# APPENDIX H

## Quantitative Risk Assessment

# Quantitative Risk Assessment – Bear Head Energy Ammonia Production Facility

FINAL REPORT

January 27, 2023

Prepared for:

Bear Head Energy Inc.

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Project Number: 121431287

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# Executive Summary

Bear Head Energy (BHE) retained Stantec Consulting Ltd. (Stantec) to complete a preliminary Quantitative Risk Assessment (QRA) associated with accidental releases from process activities at a production, storage, and loading facility (the Facility) located in the Point Tupper Industrial Park in Richmond County, Nova Scotia. The Facility is proposed to use renewable electricity to produce ammonia through the synthesis of hydrogen and nitrogen via the Haber-Bosch process.

The objective of this QRA is to review the public safety risks from potential major accident hazard events, based on the likelihood and severity of these incidents. The results of the QRA are typically compared to offsite guidelines for risk as published by the Canadian Society for Chemical Engineering. The QRA can also be used to identify risk mitigation measures as part of an overall risk management strategy for the Facility.

The QRA included the following tasks:

1. Description of the proposed facility and how it is expected to operate.
2. Identification of major accident hazards.
3. Source characterization of several loss of containment (LOC) scenarios from several processes including:
    a. Hydrogen production,
    b. Ammonia reaction,
    c. Ammonia separation, and
    d. Ammonia storage and transfer to a marine terminal.
4. Consequence modeling to determine the extents of hazard zones for various combinations of release types, hazards, and meteorological conditions.
5. Risk modeling, which combines the results of the consequence modelling with the probability of a release occurring and probability for various meteorological conditions, to provide an estimate of the likelihood of harm.

The primary hazards associated with accidental releases from the facility are through inhalation toxicity from ammonia gas. There are also flammability hazards associated with hydrogen and ammonia. Accidents or malfunctions at the Facility may result in hazardous events including:

- Dispersion of an unignited toxic cloud
- Flash Fires (impingement of a moving flame front upon ignition of a flammable dispersing cloud);
- Vapour Cloud explosions (overpressure resulting from a flame front moving rapidly through a congested area);
- Jet Fires/Fireballs/Pool Fires (exposure to thermal radiation); and

- Explosions from storage vessels or process containers (overpressure, shrapnel and thermal radiation).

Consequence modelling was completed for potential hazardous events to provide the distances to selected endpoints and the expected consequence at a location away from the source. Consequence modelling was completed for a range of weather conditions, release scenarios and configurations. The results of this modelling can be used to inform emergency responders and assist in the development of emergency response plans and during engineering and design to identify areas of the process where additional mitigation might be beneficial in reducing off-site consequences. Additionally, the consequence modelling was used as input to the subsequent risk modelling.

Risk modelling was completed to evaluate the potential for harm at locations within the facility. The modelling was completed with consideration of both the potential consequences and their likelihood of occurrence. The results of the risk modelling were compared to risk criteria published by the Canadian Society for Chemical Engineering.

The risk analysis indicated that the risk from the facility is low and that, from a risk perspective, the facility is in an appropriate location considering the other nearby land uses.

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## Abbreviations

| | |
|---|---|
| AEGL | Acute Exposure Guideline Levels |
| ASU | Air Separation Unit |
| BHE | Bear Head Energy Inc. |
| BLEVE | Boiling liquid expanding vapour explosion |
| CSChE | Canadian Society for Chemical Engineering |
| ECCC | Environment and Climate Change Canada |
| HSE | Health and Safety Executive |
| LFL | Lower flammability limit |
| LOC | Loss of containment |
| MAH | Major accident hazard |
| MEM | Multi-Energy method |
| NFPA | National Fire Protection Association |
| QRA | Quantitative risk assessment |
| RMP | Risk management plan |
| TDU | Thermal dose unit |
| TNO | Netherlands Organization for Applied Scientific Research |
| US EPA | United States Environmental Protection Agency |
| VCE | Vapour cloud explosion |
| WRC | Water Recycling Center |

# 1.0 INTRODUCTION

Bear Head Energy Inc. (BHE) retained Stantec Consulting Ltd. (Stantec) to complete a preliminary Quantitative Risk Assessment (QRA) associated with accidental releases from process activities at a production, storage, and loading facility (the Facility) located in the Point Tupper Industrial Park in Richmond County, Nova Scotia. The Facility is currently being designed to produce 5,440 tonnes/day of anhydrous ammonia. The ammonia will be produced from hydrogen and nitrogen, both generated on site, through the Haber-Bosch process

The objective of this QRA is to estimate the risks to public safety resulting from potential release of hazardous materials. The risk is based on the likelihood and severity of these incidents.

This report outlines the modelling methodology and assumptions used to conduct the QRA. The report also provides estimates of the distances to selected hazard endpoints. Finally, the report presents the results of the risk assessment compared to risk criteria developed by the Canadian Society of Chemical Engineering.

# 2.0 SYSTEM/INSTALLATION DESCRIPTION

BHE will utilize air and water to produce nitrogen and hydrogen, respectively. The hydrogen and nitrogen are combined at high pressure and temperature through the Haber-Bosch process to produce anhydrous ammonia. A site plan for the proposed Facility is shown in Figure 2-1. A simplified process flow diagram is presented in Figure 2-2. The piping layout as currently proposed is shown in Figure 2-3.

The main processes of the facility include:

- Hydrogen production, where electrolysers will separate water into hydrogen and oxygen.
- Nitrogen production, where air separation units (ASUs) will extract nitrogen from ambient air.
- Ammonia production, where pre-heaters and compression facilities are used to increase temperature and pressure sufficiently to produce ammonia from the hydrogen and nitrogen feed gases.
- Ammonia separation, where the outputs of ammonia production, including ammonia and unreacted hydrogen and nitrogen, are cooled to separate ammonia as a liquid from the output stream. Ammonia proceeds to storage, while unreacted hydrogen and nitrogen are recycled to the ammonia production process.
- An ammonia storage system and the marine terminal piping for ammonia export.

The detailed design for the facility has not been completed. For the purposes of the QRA, a draft process overview was developed to estimate flow rates, operating pressures and temperatures, and storage volumes. Summaries of the facility operating conditions for the main processes that were used for the QRA are provided in Appendix A. The facility operating conditions will continue to be refined during detailed design of the facility.

**Figure 2-1 Project Site Plan**

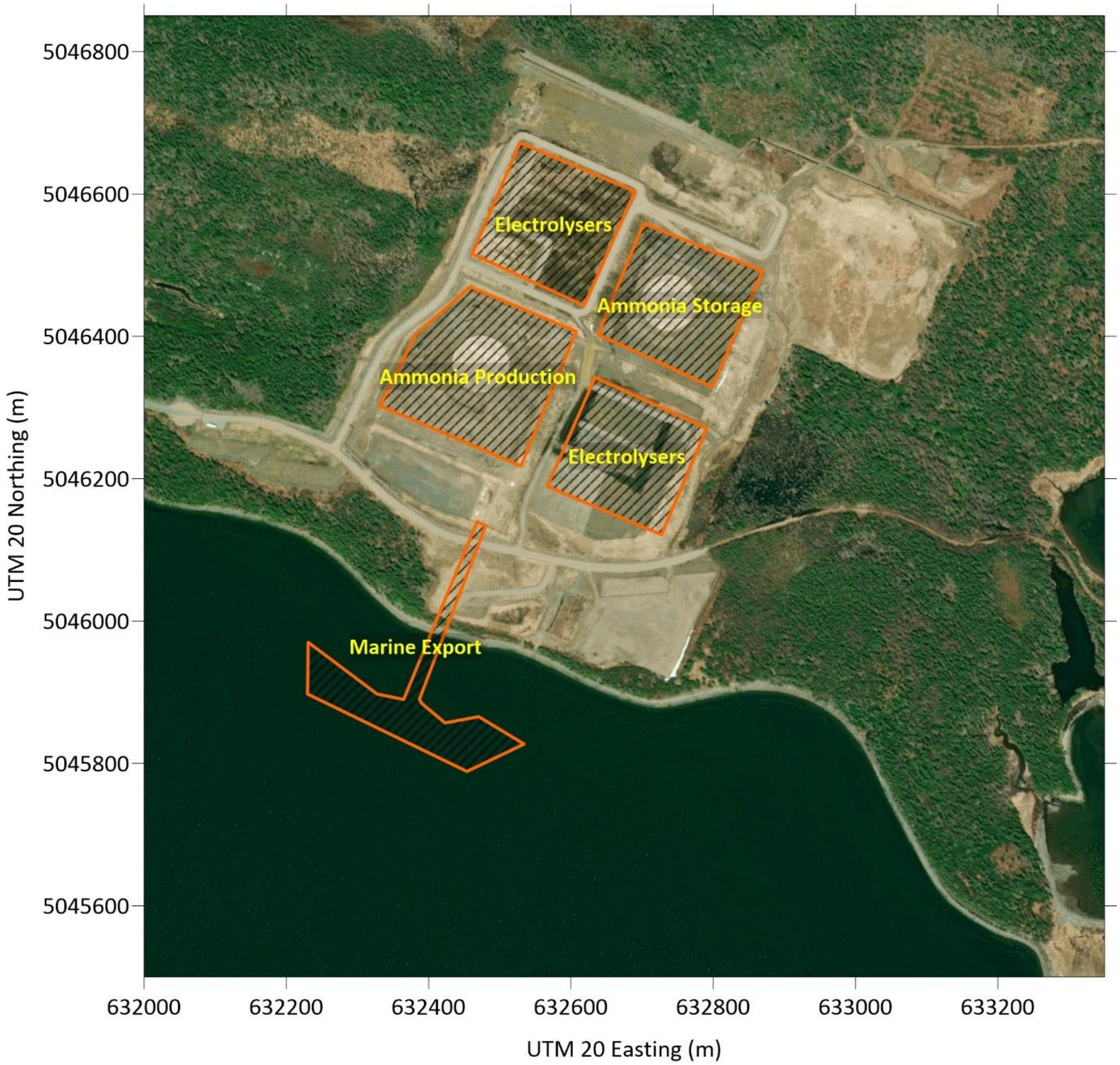


**Figure 2-2 Simplified Process Flow Diagram of the Ammonia Production Facility**

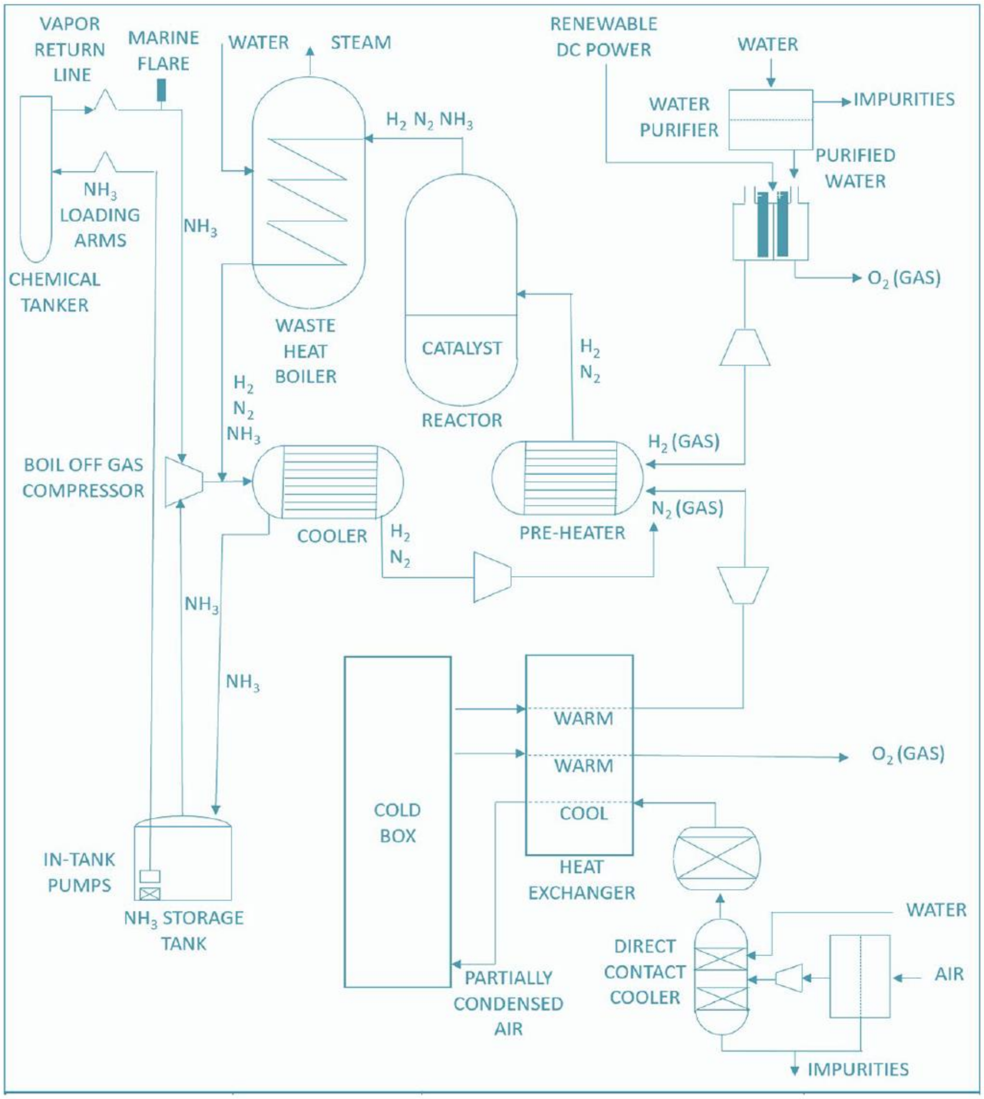
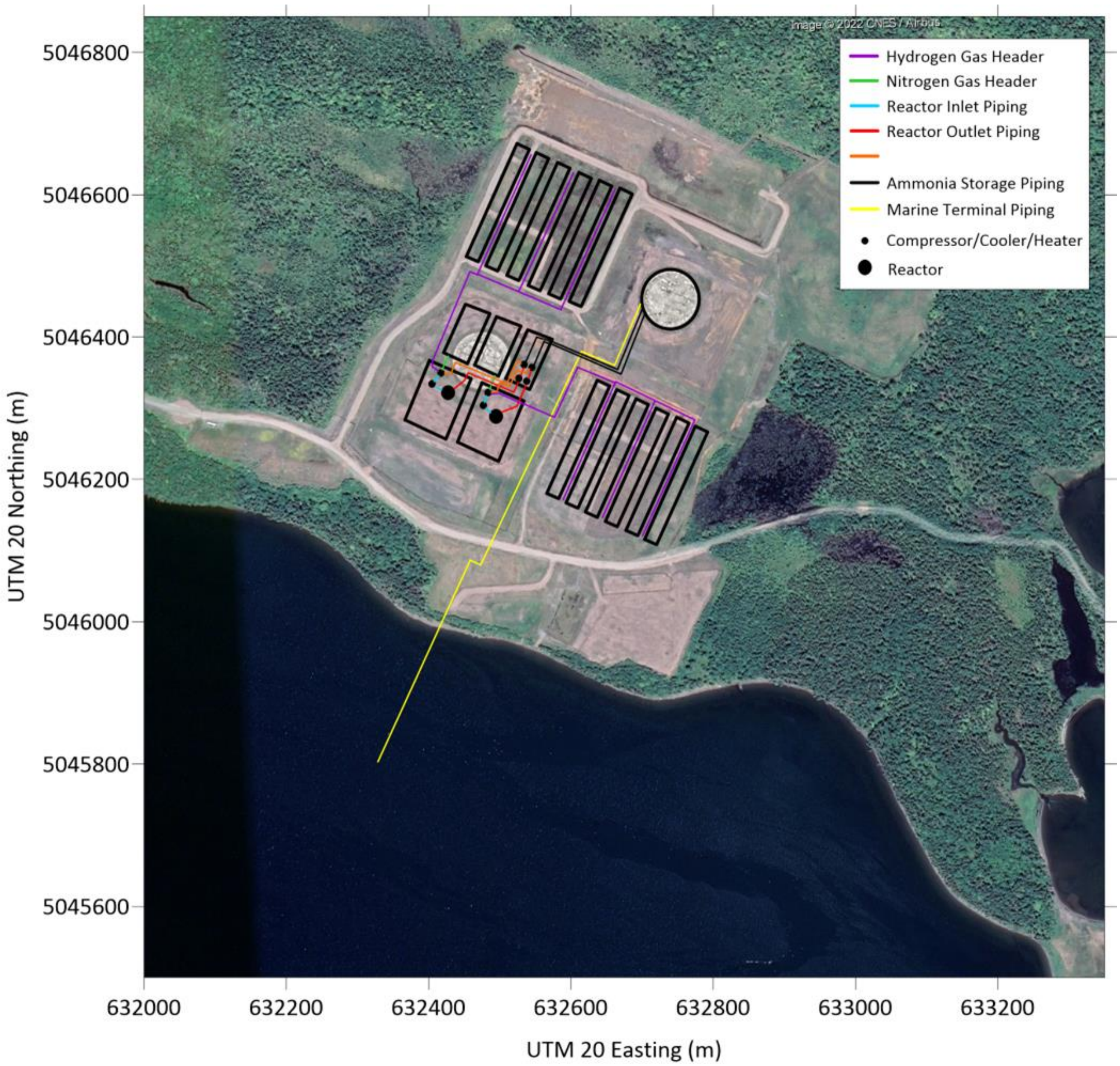


**Figure 2-3 Hypothetical Piping Layout**



## 2.1 HYDROGEN PRODUCTION

Each process train will include electrolysers which separate process inlet water into hydrogen and oxygen. Electrolysers for the initial phase will be located on the northwest side of the facility, while electrolysers for the next phase will be located on the east side of the facility. The oxygen will be vented into the atmosphere, while the hydrogen will be sent to a combined header feeding an ammonia reactor.

