides a comprehensive framework for evaluating the safety aspects of hydrogen refuelling stations (HRS) and related systems. The application of the HyRAM+ software, coupled with detailed case studies, offers valuable insights into the potential risks associated with various components and configurations.

The dispenser case study demonstrated the software's capabilities and served as a foundation for understanding the risk assessment process. The analysis of the more complex HRS infrastructure highlighted the importance of considering multiple systems and their interactions in the overall risk assessment. The alternative system, which replaced the compressor with a pump and utilized liquid hydrogen tanks, showcased the versatility of the methodology in evaluating different configurations. The calculated risk metrics, such as Potential Loss of Life (PLL), Fatal Accidental Rate (FAR), and Average Individual Risk (AIR), provided quantitative measures of risk for each system, enabling informed decision-making regarding risk mitigation strategies.

The thermal effects plots, physics models for plume dispersion and indoor accumulation, and analysis of jet flame characteristics offered valuable insights into the behaviour of hydrogen leaks and their potential consequences. These results can guide the design of appropriate safety measures, evacuation procedures, and personal protective equipment requirements.

Overall, the risk assessment methodology presented in this thesis contributes to the safe implementation and operation of hydrogen refuelling stations by providing a comprehensive framework for identifying and mitigating potential risks.

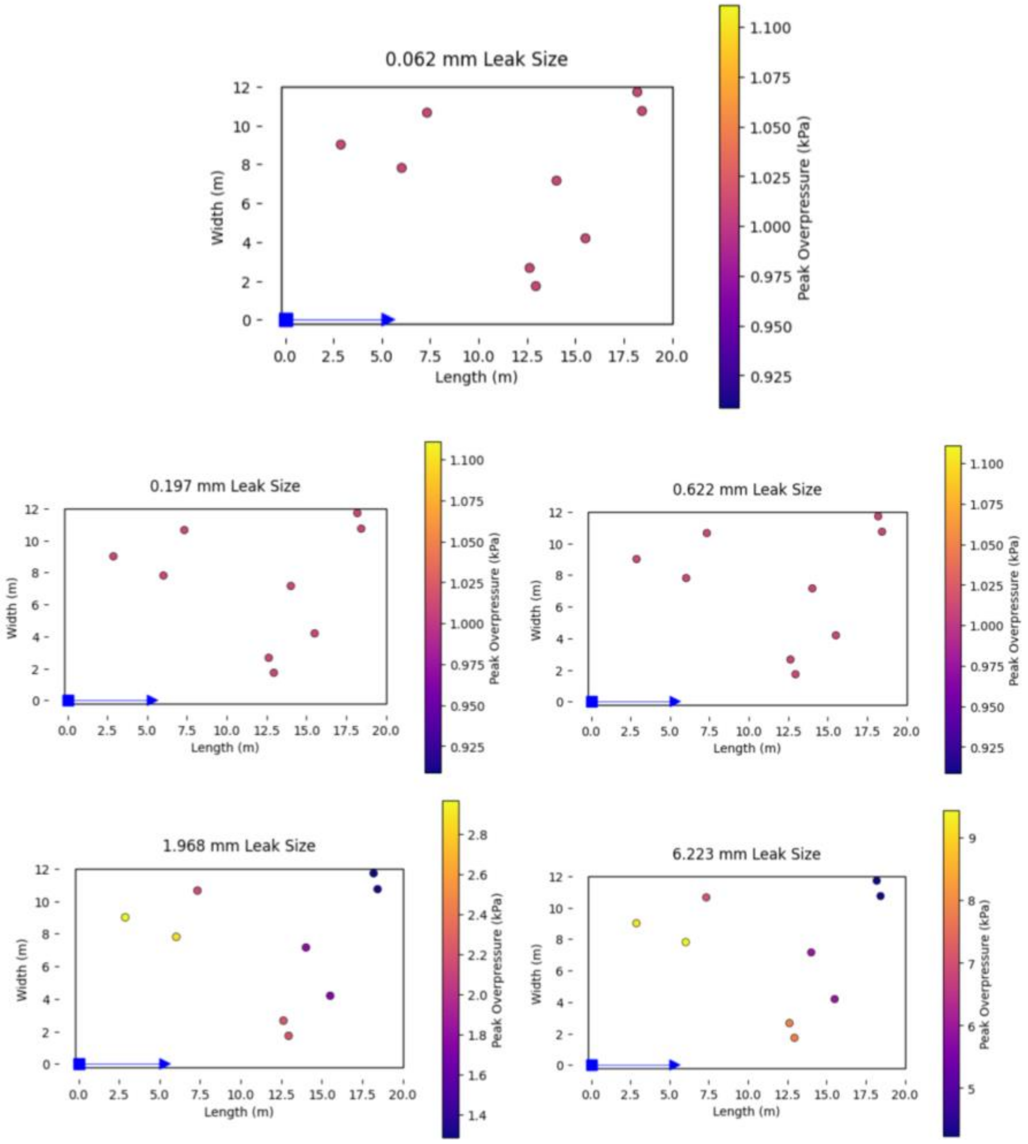
## 5.1. Future Work

The study presents a robust risk assessment methodology for hydrogen technologies. However, it suggests several areas for further investigation. These include continuous validation and refinement of models, integration of advanced computational fluid dynamics simulations, consideration of emerging technologies, expansion to other hydrogen applications, integration with risk management frameworks, and standardization and regulatory alignment. These areas aim to ensure accurate and reliable results, adapt to emerging technologies, and promote the safe and sustainable implementation of hydrogen technologies. Collaboration with industry partners, regulatory bodies, and international organizations can facilitate the standardization of risk assessment methodologies for hydrogen infrastructure.