The hydrogen gas is exported from each electrolyser via 3-inch (76.2 mm) diameter piping to the common header. The header is 10-inch (254 mm) diameter piping and is expected to operate at 5 bar(g) and ambient temperature. The initial phase may produce up to 480 tonnes of hydrogen gas per day.

## 2.2 NITROGEN PRODUCTION

Air Separation Units (ASUs) will be used to cryogenically separate nitrogen and oxygen, and are positioned on the west side of the facility in the ammonia production area. Each ASU will provide 2,271 tonnes of nitrogen gas per day.

## 2.3 AMMONIA PRODUCTION

Ammonia will be produced using the Haber-Bosch process, where hydrogen and nitrogen are brought to high pressure and elevated temperature in a reactor that also contains an iron catalyst to assist with the reaction. The feed streams of hydrogen and nitrogen are mixed in a 24-inch (609.6 mm) diameter pipe, and then undergo a multi-stage compression cycle that brings the feed stream to 150 bar(g). A preheater brings the reactor feed to approximately 300°C. The fluid composition for the flow into each reactor is estimated to be a 3:1 molar ratio of hydrogen to nitrogen gas.

The reactor will produce ammonia. The ammonia production reaction is exothermic, and so the gas temperature upon leaving the reactor is expected to reach 450°C. The outlet pipe is a 24-inch (609.6 mm) diameter pipe. The pressure is designed to drop through throttling and expansion to approximately 3.45 bar(g) upon exiting the reactor.

Not all of the hydrogen and nitrogen are converted to ammonia. The product stream is therefore initially composed of ammonia, hydrogen and nitrogen.

## 2.4 AMMONIA SEPARATION

The ammonia separation process cools the reactor outputs to isolate ammonia for storage and export. The reactor outputs are cooled in a two-stage process. Cooling from 450°C to 200°C is provided by a waste heat boiler. This boiler will recover heat for use at the Facility. The second stage of cooling is a condenser/chiller, which brings the reactor output down to -34°C, causing ammonia to become a liquid where it can be more easily separated from the leftover hydrogen and nitrogen gas.

The liquid ammonia is sent to storage, while the recovered hydrogen and nitrogen gases are recycled back to the feed compression cycle.

## 2.5 AMMONIA STORAGE AND MARINE TERMINAL

Ammonia is sent to storage via a 6-inch (76.2 mm) diameter pipe for each train. While the final design of the storage facility is not complete, it was assumed that storage would be accomplished using one tank with a storage capacity of approximately 124,000 $m^3$ of ammonia. The tank is assumed to be double walled and insulated to keep ammonia at -34°C and near atmospheric pressure. Off gases that may be produced in the storage vessel due to rapid changes in ambient temperature or pressure will be returned to the condenser and then returned to the storage vessel. The proposed tank location is on the northeast side of the facility. The estimated tank dimensions are 80 m diameter and 24.7 m in height. It was assumed that the tank was surrounded by a berm large enough to contain at least 110% of the volume of one tank.

Ammonia will be pumped from the storage facility to a marine export terminal via a 24-inch (609.6 mm) diameter pipe, where the ammonia will be the unloaded onto an export ammonia tanker. The marine terminal is located at south end of the facility.

# 3.0 Hazard Identification

Hydrogen gas will be produced from fresh water via the electrolysers, and will be used directly in the reactors to produce ammonia. The primary hazard associated with an accidental release of hydrogen gas is the flammability and reactivity of the fluid. While a release of hydrogen gas could be initially quite cold due to rapid depressurization, the hazards associated with cold temperatures are not likely to extend offsite and so are not considered in this risk assessment.

Nitrogen gas will be produced via the cryogenic separation of air, and is also used directly in the reactors to produce ammonia. The primary hazard associated with an accidental release of nitrogen gas is asphyxiation due to displaced oxygen, as well as cold temperatures during rapid depressurization. However, neither of these hazards are estimated to extend off site and are not considered further in this risk assessment.

Ammonia, as both a liquid and gas, will be produced by the Haber-Bosch process and will be present in storage vessels onsite. The primary hazard associated with an accidental release of ammonia is toxicity through inhalation. Ammonia is also flammable and so presents an additional flammability hazard.

The potential hazardous events are summarized in Table 3-1. The hazards to be investigated are fires and explosions, as well as inhalation risks. The specific hazards and their consequence endpoints are discussed in the following sections.

**Table 3-1 Hazard Summary**

| Hazard Event | Cause | Consequence |
|---|---|---|
| Jet Fire/Pool Fire | Immediate/Delayed ignition of hydrogen or ammonia | Exposure to thermal radiation. |
| Flash Fire | Delayed ignition of the dispersing vapour cloud of hydrogen or ammonia. | Exposure to the travelling flame front and associated thermal radiation exposure. |
| Inhalation | Toxic effects of ammonia vapour. | Toxic response to ammonia. |
| Vapour Cloud Explosion | Significant structural congestion in the flammable region of the hydrogen or ammonia vapour clouds, which causes flame speeds high enough to result in the formation of a pressure wave as the flame propagates through the region. | Exposure to thermal radiation, direct impingement of the travelling flame front, and exposure to damaging overpressure (both directly and through its impact on structures). |
| Process Vessel Explosion | An uncontrolled release of hydrogen gas fills the electrolyser enclosure and leads to an explosion of the process vessel. | Overpressure as a result of an explosion of the enclosure. |

## 3.1 JET FIRES/POOL FIRES

The consequences of the thermal radiation hazards associated with jet fires and pool fires are often defined using either the thermal radiation intensity level or a thermal radiation dose level. Thermal radiation intensity is a direct measure of the thermal radiation received at a target.

The effects associated with selected thermal radiation intensities are shown in Table 3-2. The thermal dose is a function of the intensity level and duration of exposure and can be used to define the anticipated effects on a receptor. The dose required to produce effects, including first, second, and third degree burns, to an unprotected human receptor is often expressed in Thermal Dose Units (TDU = 1 $(kW/m^2)^{4/3}s$). A summary of the TDUs required for different effects is provided in Table 3-3.

**Table 3-2 Effects of Thermal Radiation Intensity**

| Radiation Intensity ($kW/m^2$) | Effect |
|---|---|
| 1.2 | Received from the sun at noon in summer at the Facility latitudes. |
| 2 | Minimum to cause pain after 1 minute. |
| Less than 5 | Will cause pain in 15-20 seconds and injury after 30 seconds exposure. |
| Greater than 6 | Pain within approximately 10 seconds. |
| 12.5 | Significant chance of fatality for medium duration exposure.<br>Thin steel insulation on the side away from the fire may reach thermal stress level high enough to cause structural failure. |
| 25 | Likely fatality for extended exposure and significant chance of fatality for instantaneous exposure.<br>Spontaneous ignition of wood after long exposure.<br>Unprotected steel will reach thermal stress temperature that can cause failures. |
| 35 | Cellulosic material will pilot ignite within one minute's exposure.<br>Significant chance of fatality for people exposed instantaneously. |

NOTE:
SOURCE: U.K. HSE (2013)

**Table 3-3 Burn vs. Thermal Dose Relationship**

| Harm Caused | Infrared Radiation Thermal Dose (TDU), $(kW/m^2)^{4/3}s$ | |
|---|---|---|
| | Mean (Observations) | Range (Observations) |
| Pain | 92 | 86-103 |
| Threshold first degree burn | 105 | 80-130 |
| Threshold second degree burn | 290 | 240-350 |
| Threshold third degree burn | 1,000 | 870-2,600 |

NOTE:
SOURCE: O'Sullivan & Jagger (2004)

## 3.2 FLASH FIRES AND VAPOUR CLOUD EXPLOSIONS

Flash fire and vapour cloud explosion hazards result from the delayed ignition of a dispersing vapour cloud. The flammable extents of a release can be assessed by estimating the concentration of the fuel in the air as it is transported and dispersed away from the source. The Lower Flammable Limit (LFL) is the lowest concentration at which the released fuel will support combustion in the presence of an ignition source.

Dispersion models are often used to assess the dispersion of vapour clouds, and typically calculate time and ensemble average concentrations downwind of the release location. These models do not directly account for atmospheric concentration fluctuations that can occur during a release event, but predict the expected time-averaged concentration based on many similar events (referred to as an ensemble average). As a result, some jurisdictions recommend using a fraction of the LFL concentration for consequence and risk assessment to account for the variability about the ensemble mean. For instance, Environment and Climate Change Canada, as well as the United Kingdom Health and Safety Executive (U.K. HSE), recommend using the extents of the LFL/2 (50% of the LFL) to be the footprint of a potential flash fire (Webber, 2002).

A vapour cloud explosion occurs when the flame speeds within a flash fire are high enough to generate a damaging overpressure wave. The primary consequence of a vapour cloud explosion is a pressure wave generated by the rapidly advancing flame front, also known as overpressure. At high levels, the overpressure can cause direct damage to an individual such as rupturing of eardrums or hemorrhaging of the lungs. At lower levels, the overpressure may still cause significant damage to buildings and structures that can also be hazardous to individuals, such as shattering of glass and structural failure. Overpressure effects are summarized in Table 3-4.

A vapour cloud explosion requires significant congestion to generate the flame speeds necessary to generate damaging overpressures. For example, a complex network of piping and vessels may result in flame speeds high enough to develop a vapour cloud explosion. In addition, it is generally accepted that only the vapour in the congested region contributes to the overpressure.

**Table 3-4 Summary of Overpressure Effects**

| Pressure | | Damage |
|---|---|---|
| (psi) | (kPa) | |
| 0.02 | 0.14 | Annoying noise (137 dB), if of low frequency (10-15 Hz) |
| 0.03 | 0.21 | Occasional breaking of large glass windows already under strain |
| 0.04 | 0.28 | Loud noise (143 dB), sonic boom glass failure |
| 0.1 | 0.69 | Breakage of small windows under strain |
| 0.15 | 1.03 | Typical pressure for glass breakage |
| 0.3 | 2.07 | "Safe distance" (probability 0.95 no serious damage beyond this value); projectile limit; some damage to house ceilings; 10% window glass broken |
| 0.4 | 2.76 | Limited minor structural damage |
| 0.5-1.0 | 3.45-6.89 | Large and small windows usually shattered; occasional damage to window frames |
| 0.7 | 4.83 | Minor damage to house structures |
| 1.0 | 6.89 | Partial demolition of houses, made uninhabitable |
| 1-2 | 6.89-13.8 | Corrugated asbestos shattered; corrugated steel or aluminum panels, fastenings fail, followed by buckling; wood panels (standard housing) fastenings fail, panels blowing |
| 1.3 | 8.96 | Steel frame of clad building slightly distorted |
| 2 | 13.8 | Partial collapse of walls and roofs of houses |
| 2-3 | 13.8-20.7 | Concrete or cinder block walls, not reinforced, shattered |
| 2.3 | 15.9 | Lower limit of serious structural damage |
| 2.5 | 17.2 | 50% destruction of brickwork of houses |
| 3 | 20.7 | Heavy machines (3,000 lb) in industrial buildings suffered little damage; steel frame building distorted and pulled away from foundations |
| 3-4 | 20.7-27.6 | Frameless, self-framing steel panel building demolished; rupture of oil storage tanks |
| 4 | 27.6 | Cladding of light industrial buildings ruptured |
| 5 | 34.5 | Wooden utility poles snapped; tall hydraulic press (40,000 lb) in building slightly damaged |
| 5-7 | 34.5-48.3 | Nearly complete destruction of houses |
| 7 | 48.3 | Loaded train wagons overturned |
| 10 | 68.9 | Probable total destruction of buildings; heavy machine tools (7000 lb) moved and badly damaged, very heavy machine tools (12,000 lb) survived |
| 300 | 2068 | Limit of crater lip |

NOTE:
Based on Canadian Society for Chemical Engineering (2004)

## 3.3 VESSEL EXPLOSION

A vessel explosion can occur when the walls of a pressurized vessel are compromised resulting in a rapid expansion of the contents which in turn can generate a damaging pressure wave. Potential causes of vessel explosions include:

- External heating of the vessel, which can both weaken the structure and also raise the internal pressure of the vessel.
- Through overfilling pressure vessels beyond their rated pressure limit.
- An internal explosion from confined combustion in the vapour space of the vessel

The explosion can cause several physical effects including overpressure and fragmentation, all of which may cause damage. Additionally, if the material is flammable there is the potential for a fireball and exposure to thermal radiation.

For the proposed facility, explosions were considered possible in the unlikely event of a loss of containment within an electrolyser enclosure.

## 3.4 INHALATION

Inhalation hazards from the Facility may occur due to the toxicity of ammonia gas. Ammonia is a toxic, colorless gas with a pungent, suffocating odor (CDC 2019). Ammonia symptoms range from eye, ears and throat irritation at low concentrations, to chest pain and pulmonary edema at higher concentrations (CDC 2019). Ammonia is also listed in the Environment and Climate Change Canada Environmental Emergencies Regulations Schedule A list of hazardous materials (ECCC 2020).

The United States Environmental Protection Agency (US EPA) has developed Acute Exposure Guideline Levels (AEGL) to help assess the consequences of toxic gas releases. The AEGL levels are also recommended by ECCC for assessing the consequences of environmental emergencies (illustratively in this assessment).

There are three threshold levels for AEGL (US EPA 2022):

- AEGL-1: Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.
- AEGL-2: Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- AEGL-3: Life-threatening health effects or death.

The AEGL levels for ammonia are summarized in Table 3-5, and include threshold values for different durations of exposure.

**Table 3-5 Acute Exposure Guideline Levels for Ammonia**

| Level | Concentration Guideline (ppm) by Exposure Duration | | | | |
|---|---|---|---|---|---|
| | 10 min | 30 min | 1 hour | 4 hours | 8 hours |
| AEGL-1 | 30 | 30 | 30 | 30 | 30 |
| AEGL-2 | 220 | 220 | 160 | 110 | 110 |
| AEGL-3 | 2,700 | 1,600 | 1,100 | 550 | 390 |

# 4.0 CONSEQUENCE MODELLING ANALYSIS

## 4.1 SOURCE CHARACTERIZATION AND MODELLING METHODS

Source characterization was completed to estimate characteristics of the release during a loss of containment, including the release temperature, the ratio of liquid to gas being released, and the release rate. Accidental releases at the Facility may occur from failures of the ammonia storage vessels, process vessels including the preheaters, reactors, or coolers, piping, valves, or other assets managed in the production process.

The first step in source characterization is the development of release scenarios, which represent losses of containment at various points in the facility. Once the release scenarios are determined, source characterization for each scenario was completed using calculations from literature or through computer modelling. The results of the source characterization are then used as inputs to estimate consequence of the release.

### 4.1.1 Release Scenarios

While detailed design of the Facility has not yet been completed, a review of the processes taking place at the Facility was completed with BHE to help determine release scenarios that should be included in the QRA. This review was combined with a review of failure frequency data to select the release scenarios.

Release scenarios are often grouped in the following categories (UK HSE 2017; Crowl and Louvar 2002):

- Pinhole leaks, which normally represent the smallest leaks that might occur in the system. Pinhole leaks may be difficult to identify by visual inspection and may also be difficult to detect through deviations in process flow rates, pressures, or temperatures.
- Ruptures, which can range in size depending on the process of asset. For piping, it is common to estimate rupture sizes based on some fraction of the cross-sectional area of the pipe. For storage vessels, rupture sizes are often related to the size of pipe connections servicing the vessel but also can scale with the storage volume.
- Guillotine Ruptures, which are specific to piping, refer to scenarios where a pipe is severed leaving both ends of the pipe open to the atmosphere.
- Catastrophic failures, often specific to storage vessels. Guidance from ECCC suggests that a catastrophic failure is one where the storage vessel is emptied within approximately 10 minutes (ECCC 2020).