# Appendix A

## a. For Dispenser

### 1a. Over Pressure



0.062 mm Leak Size

0.197 mm Leak Size

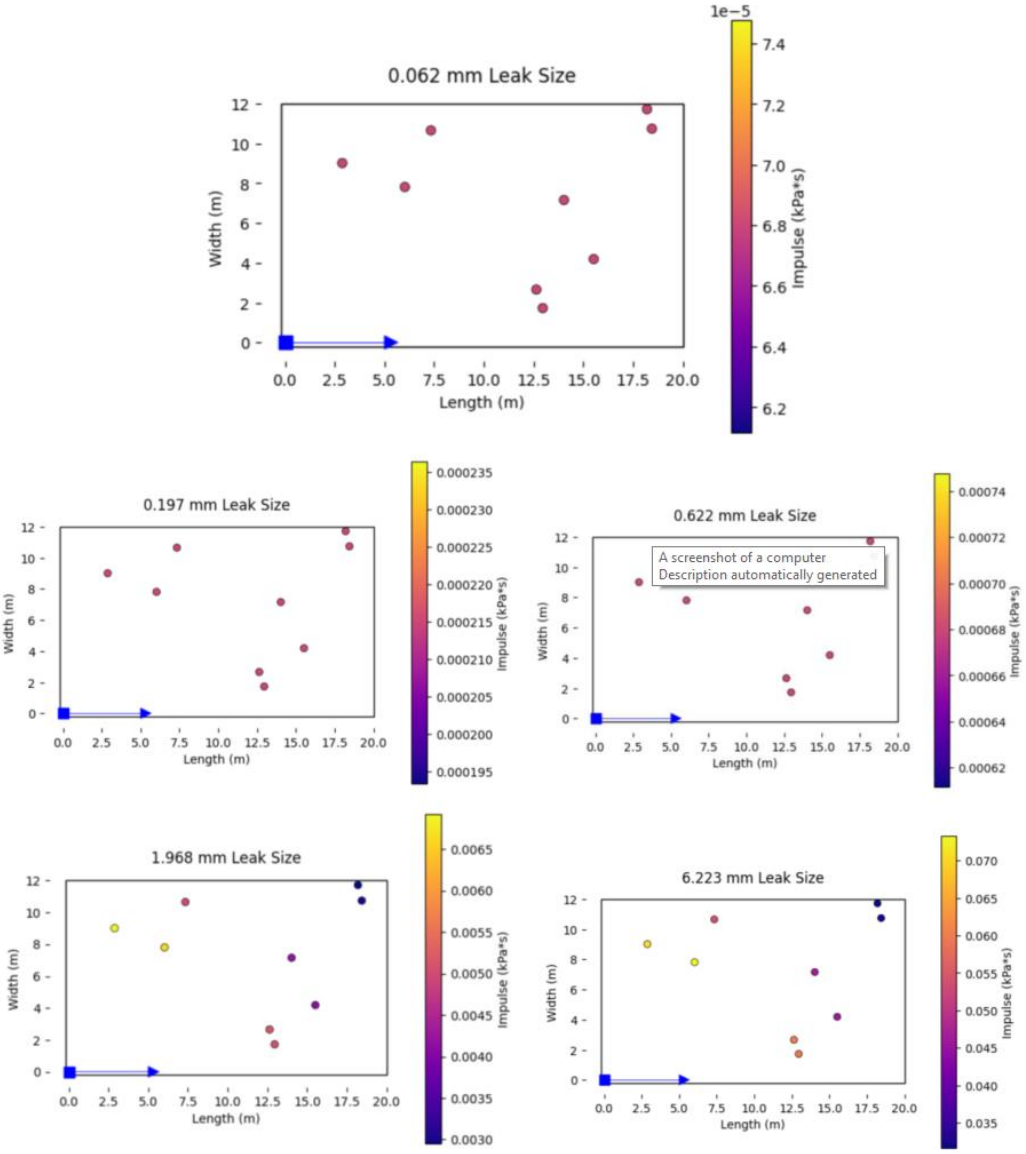
0.622 mm Leak Size

1.968 mm Leak Size

6.223 mm Leak Size

*Over Pressure Plots for Dispenser*

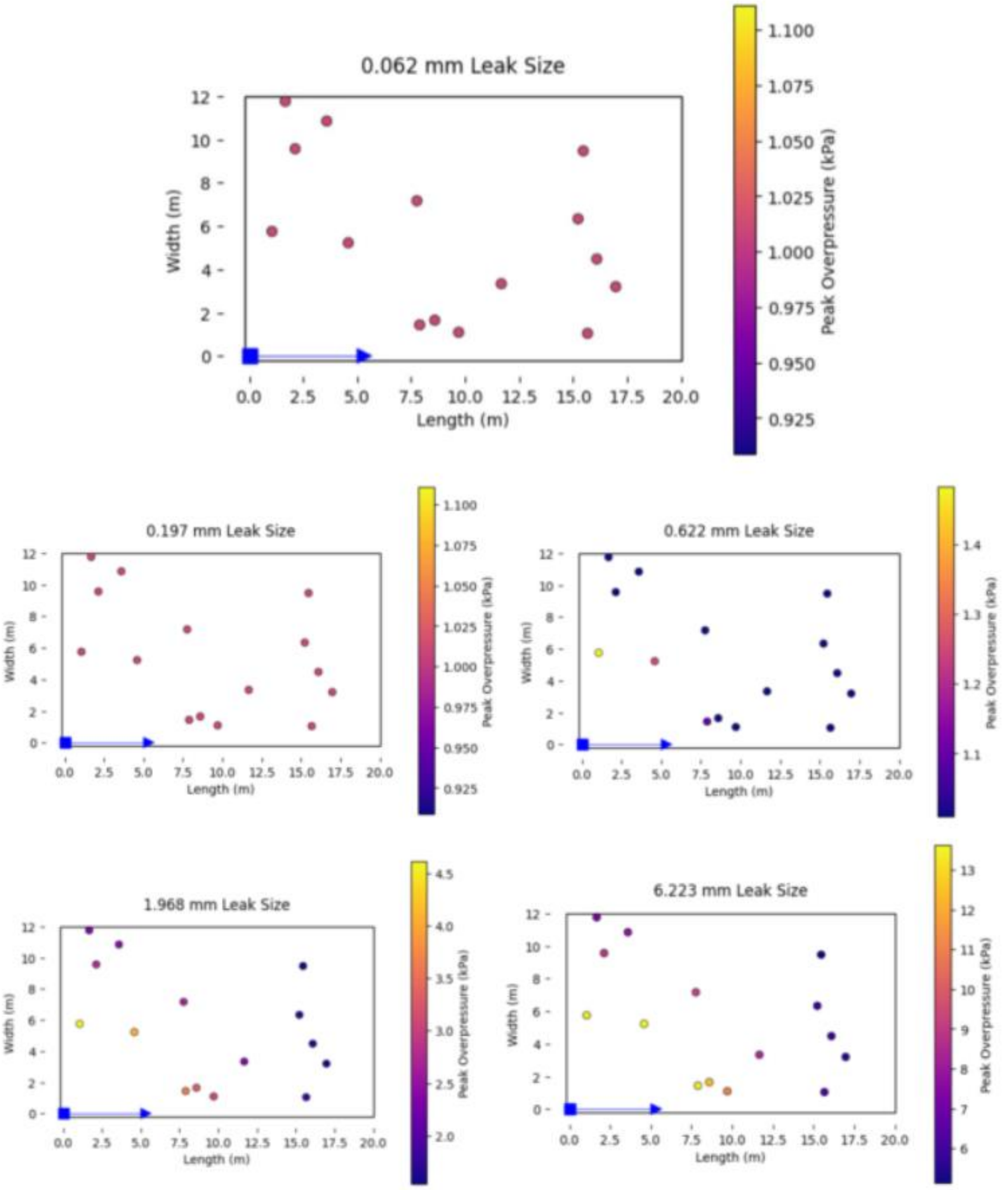
## 2a. Impulse



*Impulse Plots for Dispenser*