For process piping, it is common practice to use Emergency Shutdown Valves (ESDVs) to isolate piping during maintenance or upset conditions. For some processes automatic valves can be used that monitor fluid conditions, such as flow rate, temperature, or pressure, and close if those conditions exceed a pre-determined threshold without direct input from personnel. Due to varying conditions during normal operating conditions, and particularly for processes involving liquids such as liquid ammonia, it can be difficult for automatic valves to be used as an ESDV. For example:

- If large pressure changes occur during normal operations, the automatic system may be challenged to differentiate between an uncontrolled release and normal fluctuations.
- During smaller uncontrolled releases, there may be minimal change in the process conditions and the automatic valve may not detect that a failure has occurred.

Instead, for the purposes of responding to upset conditions, many facilities configure ESDVs to operate manually, where operators physically open or close valves as needed, or remotely, where operators control the valves remotely based on inputs from Supervisory control and data acquisition (SCADA) systems. Therefore, for the QRA, it was assumed that remotely operable valves were installed at either end of the piping. Experience with other industrial facilities where remotely operable valves are used suggest that it may take up to 15 minutes (or 900 seconds) for the valves to close during an uncontrolled release. This time accounts for:

- the time required for operators to diagnose an uncontrolled release and initiate valve closure, and
- the time required for the valve to gradually close, which typically takes 5 second per inch diameter to avoid damaging the valve, piping, or other process equipment.

To be conservative for release scenarios involving process piping, it was assumed that the valves would close 15 minutes after the onset of the release.

#### 4.1.1.1 Hydrogen Production

Loss of containment scenarios related to hydrogen production included a hydrogen release from:

- Electrolyser 3-inch diameter piping to the hydrogen gas header.
- Hydrogen gas 10-inch diameter header between the electrolysers and the reactor locations.

It was assumed that the electrolyser units would continue to produce hydrogen gas during a release.

For the piping systems, releases were considered from guillotine ruptures (complete severing of the pipe), full area ruptures (an incomplete severing of the pipe, where the rupture has an equivalent area to the pipe cross-section), holes with a diameter equivalent to one third of the pipe diameter, holes with a 25 mm diameter and leaks with an approximately 3 – 4 mm diameter.

In addition to releases from the electrolysers and piping, there could be upset conditions where the electrolyser units expel hydrogen gas into their enclosures. With oxygen present, the gases may ignite and explode within the enclosure. This release scenario leading to an explosion in the electrolyser was also included in the QRA.

#### 4.1.1.2 Ammonia Production

The loss of containment scenarios during ammonia production included:

- a release of hydrogen and nitrogen mixtures from the Haber-Bosch reactor inlet 24-inch diameter piping.
- a release of ammonia, hydrogen and nitrogen mixtures from the Haber-Bosch reactor outlet 24-inch diameter piping.

The reactor inlet piping was modelled at the preheated temperature of 300 °C, and at a pressure of 134 bar(g) (2,000 psi(g)). The total flow rate of the stream was taken as the combination of the recycle stream and the feedstock streams as shown in Figure 2-5.

Loss of containment was also considered from the reactor outlet. The reactor outlet was modelled at 450 °C and 3.45 bar(g) (50 psi(g)). The total flow rate for each reactor outlet was based on the total facility ammonia production rate of 5,440 tonnes/day.

It was assumed that a release from either the inlet or the outlet pipe of the reactor would cause gases from the reactor to also be released. The gas release rate was conservatively assumed to match the reactor throughout rate.

Similar to the hydrogen production system, releases sizes for these release scenarios included guillotine ruptures, full area ruptures, holes with a diameter equivalent to one third of the pipe diameter, holes with a 25 mm diameter and leaks with an approximately 3 – 4 mm diameter.

#### 4.1.1.3 Ammonia Separation

The loss of containment scenarios during ammonia separation included:

- releases of ammonia from the cooled reactor outlet 24-inch diameter piping.
- releases of hydrogen and nitrogen from the recycle stream after the condenser from 12-inch piping.

The outlet piping conditions were assumed to be 200 °C and 3.45 bar(g). The total flow rate and composition were the same as the reactor outlet. The recycle stream contains the hydrogen and nitrogen portion of the reactor outlet stream.

Similar to the hydrogen production system, releases were considered from guillotine ruptures, full area ruptures, holes with a diameter equivalent to one third of the pipe diameter, holes with a 25 mm diameter and leaks with an approximately 3 – 4 mm diameter.

#### 4.1.1.4 Ammonia Storage and Marine Terminal

Releases of pure liquid ammonia were considered from:

- the 6-inch diameter piping from the condensing unit to the storage system,
- an ammonia storage tank, and
- the 24-inch diameter piping from the tanks to the marine terminal.

The ammonia is anticipated to be stored at atmospheric pressure, and so the storage temperature was assumed to be -34 °C, just below the normal boiling point of-33°C. The tank was assumed to be 80% full during each release scenario, which is an assumption typically used for emergency response planning for industrial facilities (ECCC 2020; US EPA 2021).

For piping systems, it was assumed that remotely operated valves can be activated within 15 minutes of the release occurring.

For the piping systems, releases were considered from guillotine ruptures, full area ruptures, holes with a diameter equivalent to one third of the pipe diameter, holes with a 25 mm diameter and leaks with an approximately 3 – 4 mm diameter.

For the ammonia storage tank, releases considered were catastrophic (draining the tank in ten minutes), 1,000 mm diameter hole, and a 300 mm diameter hole.

#### 4.1.1.5 Summary of Release Scenarios

**A summary of the release scenarios is presented in Table 4-1 and**

Table 4-2. The location of the release scenarios in the ammonia production process are illustrated in Figure 4-2.

**Table 4-1 Summary of Locations and Ruptures Modelled**

| Location | Location Description | Dimension | Release | Release Description | Scenario |
|---|---|---|---|---|---|
| 1 | Electrolyser Connection to Header | 3-inch diameter (76.2 mm) | 1 | Guillotine Rupture | 1 |
| | | | 2 | Full Area Rupture | 2 |
| | | | 3 | 25 mm Hole | 3 |
| | | | 4 | 3 mm Leak | 4 |
| 2 | Hydrogen Gas Header | 10-inch diameter (254 mm) | 1 | Guillotine Rupture | 5 |
| | | | 2 | Full Area Rupture | 6 |
| | | | 3 | 85 mm Hole | 7 |
| | | | 4 | 25 mm Hole | 8 |
| | | | 5 | 4 mm Leak | 9 |
| 3 | Reactor Inlet | 24-inch diameter (610 mm) | 1 | Guillotine Rupture | 10 |
| | | | 2 | Full Area Rupture | 11 |
| | | | 3 | 203.2 mm Rupture | 12 |
| | | | 4 | 25 mm Hole | 13 |

**Table 4-1 Summary of Locations and Ruptures Modelled**

| Location | Location Description | Dimension | Release | Release Description | Scenario |
|---|---|---|---|---|---|
| | | | 5 | 4 mm Hole | 14 |
| 4 | Reactor Outlet at 450 °C | 24-inch diameter (610 mm) | 1 | Guillotine Rupture | 15 |
| | | | 2 | Full Area Rupture | 16 |
| | | | 3 | 203.2 mm Rupture | 17 |
| | | | 4 | 25 mm Hole | 18 |
| | | | 5 | 4 mm Hole | 19 |
| 5 | Reactor Outlet at 200 °C | 24-inch diameter (610 mm) | 1 | Guillotine Rupture | 20 |
| | | | 2 | Full Area Rupture | 21 |
| | | | 3 | 203.2 mm Rupture | 22 |
| | | | 4 | 25 mm Hole | 23 |
| | | | 5 | 4 mm Hole | 24 |
| 6 | Recycle Stream | 12-inch diameter (305 mm) | 1 | Guillotine Rupture | 25 |
| | | | 2 | Full Area Rupture | 26 |
| | | | 3 | 101.6 mm Rupture | 27 |
| | | | 4 | 25 mm Hole | 28 |
| | | | 5 | 4 mm Hole | 29 |
| 7 | Condensed Ammonia Stream | 6-inch diameter (152 mm) | 1 | Guillotine Rupture | 30 |
| | | | 2 | Full Area Rupture | 31 |
| | | | 3 | 50.6 mm Rupture | 32 |
| | | | 4 | 25 mm Hole | 33 |
| | | | 5 | 4 mm Hole | 34 |
| 8 | Ammonia Storage Tank | 124,000 $m^3$ | 1 | Catastrophic Rupture (release in 10 minutes) | 35 |
| | | | 2 | 1,000 mm Rupture | 36 |
| | | | 3 | 300 mm Hole | 37 |
| 9 | Marine Terminal Pipe | 24-inch diameter (610 mm) | 1 | Guillotine Rupture | 38 |
| | | | 2 | Full Area Rupture | 39 |
| | | | 3 | 203.2 mm Rupture | 40 |
| | | | 4 | 25 mm Hole | 41 |
| | | | 5 | 4 mm Hole | 42 |

**Table 4-2 Summary of Locations and Ruptures Modelled for Storage Vessel Explosions Considered**

| Location | Location Description | Number of Vessels | Release Description | Scenario |
|---|---|---|---|---|
| 10 | Electrolyser | 100 | Internal Combustion Leading to Vessel Explosion | 43 |

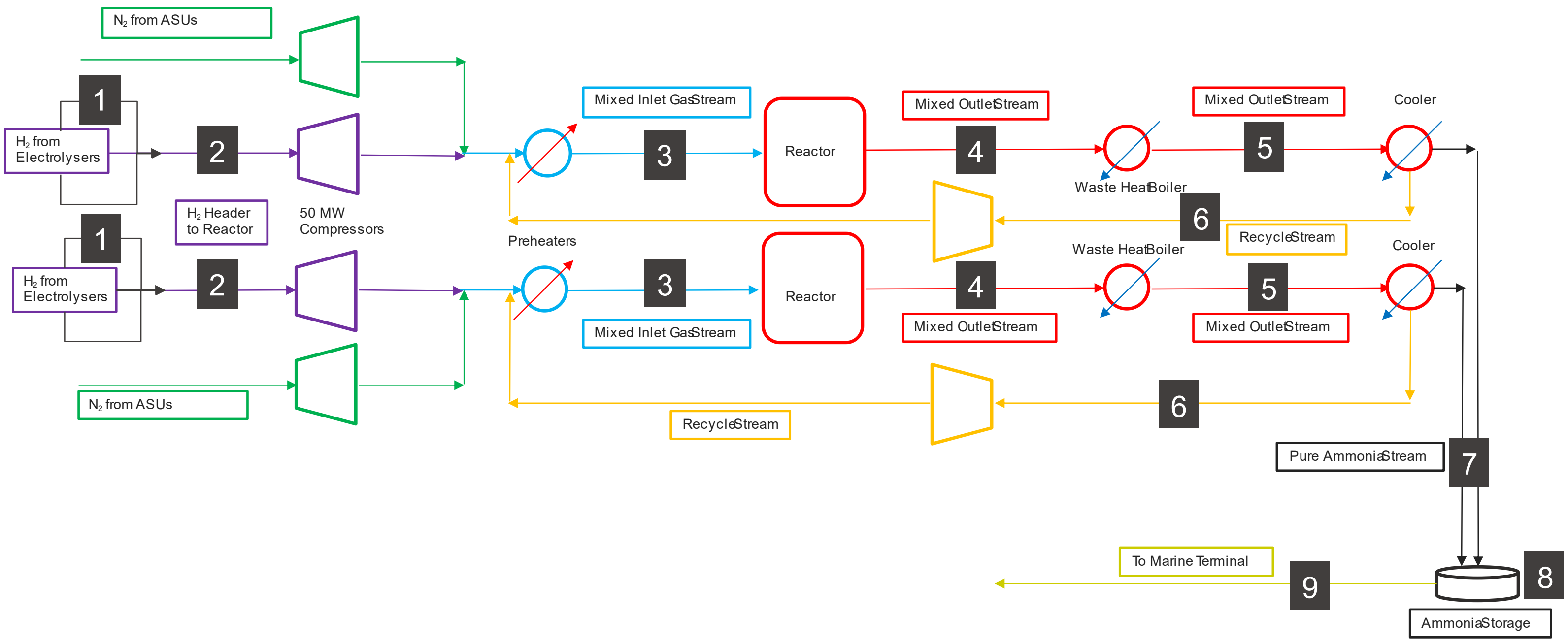



**Figure 4-1 Release Scenario Locations**

### 4.1.2 Flammable/Toxic Vapour Release Modelling

Source characterization modelling was completed to estimate the source properties occurring during releases of hydrogen, nitrogen, and ammonia. Inputs to the source characterization model include the initial fluid temperature and pressure, the stored inventory, the piping configuration, and the size of the rupture. These inputs are used to estimate the time-varying properties of the release, including the mass release rate, liquid mass fraction, and temperature. These source conditions in combination with the physical properties of the fluid are direct inputs used to predict the consequence extents during an accidental release event.

The properties of the compounds during the release were estimated using the Peng-Robinson equation of state, which is sufficient to estimate properties for pure fluids and mixtures, including mixtures containing ammonia and hydrogen. The fluid compositions for different areas of the process are summarized in Table 4-3.

**Table 4-3 Fluid Composition by Ammonia Production Process**

| Compound | Mole Fraction by Process Area | | | | | |
|---|---|---|---|---|---|---|
| | Hydrogen Production | Ammonia Production | | Ammonia Separation | | Ammonia Storage and Marine Export |
| | | Reactor Inlet | Reactor Outlet | Recycle Stream | Liquid Ammonia Outlet | |
| $H_2$ | 1.00 | 0.67 | 0.33 | 0.67 | 0 | 0 |
| $N_2$ | 0 | 0.33 | 0.17 | 0.33 | 0 | 0 |
| $NH_3$ | 0 | 0 | 0.5 | 0 | 1.0 | 1.0 |

The exit conditions as a function of time can be estimated by solving the time-varying mass, momentum and energy conservation equations for the fluid. A compressible fluid flow model with consideration of friction and heat transfer was used to estimate the source conditions during a release. The following assumptions were made:

- The fluid is real and compressible (compressible flow terms are included in the analysis);
- The vapor and liquid phases are in thermodynamic equilibrium;
- The vapor and liquid phases are assumed to travel at the same velocity (i.e., there is no slip between the vapor and liquid phases); and,
- The fluid properties are estimated using the Peng-Robinson equation of state (Peng & Robinson, 1976).

The source conditions used in the consequence modelling were estimated through mass, momentum and energy balances from the exit plane (located at the failure point) to the source plane (located at the point where the fluid has expanded to atmospheric pressure). As the fluid moves between the exit plane and the source plane, it was assumed that there is no heat transfer between the fluid and its surroundings, and the fluid does not work on its surroundings. If the flow is choked at the exit plane (i.e., the exit plane pressure is higher than the ambient pressure), an estimate of the expanded conditions was made.

The release modelling included a sensitivity analysis due to potential obstructions at the source location (such as debris) that may occur during a loss of containment. The obstructions do not change the release rate or temperature at the source but can change the exit velocity. Changes to the exit velocity are most important for the initial conditions of a dispersing gas cloud. The sensitivity analysis incorporated drag coefficients to the source conditions to simulate the effect of an obstruction. Three different drag coefficients were used, which corresponded to removing 0% (i.e., no obstruction), 40% and 66% of the momentum from the release.

### 4.1.3 Pool Spill Modelling

Source conditions during a release were used as inputs to pool spill modeling to predict spill sizes from the source. The spill modeling included the competing effects of liquid entering the pool from the source and mass leaving the pool due to boiling and or evaporation into the atmosphere. During an ammonia release, vapourization can occur through boiling or evaporation as the pool expands from the source. The release of vapors from a liquid pool depends on parameters including:

- The spill rate into the pool;
- Fluid and ground temperatures;
- Ambient atmospheric conditions, including air temperature, wind speed, and air turbulence;
- Source area; and
- The volatility of the fluid.

The pool model approach uses empirical mass transfer correlations and assumes diffusion into clean air over the pool (MacKay et al. 1973; Briscoe and Shaw, 1980; Fernandez 2012). The concentration of ammonia at the vapor/liquid interface is assumed equal to the ratio of the ammonia partial pressure and the ambient pressure. This predicted concentration is then used to estimate mass transfer of ammonia from the pool.

Energy exchange can occur either through evaporation of vapor from the pool, energy gains or losses through the ground, energy changes as liquid is added to the pool, energy exchange with the ambient surroundings. The pool temperature is estimated based on a heat and mass balance with consideration of heat transfer modes including:

- Incoming solar radiation
- Incoming and outgoing long wave radiation;
- Conduction or convection from the substrate (ground or water); and
- Convection from the ambient surroundings.