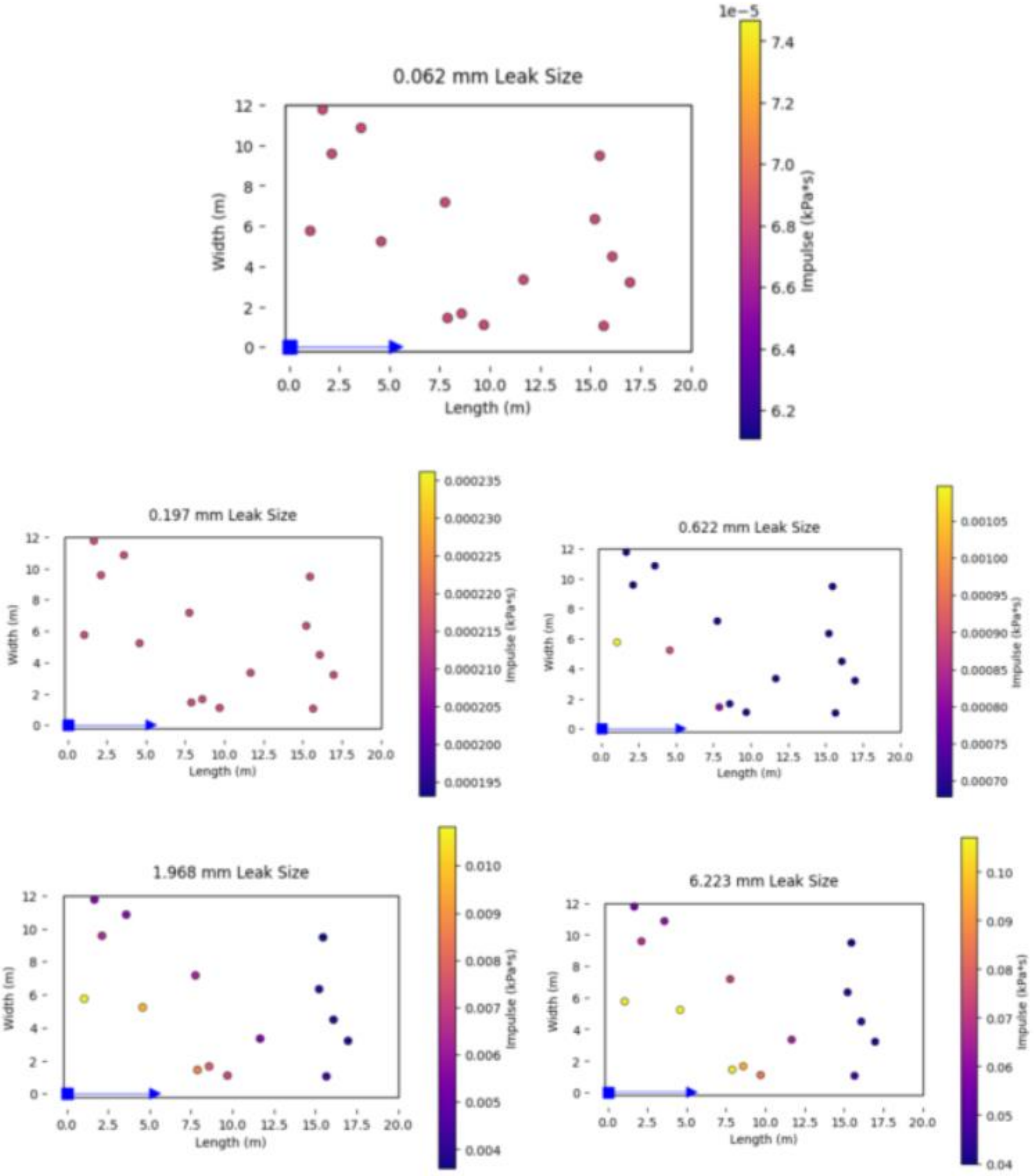
## b. For HRS

## 1b. Over Pressure



*Over Pressure Plots for HRS*

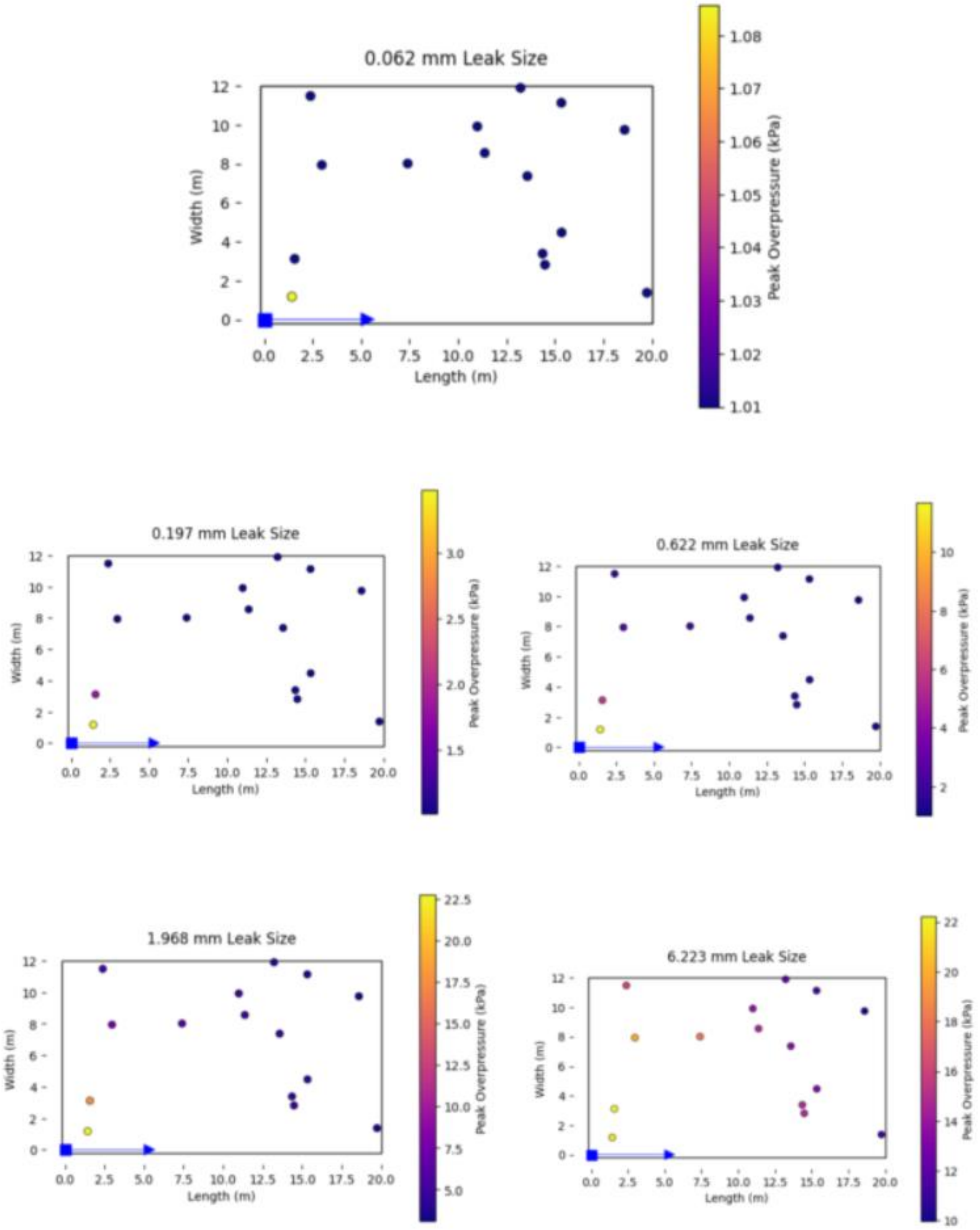
## 2b. Impulse



*Impulse Plots for HRS*

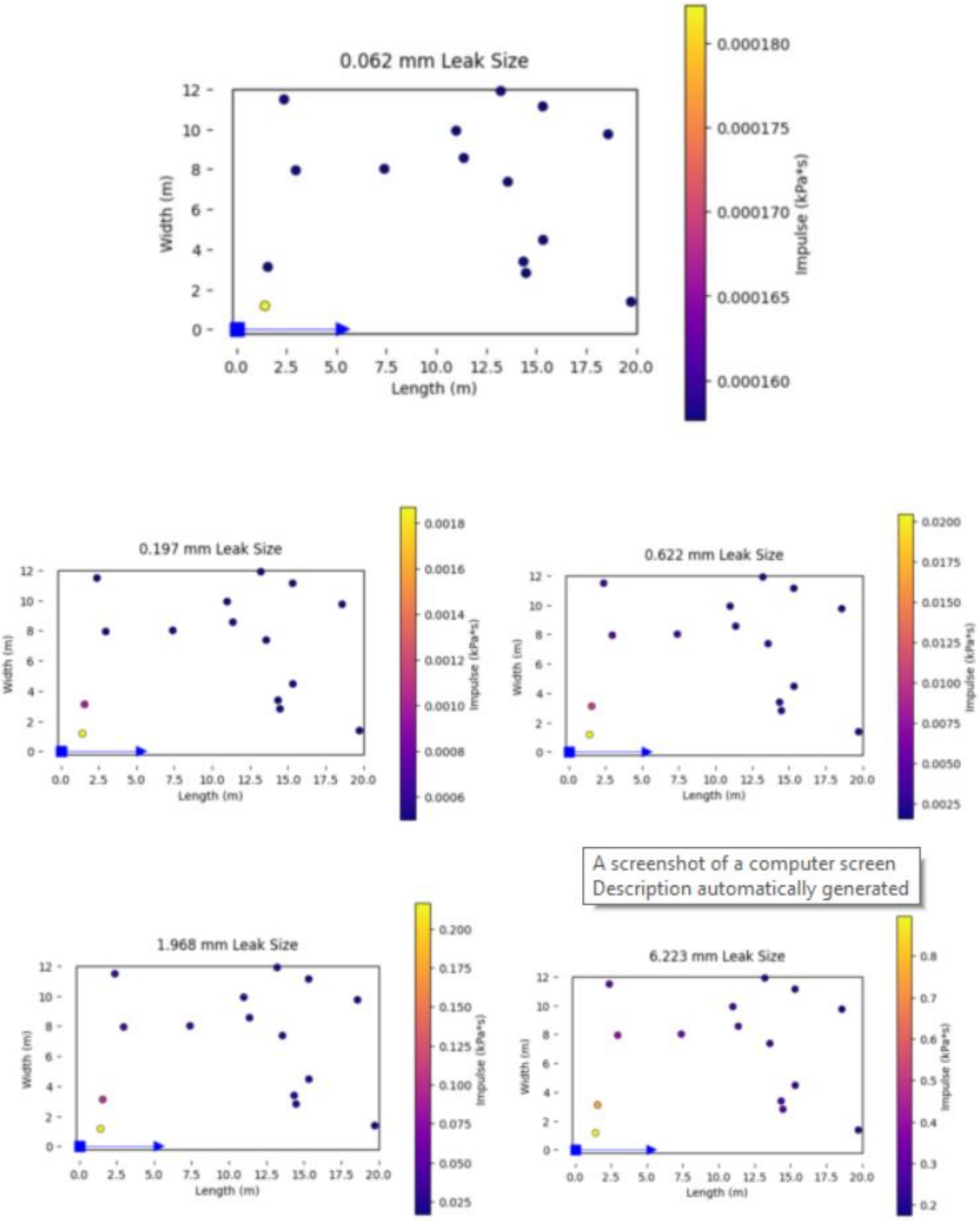
## c. For HRS with liquid hydrogen

### 1c. Over