The vapourization rate into the atmosphere depends on the meteorological conditions at the time of the release. The primary ambient parameter driving atmospheric uptake is the wind speed. However, parameters that can have secondary effects on the evaporation rate include turbulence in the atmosphere and ambient temperature.

The ambient temperature affects the rate of heat transfer to and from the pool and therefor affects vapourization rates, with warmer air tending to cause more vapourization. Ammonia's boiling point is -34 °C, and so air temperatures are expected to regularly be well above that temperature throughout the year. Ground surface temperatures were assumed to initially be equal to the air temperatures, however the model also allows the ground temperature to change through interaction with the pool during the spill.

### 4.1.4 Vessel and Container Explosion Modelling

Modelling was completed to estimate the extent of damaging overpressures associated with an explosion from a hydrogen electrolyser. It was assumed there was a stoichiometric mixture of fuel and air in the electrolyser enclosure. Use of the stoichiometric ratio results in the maximum amount of fuel within the enclosure volume being consumed during an explosion event and the maximum expansion ratio of the combustion products. This is the recommended approach for estimating fuel availability for explosion hazards (Merx et al., 2005). Explosions assumed that the flammable component was 100% hydrogen.

## 4.2 SOURCE MODELLING RESULTS

Source modelling results, including an overview of the time-varying release rates, are summarized by process area for the Facility. Figures illustrating the time-varying release rate are found in Appendix B.

### 4.2.1 Hydrogen and Ammonia Production

The gas upstream of the reactor is composed of 100% hydrogen, while the gas downstream of the reactor is composed of hydrogen, ammonia, and nitrogen. The peak release rate occurs during the first few moments of the release, then decreases to the production rate of either the electrolysers or the reactor. The release rate is highest for the larger release hole sizes.

The predicted release rates upstream and downstream of the reactor are shown in Figures B-1 and B-2, respectively.

### 4.2.2 Ammonia Separation

The release rate is relatively constant until the remotely operated valves are activated at 900 seconds. The pool has an effective radius of approximately 25 m in the largest release scenario and begins to decrease in size after the valves close due to the ongoing evaporation of the pool. The peak evaporation rate coincides with the peak pool radius.

The predicted liquid release rate from the process piping between the cooler and the ammonia storage tank is shown in Figure B-3. The pool spill size with time is shown in Figure B-4. The evaporation rate from the pool is shown in Figure B-5.

### 4.2.3 Piping to Marine Terminal

The diameter of the piping to the marine terminal is larger and the flow rate is higher than the piping from the cooler, and so both the pool spill size and evaporation rates are higher. The evaporation rate from the pool peaks at just over 400 kg/s at the same time that the maximum pool radius occurs.

The releases rates for failure scenarios between the ammonia storage tank and the marine terminal are shown in Figure B-6. The time series of the pool spill effective radius is shown in Figure B-7. The evaporation rate from the pool is shown in Figure B-8.

### 4.2.4 Ammonia Storage

The catastrophic release has the largest flow rate. It was assumed that the ammonia tanks are contained within a berm, and so the pool spill extents are limited to the size of the berm. While the peak evaporation rate for releases from the ammonia tank is lower than the marine terminal spill case, the pool is deeper due to the secondary containment and so a higher evaporation rate is maintained for longer.

The releases rates for failure scenarios from the ammonia storage tank are shown in Figure B-9. The change in effective pool radius with time is shown in Figure B-10. The evaporation rate from the pool is shown in Figure B-11.

## 4.3 CONSEQUENCE MODELLING METHODS

Consequence modelling estimates the physical effects of a hazardous event. The consequences associated with the release of a flammable fuel can be influenced by factors including the manner in which the plume disperses downwind, the release rate profile, storage conditions and the physical and thermodynamic properties of the fluid.

### 4.3.1 Meteorology

The weather conditions during the time of the release will affect the location and size of the hazard zones for cases related to toxic gas exposure or when considering the delayed ignition of a flammable plume. The dilution capability of the atmosphere depends on the meteorological conditions at the time of the release. The Pasquill-Gifford classification scheme with six categories ranging from A (very unstable) to F (moderately stable) to characterize the atmosphere is often used. The occurrence of these stability conditions can be summarized as follows:

- Unstable conditions A through C are characterized by strong to moderate incoming solar radiation and low to moderate wind speeds. Unstable conditions typically occur on calm, warm and sunny days when ground heating results in vertical motion of air within the layer of the atmosphere close to the surface. This vertical motion results in increased turbulence. Unstable conditions are restricted to daylight hours.
- Neutral stability, D, often occurs during overcast conditions or conditions with moderate to high wind speeds. Neutral stability can occur at any time during the day or night.
- Stable conditions E and F typically occur on calm, cool clear nights when radiation cooling of the ground relative to the layer of air above it results in a stable temperature gradient (temperature increasing with altitude). This stable gradient dampens vertical motion and results in a reduction in the level of turbulence. Stable conditions generally occur during night-time.

Table 4-4 provides the meteorological conditions used in the consequence modelling. Modelling the release over this range of possible conditions is an attempt to ensure that a reasonable worst-case meteorology is represented thereby providing a conservative estimate of the hazard extents for a given release event.

**Table 4-4 Meteorological Conditions Used in the Consequence Modelling**

| Meteorology Code | Stability Class | Wind Speed | | Description |
|---|---|---|---|---|
| | | (m/s) | (kmph) | |
| A1.5 | A | 1.5 | 5.4 | Typically occurs on warm, sunny days, late morning to mid-afternoon when the sun is at its peak. |
| B2 | B | 2 | 7.2 | |
| C2 | C | 2 | 7.2 | |
| C4 | C | 4 | 14.4 | |
| D2 | D | 2 | 7.2 | Overcast conditions, day or night, anytime of the year |
| D5 | D | 5 | 18 | Moderate to high wind speed conditions, any time of day |
| D10 | D | 10 | 36 | |
| E3 | E | 3 | 10.8 | Nighttime conditions, slightly overcast |
| E5 | E | 5 | 18 | |
| F2 | F | 2 | 7.2 | Clear nights |
| F4 | F | 4 | 14.4 | |

Other factors for the dispersion modelling are as follows:

- An ambient temperature of 25°C.
- A surface roughness of 3 cm (Lloyd's Register 2022).

### 4.3.2 Dispersion Modelling

Dispersion modelling is performed to determine the concentration of pollutants at ground level, downwind of a release. The U.S. EPA SLAB dispersion model, which can estimate the dispersion of releases with a density equal to or greater than that of air (in addition to buoyant releases), was used in the assessment. The SLAB dispersion model was developed at the Lawrence Livermore Labs and contains algorithms that can model the physics of these releases including gravity slumping, reduced air entrainment resulting from stable density gradients (i.e., density within the plume is larger than that of the ambient air) and the thermodynamics of phase change within the plume. The SLAB model finds regular use in meeting dispersion modelling requirements in the U.S. EPA Risk Management Plan (RMP).

SLAB is a widely used and publicly available dispersion model and is listed by the US EPA as an alternative model that can be used for dispersion assessments. Validation studies of consequence models are generally limited due to the relative scarcity of full-scale measurement data against which to make comparisons. In a review study by Gudivakaa and Kumara (1990) they noted "In predicting ground level concentrations, the SLAB model performed well in all atmospheric conditions and calm conditions." Another study by Ermak et al. (1982) noted that the SLAB model generally predicted the maximum distance to the lower flammability limit (LFL) and cloud width quite well and that the SLAB model accurately predicted the length of time required for the cloud to disperse to a level below the LFL, even in a low wind speed test.

To address the transient behavior of the predicted mass release rate, additional post processing was done on the SLAB model output. The post processor implements the method of observers as is done in the Degadis (Spicer and Havens 1989) and HGSYSTEM models. A separate SLAB model run was conducted at each of a set of discrete time steps. The individual SLAB runs were interpreted as releases of successive planar puffs. The source input parameters for each puff; including the liquid mass fraction, temperature, and release rate were obtained from the RELEASE model output for the considered time step. The concentration at a downwind location is then estimated by integrating the contribution of the time series of planar puffs with the consideration of "along wind" diffusion.

### 4.3.3 Flammability and Vapour Cloud Explosion

The flammable extents of the dispersing plume were calculated using the dispersion model, with considered concentration endpoints of the LFL and LFL/2. ECCC considers the LFL concentration as a region within which fatalities are possible (ECCC, 2020), which is consistent with guidance from the U.K. HSE and NFPA (UK HSE, 2010; NFPA 59a, 2019).

Hazard extents resulting from a vapour cloud explosion were calculated using the Multi-Energy Method (MEM) (Crowl and Louvar 2002). The calculation of overpressure using this method is based partly on the level of obstruction and confinement as defined in MEM – the greater the congestion and confinement, the farther the hazard extent for a given overpressure. Typically, the blast is classified by the level of congestion and those areas of the plume in a congested area have a greater contribution to the overpressure than those that are outside of the congested area. While design has not been finalized, congestion was assumed to be present for the studied releases.

Fatalities from overpressure can occur either through direct exposure to the pressure wave or indirectly from building damage or contact from flying debris. An individual inside a building is likely to be protected from the transient thermal radiation effects of a flash fire but may be susceptible to potential damage to the building triggered by a vapour cloud explosion (if it occurs). In terms of the flash fire and vapour cloud explosion events this assessment assumes the worst-case location (indoors vs outdoors) of a receptor in terms of the likelihood of fatality. Potential fatalities are considered possible at overpressure endpoints of 25 kPa(g) or the LFL – whichever is greater (U.K. HSE, 2010). Therefore, larger of either the LFL extent or the overpressure threshold of 25 kPa(g) was used in this assessment.

### 4.3.4 Inhalation and Toxicity

The downwind concentration from an ammonia release was estimated using dispersion modelling. In emergency response planning, ECCC, along with other jurisdictions, recommend using the US EPA Acute Exposure Guideline Levels (AEGL) as a hazard endpoint for toxic substances. Consequence modelling of the downwind extent to the AELG-2 and AEGL-3 were reviewed in this assessment.

For the purpose of a QRA, it is also common to use exposure thresholds tied more directly to the chance of a fatality occurring. During a release event, individuals may be exposed to a range of concentrations. The time series concentrations to which a person is exposed, and the duration of exposure experienced during an accidental release, contribute to form a toxic load that is received for the event. The toxic load can then be used to estimate the chance of a fatality. The toxic load estimate is considered to be a reasonable and appropriate means of assessing the consequence of a release event that results in exposure to toxic materials including ammonia (Crowl and Louvar 2002). Therefore, the time varying nature of the release was considered as part of the consequence modelling to estimate the toxic load during a release.

The cumulative toxic load associated with exposure to a fluctuating concentration time-series can be defined by Equation 4-1 (Lloyd's Register 2022):

$$L = \int_{t=0}^{T} C^n dt \qquad \textbf{Equation 4-1}$$

Where: *L* is the toxic load experienced by an individual, *C* represents the time varying fluctuating concentration, and *n* is the toxic load parameter. For ammonia, a value of 2 was used for *n* (Lloyd's Register 2022).

The toxic load can be related to the chance of a fatality through a probit function, which is specific to the hazardous substance under consideration. The probit function for ammonia for this QRA is provided in Equation 4-2 (Lloyd's Register 2022):

$$-35.9 + 1.85 \ln(L) \qquad \textbf{Equation 4-2}$$

Where *L* is the toxic load as defined in Equation 4-1.

Probability of fatality was calculated assuming that the affected individual is outdoors. This assumption will likely overstate the risk as being indoors typically provide some additional protection from exposure.

### 4.3.5 Thermal Radiation

It is common to model the consequence from thermal radiation exposure by estimating the thermal dose. The thermal dose is a measure of the quantity of thermal radiation and the duration of exposure. For the current assessment, the thermal radiation consequence was estimated using best-practice algorithms established by the American Institute for Chemical Engineering's Center for Chemical Process Safety (Cook, 1987). These algorithms account for the time varying burning rate that is obtained from the source characterization modelling.

An individual will accumulate a thermal dose over the duration of the release that is dependent on the time varying intensity level of thermal radiation emitted from the source and the time varying distance between the individual and the release point. The release rate and thermal radiation intensity are time varying, so the thermal radiation dose can be estimated using:

$$D = \int_0^T I^{\frac{4}{3}}\,dt$$ **Equation 4-3**

where D is the dose (1 Thermal Dose Unit (TDU) = 1 $(kW/m^2)^{(4/3)}s$), I is the thermal radiation intensity ($kW/m^2$) and T is the exposure duration (seconds). The thermal dose unit accounts for the duration and exposure level. The following additional assumptions were made relating to the thermal dose estimation for an individual in the vicinity of an ignited release:

- At the onset of the release, the individual is assumed to remain stationary "stunned" for 5 seconds;
- The individual will move directly away from the release at a speed of 2.5 m/s (9.0 km/h); and,
- The individual is assumed to be oriented to receive the maximum thermal radiation from the source.
- A relative humidity of 50% during the fire.

The probability of lethality can then be estimated using the following equation and assuming probit parameters of a = -14.9 and b = 2.56 (U.K. HSE, 2010).

$$P(D) = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{b\ln(D) + a - 5}{\sqrt{2}}\right)\right]$$ **Equation 4-4**

Probability of lethality was calculated assuming that the affected individual is outdoors. Being indoors would grant some protection, and therefore this methodology was considered to overstate the risk at a given location.

Two scenarios were considered for each release:

- Early Ignition, where the release is ignited immediately; and,
- Late Ignition, where ignition occurs 60 seconds after the release begins.

For the purposes of emergency response planning, ECCC also recommends a thermal radiation threshold of 5 $kW/m^2$. This threshold was also modelled for the release scenarios.

### 4.3.6 Vessel Explosions

Vessel explosions can occur as a result of initiating events including external heating, fires, overfilling, and fast chemical reactions such as combustion. The explosions can lead to damaging overpressure for people and structures nearby. For the current assessment, it was assumed that the initiating event for the electrolysers were a gas leak into the enclosure, and subsequent ignition.

The overpressure was calculated using well-established methods that relate the available expansion energy and empirical relationships for pentolite (Crowl and Louvar 2002). It was assumed that all the safety mechanisms associated with venting of the combustion products in the electrolysers fail to function and allow the pressure inside the enclosure to build-up. If ignited, the available expansion energy within the enclosure was based on the resulting increasing temperature, the generation of combustion products and the subsequent increase in pressure.

The overpressure endpoints considered were the same as those used for a vapour cloud explosion.

## 4.4 CONSEQUENCE MODELLING RESULTS

The extents to selected endpoint criteria (flammable extents, thermal radiation extents, overpressure consequences, and toxic exposure) are provided in the following subsections for each of the major process sections. Summary tables of the maximum downwind extent to the hazard endpoints of concern are provided in Appendix C.

### 4.4.1 Hydrogen and Ammonia Production

The maximum downwind extent to the hazard endpoints of concern for the hydrogen and ammonia production processes is provided in Table 4-5. The maximum extents for these processes tended to occur during neutral atmospheric stability and moderate to high winds. The farthest thermal radiation extents occur with gas streams containing higher concentrations of hydrogen gas found in the electrolyser header and the reactor inlet piping.

**Table 4-5 Maximum Hazard Endpoint Extents for Hydrogen and Ammonia Production Processes**

| Consequence | Hazard Endpoint | Maximum Extent (m) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Low Pressure Hydrogen Piping | | Reactor Supply Gas | | Reactor Outlet Gas | |
| | | Piping from Electrolyzer to Header | Piping from Header to Reactor Compressor | Reactor Inlet Piping | Recycle Stream | Piping between Reactor and Waste Heat Boiler | Piping between Waste Heat Boiler and Cooler |
| Flammability | LFL | 211 | 218 | 93 | 78 | - | - |
| | LFL/2 | 314 | 322 | 134 | 136 | - | - |
| Thermal Radiation | 5 $kW/m^2$ | 70 | 210 | 270 | 80 | 40 | 30 |
| | 342 TDUs | 0 | 30 | 20 | 10 | 0 | 0 |
| Toxic Inhalation | AEGL-2 | - | - | - | - | 545 | 529 |
| | AEGL-3 | - | - | - | - | 182 | 177 |

### 4.4.2 Ammonia Separation

The maximum downwind extent to the hazard endpoints of concern for the ammonia separation process is provided in Table 4-6. The maximum extents for this process tended to occur during stable atmospheric conditions and low to moderate winds. The thermal radiation extents are lower than the gas streams since the flammability of ammonia gas is lower than hydrogen gas.

**Table 4-6 Maximum Hazard Endpoint Extents for Ammonia Separation Process**

| Consequence | Hazard Endpoint | Maximum Extent (m) |
|---|---|---|
| Toxic Inhalation | AEGL-2 | 4,405 |
| | AEGL-3 | 1,198 |
| Thermal Radiation | 5 kW/m$^2$ | 40 |
| | 342 TDUs | 10 |

### 4.4.3 Piping to Marine Terminal

The maximum downwind extent for the AEGL-2 (160 ppm over 60 minutes) and AEGL-3 (1100 ppm over 60 minutes) for liquid ammonia releases between the storage tank and the marine terminal are shown in Table 4-7. The maximum downwind extent occurs for more stable atmospheres and for low to moderate winds. For the current assessment the dispersion modelling domain was limited to 20 km based on consideration of the likelihood that the weather conditions (wind speed, direction and atmospheric stability) will persist. This domain allows for low wind speed stable conditions to persist in the same direction for about 3 hours.

The liquid spill generates more ammonia vapours available for combustion, which leads to a slight increase in the thermal radiation extent compared to the ammonia separation or the ammonia production processes.

**Table 4-7 Maximum Hazard Endpoint Extents for Marine Terminal Export Process**

| Consequence | Hazard Endpoint | Maximum Extent (m) |
|---|---|---|
| Toxic Inhalation | AEGL-2 | > 20,000 |
| | AEGL-3 | 8,263 |
| Thermal Radiation | 5 kW/m$^2$ | 250 |
| | 342 TDUs | 90 |

### 4.4.4 Ammonia Storage

The maximum downwind extent for the AEGL-2 (160 ppm over 60 minutes) and AEGL-3 (1100 ppm over 60 minutes) for liquid ammonia releases from the storage tank are shown in Table 4-8. The maximum downwind extent occurs for more stable atmospheres and for low to moderate winds.

**Table 4-8 Maximum Hazard Endpoint Extents for Ammonia Storage**

| Consequence | Hazard Endpoint | Maximum Extent (m) |
|---|---|---|
| Toxic Inhalation | AEGL-2 | > 20,000 |
| | AEGL-3 | 12,454 |

# 5.0 QUANTITATIVE RISK ASSESSMENT

Risk assessment provides a means of evaluating the safety of an industrial activity by comparing the risk associated with the activity to accepted guidelines. While knowledge of a credible worst-case hazard extent is useful for emergency planning purposes, this information does not necessarily provide a complete measure of safety. The identification of the extents of a hazard is not traditionally nor solely used to determine the acceptability of facility siting. Safety refers to the acceptability of the risk. Safety considers the likelihood that an accident will occur and produce an adverse outcome. For example, a facility may be considered safe, even if the consequences associated with uncontrolled releases may be large, provided that the frequency of occurrence is low or not measurable.

## 5.1 QUANTITATIVE RISK ASSESSMENT METHODS

Quantitative risk analysis provides a means of generating numerical estimates of risk by combining the consequences associated with a range of accidental release events with their expected frequency. Risk provides an estimate of the likelihood of harm: either to an individual or to society as a whole. A common and convenient expression for individual risk is:

$$Risk = Frequency \times Consequence$$

| | | |
|---|---|---|
| Where: | Frequency | = an approximation of the annual likelihood of an event; and |
| | Consequence | = the probability of lethality for a specified event. |

Results of the risk analysis provide a numerical measure of the incremental individual risk or group (societal) risk associated with an accidental release from the facility.

Individual risk was estimated and compared with recommended public safety risk exposure guidelines developed by the CSChE (CSChE 2008). Risk depends on many factors, including wind direction and wind speed/atmospheric stability probabilities, release location within the facility, and the probability of lethality for a particular hazard at the point being assessed. Equation 5-5 and equation 5-6 can be used to estimate the individual risk for point sources (e.g., vessels) and lines sources (e.g. pipelines or facility piping) respectively.

$$R_{ind,point}(x,y) = \sum_{j}^{J} f_j \sum_{i}^{I} f_i \int_{0}^{2\pi} f(\theta) P_{ij}\,(\theta, x, y) d\theta$$ **Equation 5-5**

$$R_{ind,line}(x,y) = \sum_{j}^{J} f_j \sum_{i}^{I} f_i \int_{0}^{S} \int_{0}^{2\pi} f(\theta) g(s) P_{ij}\,(\theta, x, y, s) d\theta\, ds$$ **Equation 5-6**

where:

| | | |
|---|---|---|
| $R_{ind,point}$ | = | The individual risk estimated at a location (x,y) for a point source, |
| $R_{ind,line}$ | = | The individual risk estimated at a location (x,y) for a line source, |
| $\theta$ | = | The wind direction, |
| $s$ | = | The distance along the line segment, |
| $f(\theta)$ | = | The wind direction probability distribution as a function of wind direction, |
| $g(s)$ | = | The line segment probability distribution as a function of position along the segment, |
| $I$ | = | The index of the weather case, |
| $j$ | = | The index of the release scenario and geometry, |
| $f_i$ | = | The frequency of the weather case (weather probability distribution), |
| $f_j$ | = | The frequency of the release scenario and geometry, |
| $P_{ij}$ | = | The probability of lethality or irreversible harm for a given release scenario and weather condition and as a function of the wind direction and location along the pipeline |

For a particular hazard (e.g., flash fire, jet fire or un-ignited cloud), the probability $P_{ij}$ includes consideration of the probability of the release size, probability of release orientation (horizontal or vertical), probability of ignition (instantaneous or delayed), and the probability of an individual (at the location being assessed) being indoors/outdoors. The equation used for linear sources such as facility piping is similar, however it also addresses the variation in hazards and probabilities along the pipeline through the addition of an additional variable of integration and additional functional relationships.

### 5.1.1 Human Vulnerability

A summary of the thresholds for fatality used in the quantitative risk analysis are presented in Table 5-1.

**Table 5-1 Summary of Fatal Consequence Thresholds used for Quantitative Risk Analysis**

| Event Type | Fatality |
|---|---|
| Flash Fire | >LFL (100% Fatality) |
| Vapour Cloud Explosion/BLEVE | >25 kPa overpressure (100% Fatality) |
| Fireball | Probit Equation |
| Jet Fire | Probit Equation |
| Ammonia Inhalation | Probit Equation |

### 5.1.2 Probability and Frequency Information

A variety of probability and frequency information is needed to evaluate risk. Details of these data are provided in the following sections.

#### 5.1.2.1 Failure Frequency Analysis

Frequency analysis is used to quantify the occurrence of accidental release events such as an uncontrolled release. Accident frequency information provides a historical measure of how often similar events have occurred in the past. Site specific failure frequencies are not available as the facility is still in the early design stages. A common alternative to site-specific failure estimate is to use databases of failure frequencies for similar processes or assets. For this quantitative risk analysis, release frequencies were obtained from release frequency data published by the U.K. HSE (U.K. HSE 2017). This data is often used for quantitative risk analyses for land use planning purposes, particularly for facilities in the planning or design stages (U.K. HSE 2017).

Table 5-2 provides a summary of the failure frequencies used for this quantitative risk analysis.

**Table 5-2 Failure Frequencies used in the Quantitative Risk Analysis**

| Component | Failure | Frequency | Units | Additional Information |
|---|---|---|---|---|
| 76.2 mm Piping (Electrolyser Connector) | Guillotine Rupture | 2.50E-07 | failures/m/yr | [a] |
| | Full Rupture | 2.50E-07 | failures/m/yr | [b] |
| | Hole | 1.00E-06 | failures/m/yr | 25 mm Hole |
| | Leak | 2.00E-06 | failures/m/yr | 3 mm Hole |
| 254 mm Piping (Hydrogen Production Header) | Guillotine Rupture | 1.00E-07 | failures/m/yr | [a] |
| | Full Rupture | 1.00E-07 | failures/m/yr | [b] |
| | Rupture | 4.00E-07 | failures/m/yr | 84.7 mm Hole |
| | Hole | 7.00E-07 | failures/m/yr | 25 mm Hole |
| | Leak | 1.00E-06 | failures/m/yr | 4 mm Hole |
| 609.6 mm Piping (Reactor Inlets, Reactor Outlets, Marine Terminal Piping) | Guillotine Rupture | 2.00E-08 | failures/m/yr | [a] |
| | Full Rupture | 2.00E-08 | failures/m/yr | [b] |
| | Rupture | 1.00E-07 | failures/m/yr | 203.2 mm Hole |
| | Hole | 4.00E-07 | failures/m/yr | 25 mm Hole |
| | Leak | 7.00E-07 | failures/m/yr | 4 mm Hole |
| 304.8 mm Piping (Recycle Streams) | Guillotine Rupture | 1.00E-07 | failures/m/yr | [a] |
| | Full Rupture | 1.00E-07 | failures/m/yr | [b] |
| | Rupture | 4.00E-07 | failures/m/yr | 101.6 mm Hole |
| | Hole | 7.00E-07 | failures/m/yr | 25 mm Hole |
| | Leak | 1.00E-06 | failures/m/yr | 4 mm Hole |
| 152.4 mm Piping (Condensed Ammonia Piping) | Guillotine Rupture | 1.00E-07 | failures/m/yr | [a] |
| | Full Rupture | 1.00E-07 | failures/m/yr | [b] |
| | Rupture | 4.00E-07 | failures/m/yr | 50.8 mm Hole |
| | Hole | 7.00E-07 | failures/m/yr | 25 mm Hole |
| | Leak | 1.00E-06 | failures/m/yr | 4 mm Hole |
| Ammonia Storage Tank (Double walled) | Catastrophic Release | 5.00E-07 | failures/yr | Hole sufficient to drain the tank contents within 10 minutes. |
| | Major Release | 1.00E-05 | failures/yr | 1,000 mm Rupture |
| | Minor Release | 8.00E-05 | failures/yr | 300 mm Rupture |
| Electrolysers | Vessel Explosion | | failures/yr | |

Notes:
[a] a guillotine rupture is equivalent to cleaving of the pipe, with releases possible from both sides of the break.
[b] a full area rupture is a hole in the pipe wall with an area equal to the cross-sectional area of the pipe

#### 5.1.2.2 Hazard Event Conditional Probability

Event trees are often used to assist in the development, and quantification of the conditional probabilities of possible hazard outcomes following an accidental release. Figure 5-1 shows a simplified event tree template used in the current assessment for vessel and piping releases. A sample event tree for one example, with the associated conditional probabilities for a guillotine rupture of the 3-inch connector from the electrolyser to the header, is shown in Figure 5-2. The probabilities shown in Figure 5-2 assume the release event has occurred (event frequency is 1), and therefore require the context of the event frequencies summarized in Table 5-2 to represent the total event likelihood.

Given that a release has occurred, the released fluid has a chance to ignite immediately or ignite after leaving the release point (also known as delayed ignition). The total ignition chance is the sum of the probabilities of both branches ($x + (1 - x)y$). The remaining fraction is the frequency that the release does not ignite. For toxic materials that are also flammable, such as ammonia, and where the toxic hazard is much greater than its flammable hazard, best practices suggest assuming a worst case where ignition does not occur.

For highly reactive materials such as hydrogen, best practices suggest assuming that an immediate ignition chance depends on the flowrate as follows (TNO Purple Book, 2005):

- 20% for low flow rates,
- 50% for moderate flow rates, and
- 70% for large flow rates).

**Figure 5-1 Event Tree Template to Estimate the Conditional Event Probability for Considered Hazard Events**

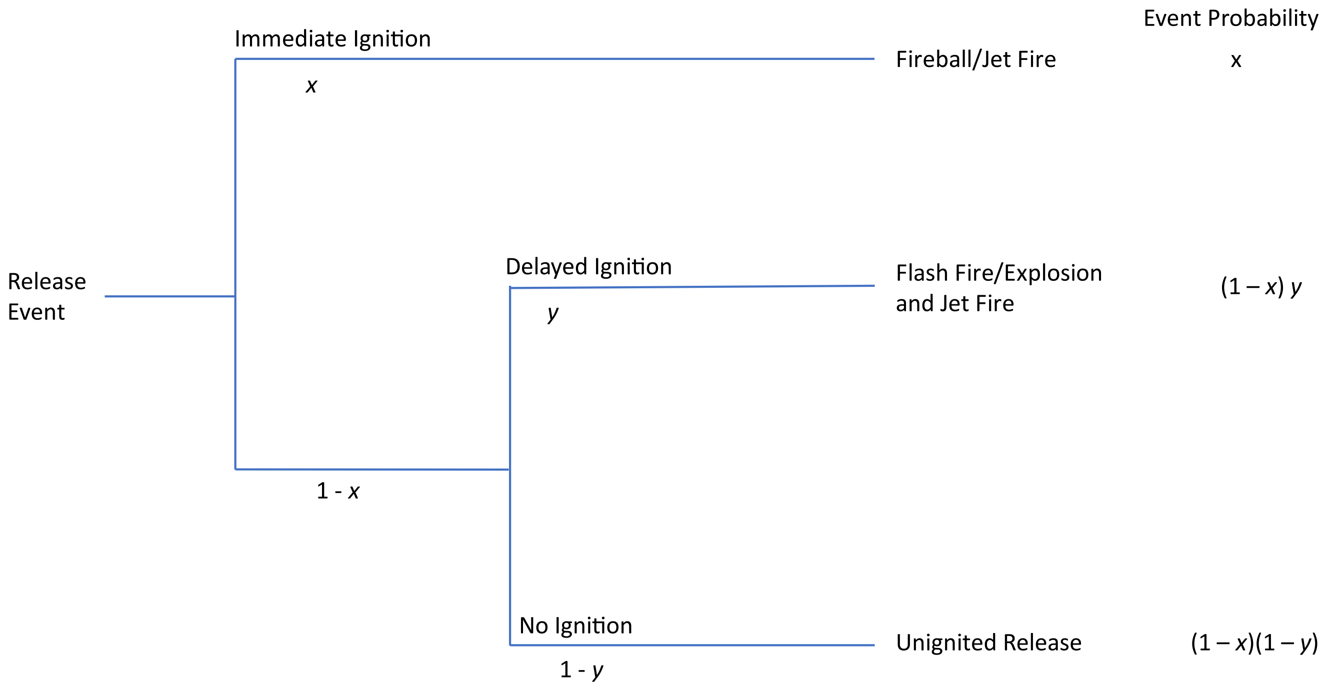
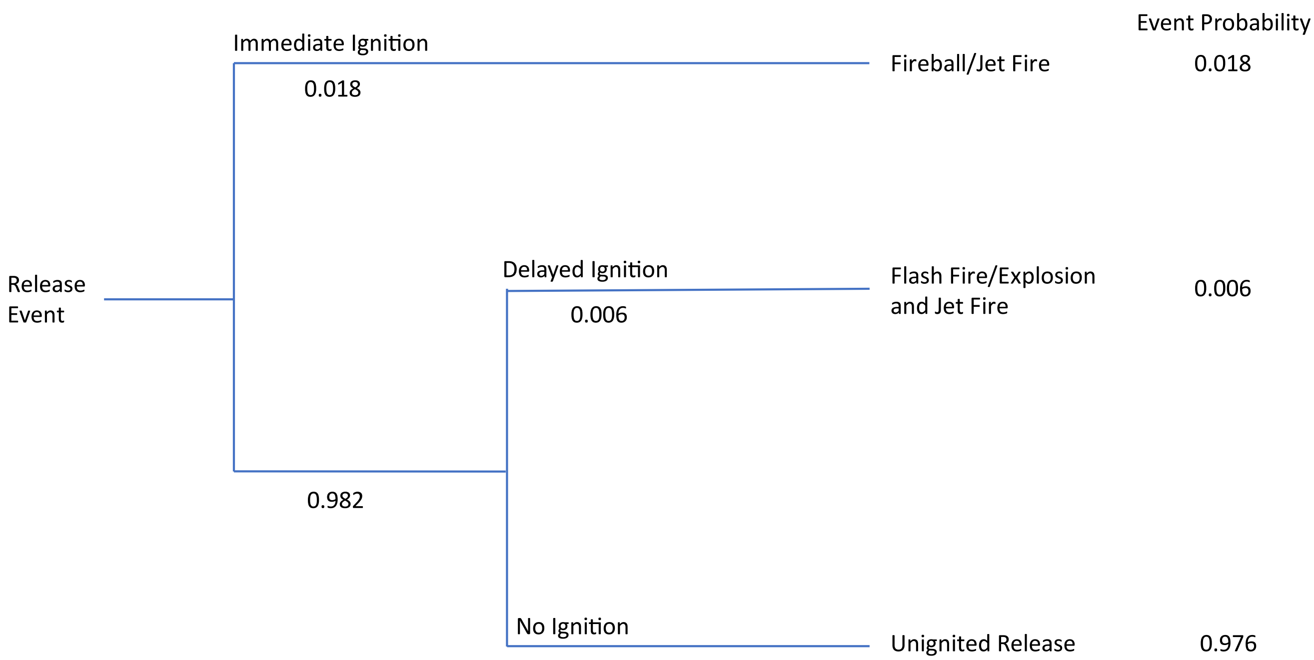



**Figure 5-2 Event Tree Example for Hydrogen Header Guillotine Rupture**



### 5.1.2.3 Site-Specific Meteorology

The frequency of occurrence of the weather conditions including atmospheric stability, wind speed and wind direction are required for the risk assessment. A description of the methodology used to obtain the weather frequency information is provided within this section.