Pressure



*Over Pressure Plots for HRS with liquid hydrogen in tanks.*

## 2c. Impulse



A screenshot of a computer screen
Description automatically generated

*Impulse Plots for HRS with liquid hydrogen in tanks.*

# References

(DSB), D. f. s. o. b. (2012). *Sikkerheten rundt anlegg som håndterer brannfarlige, reaksjonsfarlige, trykksatte og eksplosjonsfarlige stoffer*. https://www.dsbinfo.no/DSBno/2013/Tema/Sikkerhetenrundtanleggsomhndtererbrannfarligereaksjonsfarligetrykksatteogeksplosjonsfarligestoffer/

(DSB), D. f. s. o. b. (2016). *Veileder om sikkerheten rundt storulykkevirksomheter*. https://www.dsbinfo.no/DSBno/2017/tema/veilederom-sikkerhetenrundtstorulykkevirksomheter/

Agll, A. A. A., Hamad, T. A., Hamad, Y. M., Bapat, S. G., & Sheffield, J. W. (2016). Development of design a drop-in hydrogen fueling station to support the early market buildout of hydrogen infrastructure. *International Journal of Hydrogen Energy*, *41*(10), 5284-5295. https://doi.org/https://doi.org/10.1016/j.ijhydene.2016.01.138

Ajanovic, A., & Haas, R. (2018). Economic prospects and policy framework for hydrogen as fuel in the transport sector. *Energy Policy*, *123*, 280-288. https://doi.org/https://doi.org/10.1016/j.enpol.2018.08.063

Ehrhart, B. D., & Hecht, E. S. (2022). *Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 5.0 Technical Reference Manual*. https://www.osti.gov/biblio/1900089

https://www.osti.gov/servlets/purl/1900089

Feliciano, G., Ehrhart, B. D., & Muna, A. B. (2019). *HyRAM V2.0 User Guide*. https://www.osti.gov/biblio/1762969

https://www.osti.gov/servlets/purl/1762969

Groth, K., Hecht, E., Reynolds, J. T., Blaylock, M. L., & Carrier, E. E. (2017). *Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.1 technical reference manual*. https://www.osti.gov/biblio/1365456

https://www.osti.gov/servlets/purl/1365456

Huser, A., Bucelli, M., Zakariyya, K., Skinnemoen, M.M., Nadim, P. (2021). Quantitative Risk Analysis of Scaled-Up Hydrogen Facilities. https://hysafe.info/uploads/papers/2021/27.pdf

*IEA*. (2019). https://www.iea.org/reports/the-future-of-hydrogen

Jouybari, A. K., Ilinca, A., Ghorbani, B., & Rooholamini, S. (2022). Thermodynamic and exergy evaluation of an innovative hydrogen liquefaction structure based on ejector-compression refrigeration unit, cascade multi-component refrigerant system, and Kalina power plant. *International Journal of Hydrogen Energy*, *47*(62), 26369-26393. https://doi.org/https://doi.org/10.1016/j.ijhydene.2022.01.190

Kovač, A., Paranos, M., & Marciuš, D. (2021). Hydrogen in energy transition: A review. *International Journal of Hydrogen Energy*, *46*(16), 10016-10035. https://doi.org/https://doi.org/10.1016/j.ijhydene.2020.11.256

Li, Y., Cui, F., & Li, L. (2018). An integrated optimization model for the location of hydrogen refueling stations. *International Journal of Hydrogen Energy*, *43*(42), 19636-19649. https://doi.org/https://doi.org/10.1016/j.ijhydene.2018.08.215

Lototskyy, M. V., Yartys, V. A., Pollet, B. G., & Bowman, R. C. (2014). Metal hydride hydrogen compressors: A review. *International Journal of Hydrogen Energy*, *39*, 5818-5851.

Riedl, S. M. (2020). Development of a Hydrogen Refueling Station Design Tool. *International Journal of Hydrogen Energy*, *45*, 1-9.

Rievaj, V., Gaňa, J., & Synák, F. (2019). Is hydrogen the fuel of the future? *Transportation Research Procedia*, *40*, 469-474. https://doi.org/10.1016/j.trpro.2019.07.068

Robert, B. H. (2020). VISIONS OF A HYDROGENECONOMY - THE ELEMENT HYDROGEN. https://www.linkedin.com/pulse/visions-hydrogeneconomy-element-hydrogen-hatvani-robert/

Sadi, M., & Deymi-Dashtebayaz, M. (2019). Hydrogen refueling process from the buffer and the cascade storage banks to HV cylinder. *International Journal of Hydrogen Energy*, *44*(33), 18496-18504. https://doi.org/https://doi.org/10.1016/j.ijhydene.2019.05.023

Tanvir, F. (2019). *Hydrogen is back in Vogue*. https://adi-analytics.com/2019/11/12/hydrogen-is-back-in-vogue/

Tarhan, C., & Çil, M. A. (2021). A study on hydrogen, the clean energy of the future: Hydrogen storage methods. *Journal of energy storage*, *40*, 102676.

Vysus. (2021). *Guidelines for Quantitative Risk Analysis of Facilities Handling Hazardous Substances*. https://www.dsb.no/contentassets/dbd79a7d06e0473bb2d44ba9760cc4a6/prj11100262033_final_report_rev_2021-2.pdf

NTNU

Norwegian University of
Science and Technology