#### Meteorological Observation Site

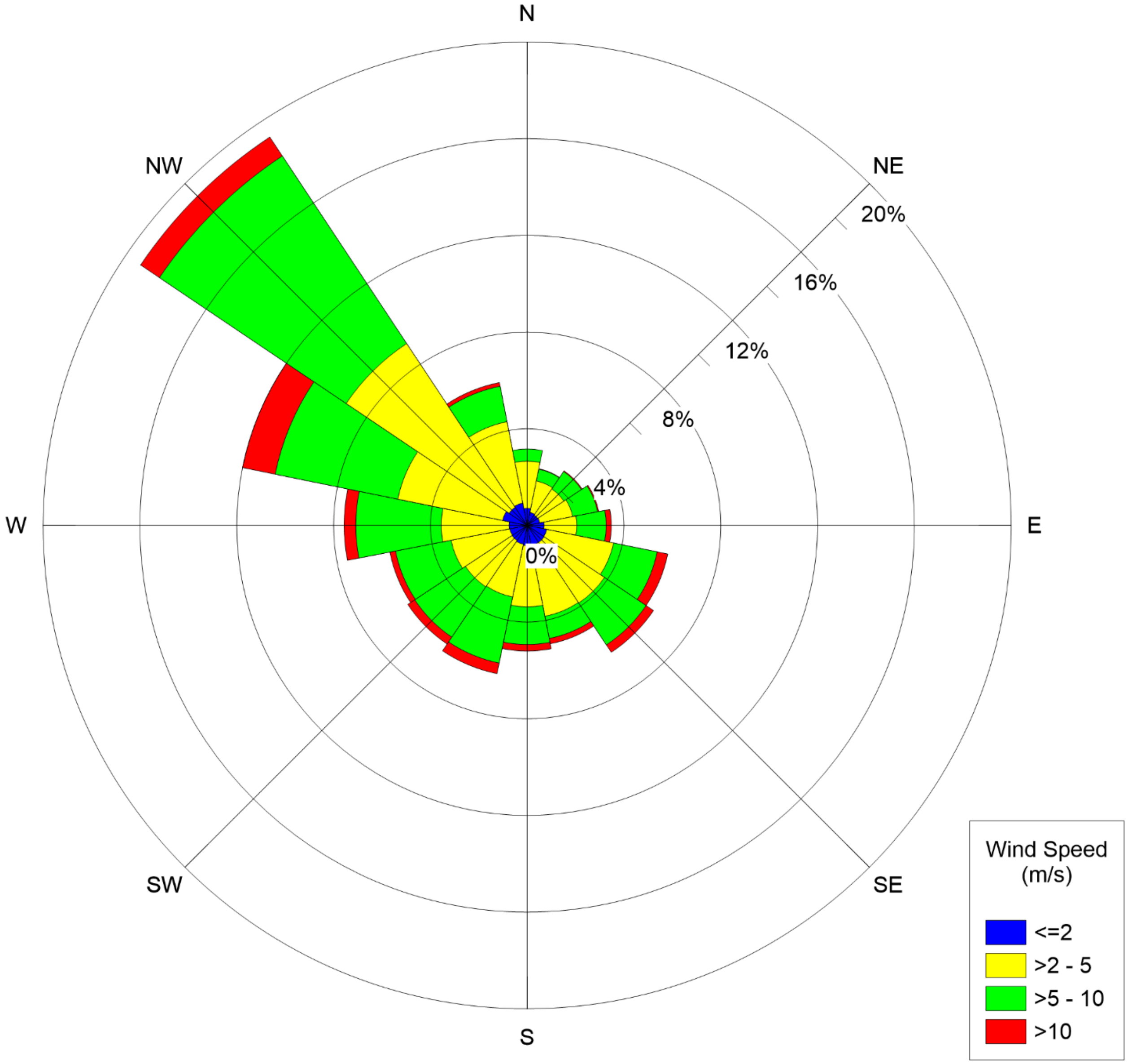
Surface meteorological data from 2020 to 2022 was obtained from weather forecast modelling data provided by Lakes Environmental.

The windspeed and atmospheric stability classes were used to calculate the frequency of meteorological conditions at the Project site. These frequencies are summarized in Table 5-3. A wind speed and wind direction frequency distribution diagram (also known as a wind rose) is shown in Figure 5-3.

**Table 5-3 Frequency of Meteorological Conditions (Data from Lakes Environmental for 2020 - 2022)**

| Meteorology Code | Stability Class | Wind Speed | | Frequency of Occurrence |
|---|---|---|---|---|
| | | (m/s) | (km/h) | |
| A1.5 | A | 1.5 | 5.4 | 1.44 |
| B2 | B | 2 | 7.2 | 4.24 |
| C2 | C | 2 | 7.2 | 10.18 |
| C4 | C | 4 | 14.4 | 21.72 |
| D2 | D | 2 | 7.2 | 7.22 |
| D5 | D | 5 | 18 | 21.97 |
| D10 | D | 10 | 36 | 13.51 |
| E3 | E | 3 | 10.8 | 6.73 |
| E5 | E | 5 | 18 | 8.98 |
| F1.5 | F | 1.5 | 5.4 | 3.12 |
| F3 | F | 3 | 10.8 | 0.89 |

**Figure 5-3 Wind Rose of the Project Site (Data from Lakes Environmental for 2019–- 2021)**




Note – Direction is for "wind blowing from"

### 5.1.3 Risk Acceptability Criteria

The Canadian Society for Chemical Engineering (CSChE) has developed risk exposure guidelines for land use planning purposes in Canada, and these guidelines were used for this quantitative risk analysis (MIARC 2007). These risk exposure guidelines relate a type of land use, such as industrial or residential, to an acceptable level of risk. The risk exposure guidelines are shown in Figure 5-4.

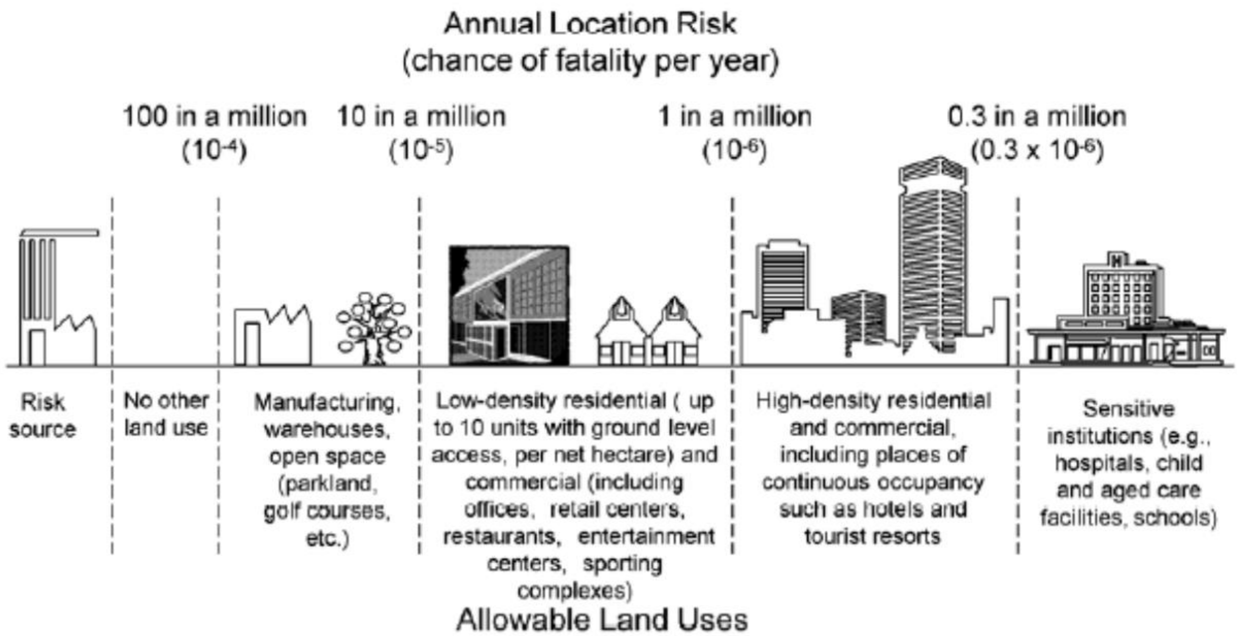



**Figure 5-4** **Individual Risk Exposure Guidelines used for Quantitative Risk Analysis (Source: Canadian Society for Chemical Engineering, 2008)**

The risk involved with an industrial activity is considered broadly acceptable when the risk is at a value below 1 in 1,000,000 chance of a fatality per annum, although the CSChE also provides additional risk criteria of 0.3 in 1,000,000 chance of fatality per annum for sensitive institutions such as hospitals, childcare centres, and nursing homes.

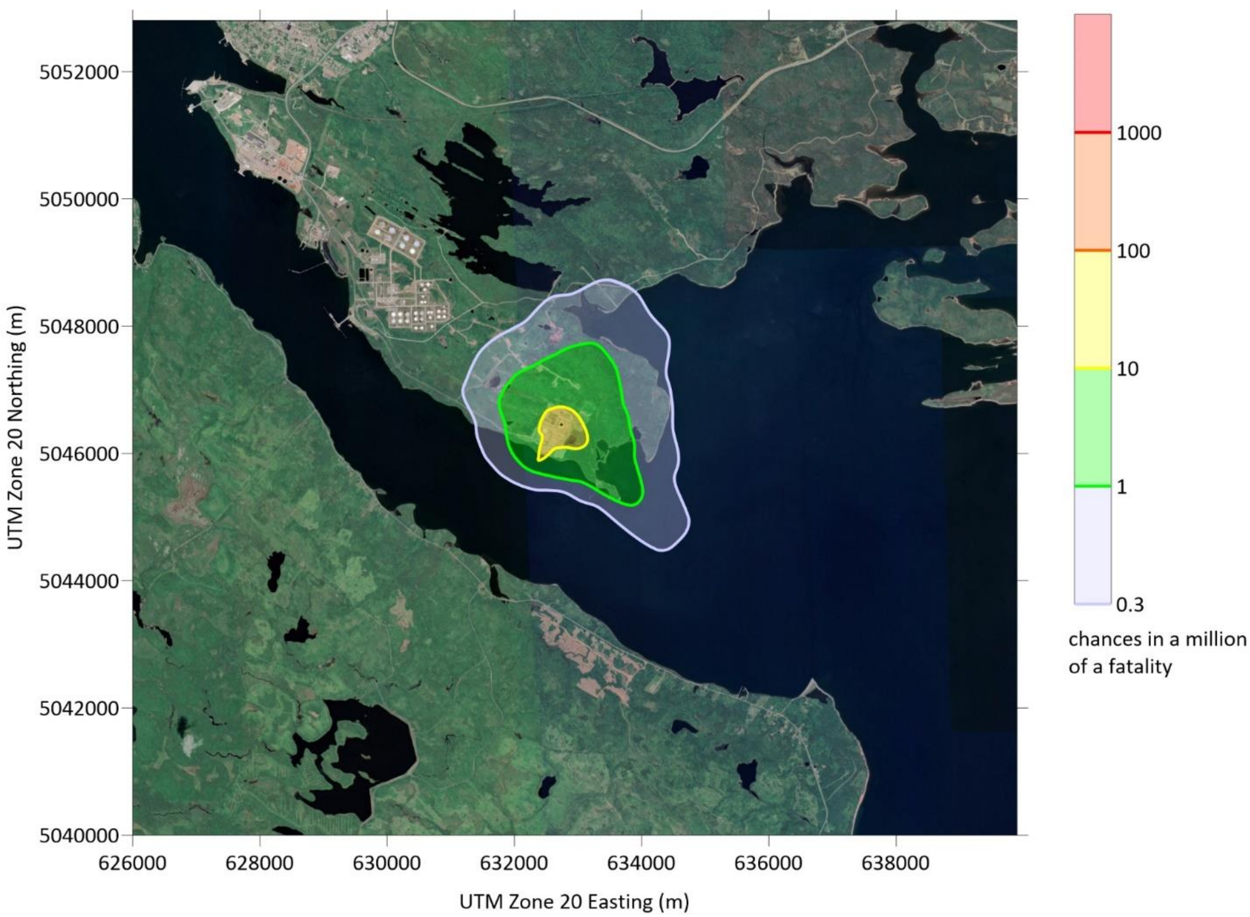
## 5.2 QUANTITATIVE RISK ASSESSMENT RESULTS

The total estimated individual risk from the facility is shown in Figure 5-5. The risk calculation includes:

- The consequence modelling results summarized in Section 4.4 and Appendix C for the release scenarios summarized in Table 4-1,
- The failure probabilities for the various Facility assets as provided in Table 5-2, and
- The meteorological frequencies for the Project location summarized in Table 5-3

The risk contour intervals shown in Figure 5-5 align with the Individual Risk Exposure Guidelines recommended by the Canadian Society for Chemical Engineering ICSChE). The most stringent guideline level recommended by the CSChE is 0.3 chances in a million of a fatality. This guideline level represents an acceptable level of risk for vulnerable populations, such as schools, day care centres, hospitals, and long-term care facilities. There are no residences or other sensitive receptors within the 0.3 chances in a million contour. The risk contours therefore indicate that the public safety risk from the project is low and that, from a public safety perspective, the facility is appropriately sited relative to adjacent land uses.

**Figure 5-5 Predicted Individual Fatality Risk Contours of all Release Scenarios for the Project**



# 6.0 MODELLING SENSITIVITY AND UNCERTAINTY

Uncertainty associated with risk assessment predictions could stem from the following areas:

- Uncertainty in emissions estimation and due to preliminary engineering data
- Uncertainty in consequence modeling (including limitations of the model physics and formulations and meteorology); and,
- Uncertainty with failure frequency data.

Facility releases were estimated using a model which has been validated against measured data from several actual releases of different fluids, pipeline configurations and pressures. The model has validated well versus these data. In the release modeling the obstruction drag coefficient was varied and the consequences for the worst case were presented. For the risk modelling, the consequences resulting from each release scenario were considered in the assessment. Thus, the modeling is expected to capture the range of release scenarios that would produce conservative estimates of downwind extents to the selected consequence criteria.

Dispersion modeling was conducted using the publicly available dispersion model, SLAB, which has also undergone considerable validation and been shown to perform well versus actual measurement data. Therefore, the uncertainty associated with the consequence modeling is expected to be low.

The thermal radiation consequence modelling was completed using established algorithms and for the fluids considered and operating conditions the uncertainty in these predictions is expected to be low.

The failure frequency data was obtained from the UK HSE Failure Rates and Event Data, which are recommend for use for new facilities.

Overall, the consequence and risk assessment analysis provided in this report are expected to provide reasonable and conservative estimates of the actual hazard extents and risk levels associated with facility operations.

# 7.0 CONCLUSIONS

Source characterization and consequence modelling were completed to estimate the consequence extents and public safety risk for a production, storage, and loading facility located in the Point Tupper Industrial Park in Richmond County, Nova Scotia. The source modelling considered time varying releases from pressurized storage. Consequence modelling considered the impacts of hazardous events including flash fires, vapour cloud explosions, jet fires, vessel and container explosions, and toxic vapour releases.

The potential loss of containment scenarios were developed through a review of the processes associated with the facility and in discussions held with the BHE Project Team. Assumptions made to complete the assessment are covered throughout the report. The assessments were made on preliminary engineering information. This information will be refined during detailed design

The primary hazards identified were the toxic inhalation hazards associated with ammonia. There were also flammability hazards associated with hydrogen and ammonia. The flammable hazard events considered included flash fires, jet fires, pool fires, storage vessel explosions, enclosure explosions, and vapor cloud explosions. Release scenarios included catastrophic ruptures (less likely) and leaks (more likely).

Dispersion and thermal radiation consequence modeling were conducted over a range of weather conditions, obstruction drag assumptions, and release scenarios. Liquid pool spill releases of ammonia lead to the farthest maximum extents due to the toxic inhalation hazard of ammonia as it vapourizes into the atmosphere.

Risk calculations were performed to evaluate the potential for harm associated with facility operations with consideration of both the potential consequences and their likelihood of occurrence.

Individual risk of fatality is estimated to be low when compared to best available guidelines from the Canadian Society for Chemical Engineering, and the facility appears to be properly situated near adjacent land uses.

# 8.0 CLOSURE

This report has been prepared for the sole benefit of Bear Head Energy and their representatives. The report may not be used or relied upon by any other person or entity without the express written consent of Stantec and Bear Head Energy.

Any use which a third party makes of this report, or any reliance on decisions made based on it, is the responsibilities of such third parties. Stantec accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

Should additional information become available which differs significantly from our understanding of conditions presented in this report, we request that this information be brought to our attention so that we may reassess the conclusions provided herein.

# 9.0 REFERENCES

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# Appendix A PRELIMINARY PROCESS OPERATING CONDITIONS USED FOR QRA INPUTS

The following process operating conditions were used as input into the Quantitative Risk Assessment for the Facility. These conditions represent the best available information at the time of the assessment. These conditions may change during detailed design of the Facility.

**Table A-9-1 Operating Conditions for Hydrogen Production Process between Electrolyzers and Reactor**

| Operating Parameter | Unit of Measurement | Value (per train) |
|---|---|---|
| Hydrogen Flow Rate | Tonnes per day | 480 |
| Fluid Pressure | Bar (g) | 5 |
| Fluid Temperature | °C | Ambient temperature |
| Pipe Diameter (Individual Electrolyzer) | Inches | 3 |
| Pipe Diameter (Electrolyzer Header) | Inches | 10 |

**Table A-9-2 Operating Conditions for Hydrogen and Nitrogen Supply Process to Reactor**

| Operating Parameter | Unit of Measurement | Value (per train) |
|---|---|---|
| Nitrogen Flow Rate (from ASUs) | Tonnes per day | 2,271 |
| Nitrogen Flow Rate (from Recycle Stream) | Tonnes per day | 1,110 |
| Hydrogen Flow Rate (from Electrolyzers) | Tonnes per day | 480 |
| Hydrogen Flow Rate (from Recycle Stream) | Tonnes per day | 240 |
| Fluid Pressure | Bar (g) | 140 |
| Fluid Temperature | °C | 300 |
| Pipe Diameter | Inches | 24 |

**Table A-9-3 Operating Conditions for Ammonia Reactor Outlet Process**

| Operating Parameter | Unit of Measurement | Value (per train) |
|---|---|---|
| Nitrogen Flow Rate | Tonnes per day | 1,110 |
| Hydrogen Flow Rate | Tonnes per day | 240 |
| Ammonia Flow Rate | Tonnes per day | 2,720 |
| Fluid Pressure | Bar (g) | 3.45 |
| Fluid Temperature | °C | 450 |
| Pipe Diameter | Inches | 24 |

**Table A-9-4 Operating Conditions for Gas Recycle Stream between Ammonia Condenser and Reactor**

| Operating Parameter | Unit of Measurement | Value (per train) |
|---|---|---|
| Nitrogen Flow Rate | Tonnes per day | 1,110 |
| Hydrogen Flow Rate | Tonnes per day | 240 |
| Fluid Pressure | Bar (g) | 3.45 |
| Fluid Temperature | °C | -34 |

| | | |
|---|---|---|
| Pipe Diameter | Inches | 12 |

**Table A-9-5 Operating Conditions between Ammonia Condenser and Ammonia Storage**

| Operating Parameter | Unit of Measurement | Value (per train) |
|---|---|---|
| Ammonia Flow Rate | Tonnes per day | 2,720 |
| Fluid Pressure | Bar (g) | Ambient Pressure |
| Fluid Temperature | °C | -34 |
| Pipe Diameter | Inches | 6 |

**Table A-9-6 Ammonia Storage Vessel Operating Conditions**

| Operating Parameter | Unit of Measurement | Value (per train) |
|---|---|---|
| Ammonia Storage Capacity | Cubic metres | 124,000 |
| Storage Pressure | Bar (g) | Ambient Pressure |
| Storage Temperature | °C | -34 |
| Vessel Diameter | Metres | 80 |
| Vessel Height | Metres | 24.7 |
| Containment Berm Radius | Metres | 176 |

**Table A-9-7 Operating Conditions for Marine Export Pipeline**

| Operating Parameter | Unit of Measurement | Value (per train) |
|---|---|---|
| Ammonia Flow Rate | Cubic Metres per Hour | 6,667 |
| Fluid Pressure | Bar (g) | Ambient Pressure |
| Fluid Temperature | °C | -34 |
| Pipe Diameter | Inches | 24 |

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# Appendix B TIME-VARYING SOURCE CHARACTERIZATION RESULTS

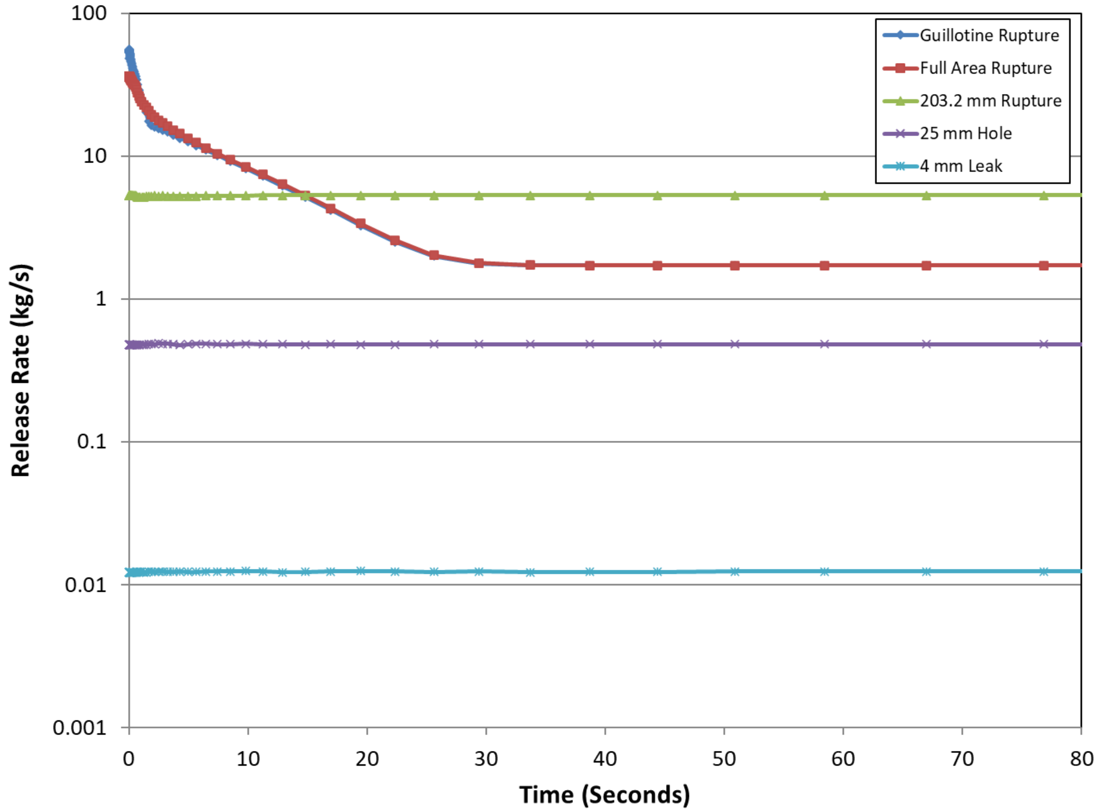


**Figure B-1** **Release Rate Time Series for Hydrogen between the Electrolyzers and the Reactor for Different Release Sizes**

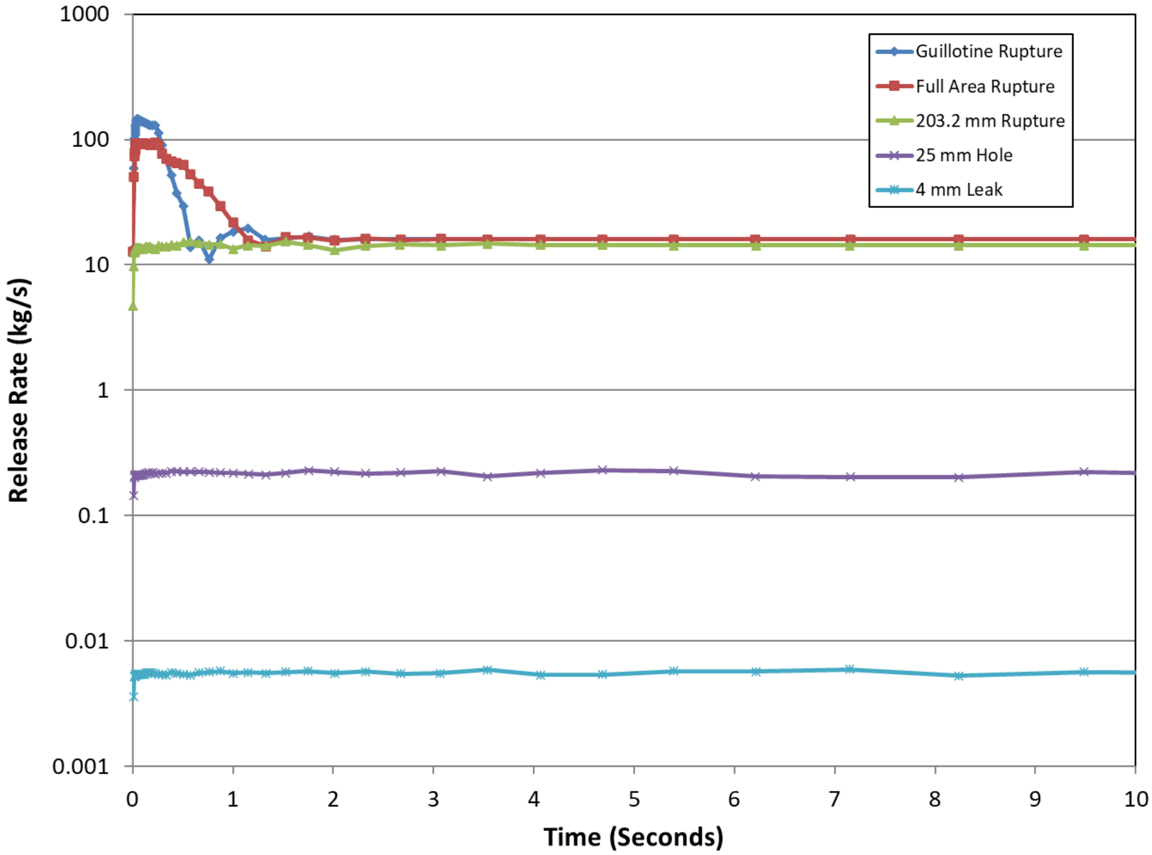


**Figure B-2** **Release Rate Time Series for Process Gas from the Reactor for Different Release Sizes**

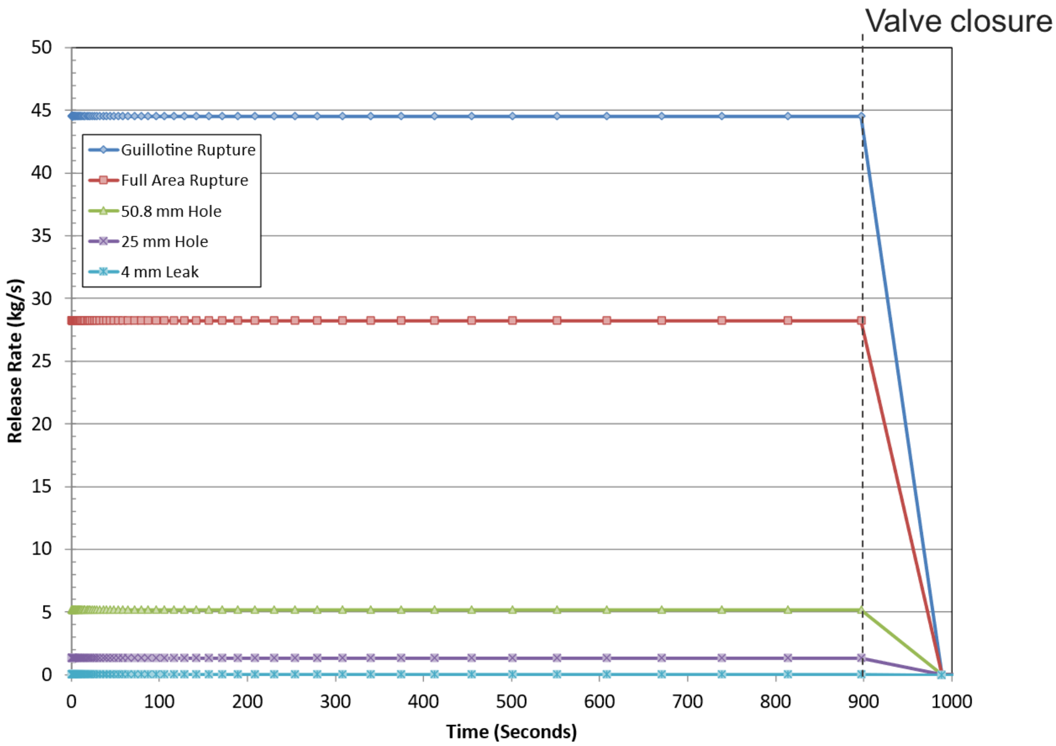


**Figure B-3** **Release Rate Time Series for Liquid Ammonia between Process Cooler and Ammonia Storage Tank**

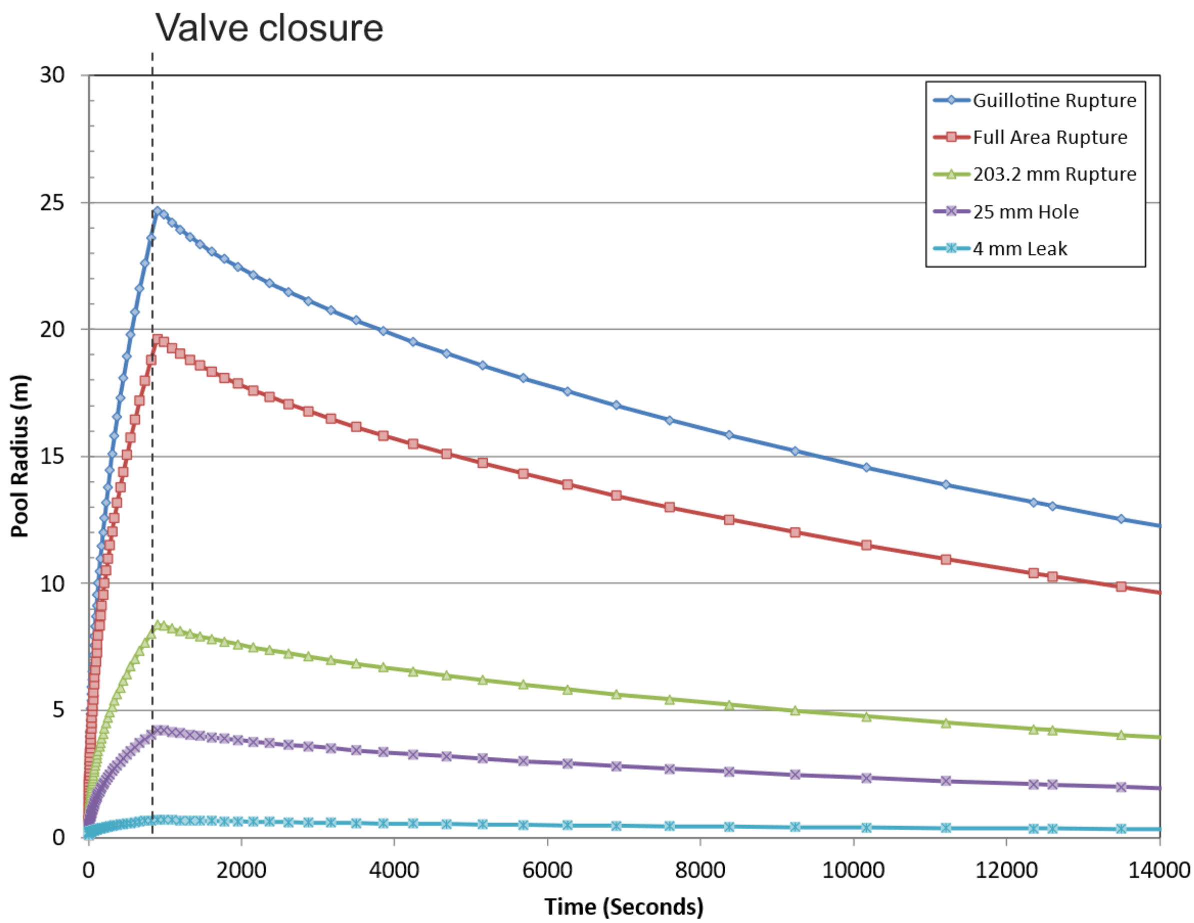


**Figure B-4 Pool Radius Time Series for Liquid Ammonia Spill from Pipe between Process Cooler and Ammonia Storage Tank**

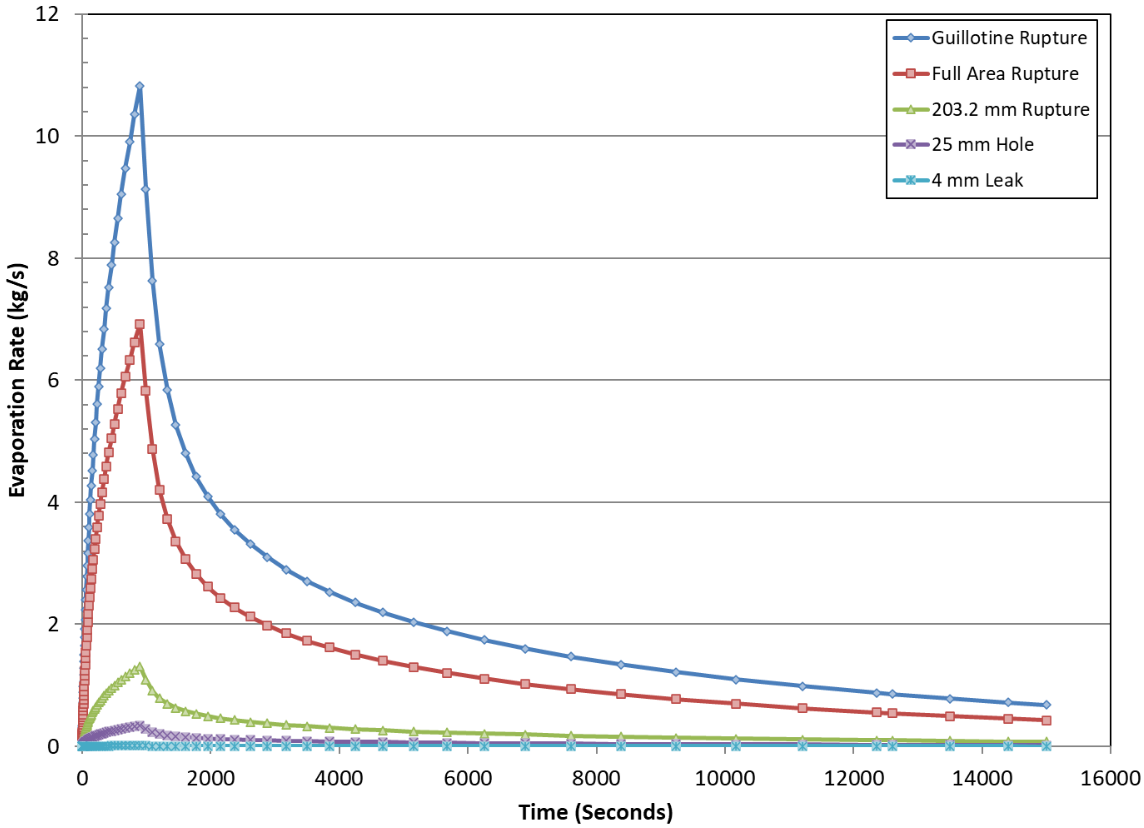


**Figure B-5** **Evaporation Rate from Ammonia Pool during Ammonia Release from Ammonia Separation Piping**

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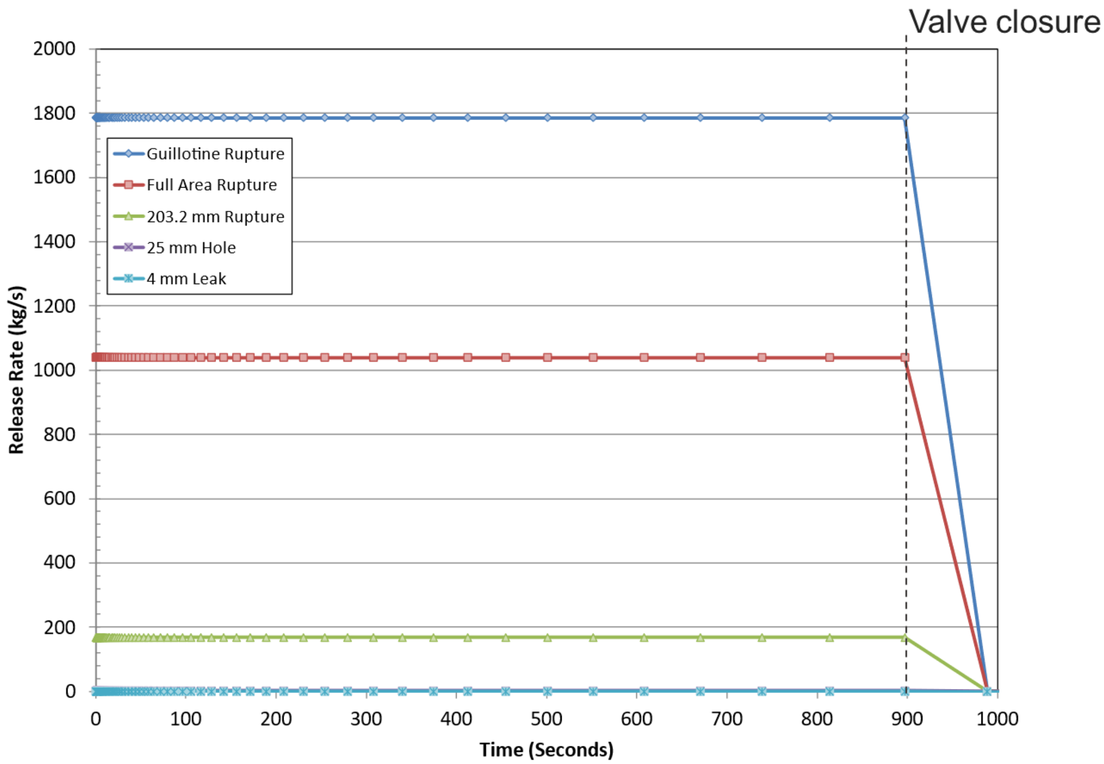


**Figure B-6** **Release Rate Time Series for Liquid Ammonia between Ammonia Storage Tank and Marine Terminal**

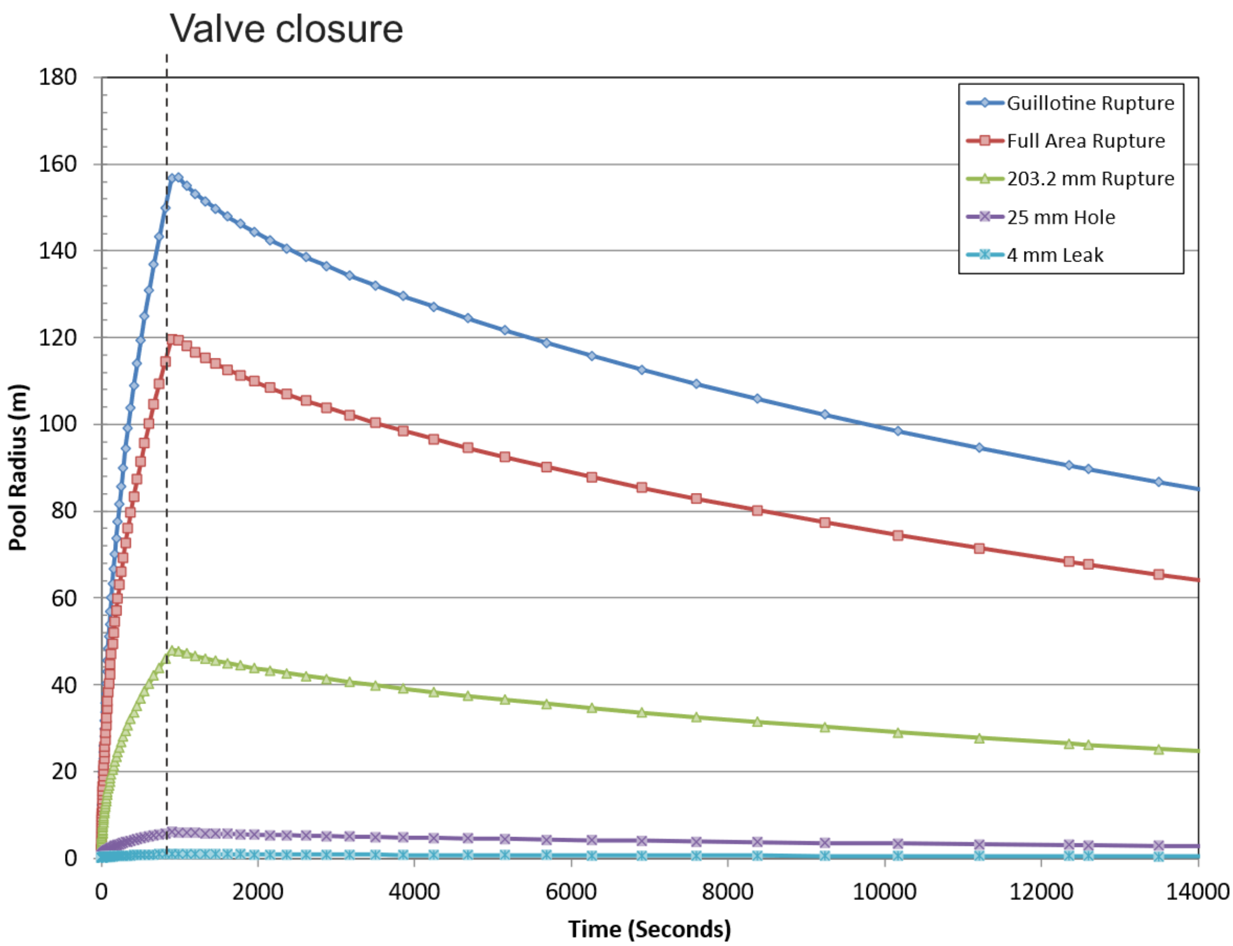


**Figure B-7** **Pool Radius Time Series for Liquid Ammonia Spill from Pipe between Ammonia Storage Tank and Marine Terminal**

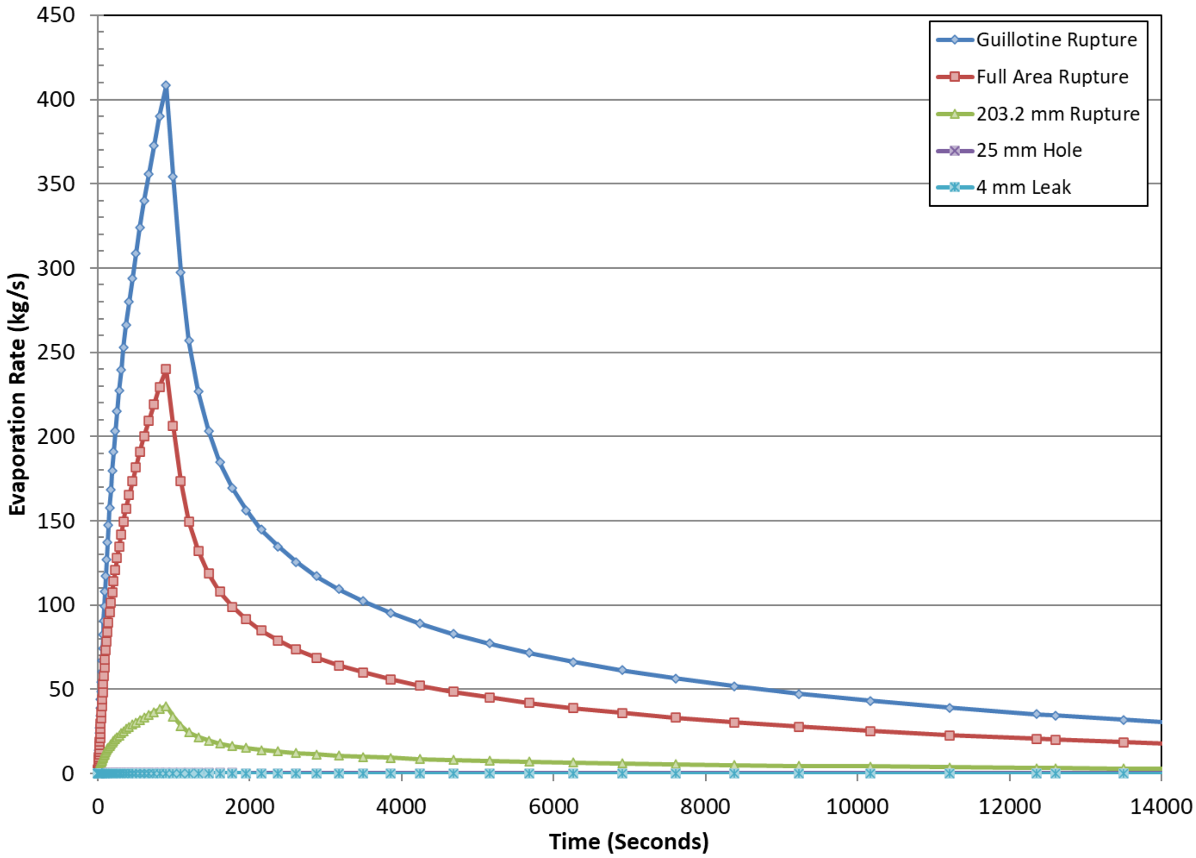


**Figure B-8** **Evaporation Rate from Ammonia Pool during Ammonia Release from Marine Terminal Piping**

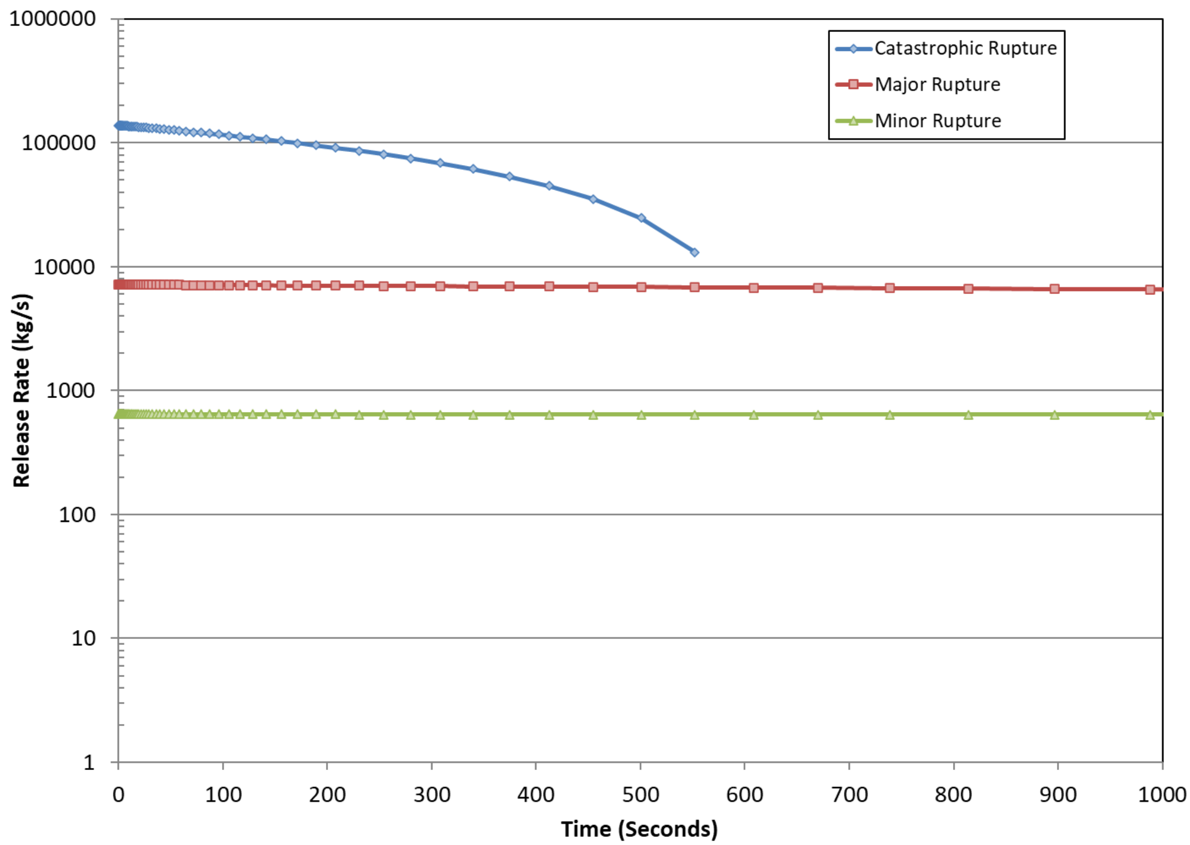


**Figure B-9 Mass Release Rates for Liquid Ammonia Spills from the Ammonia Storage Tanks**

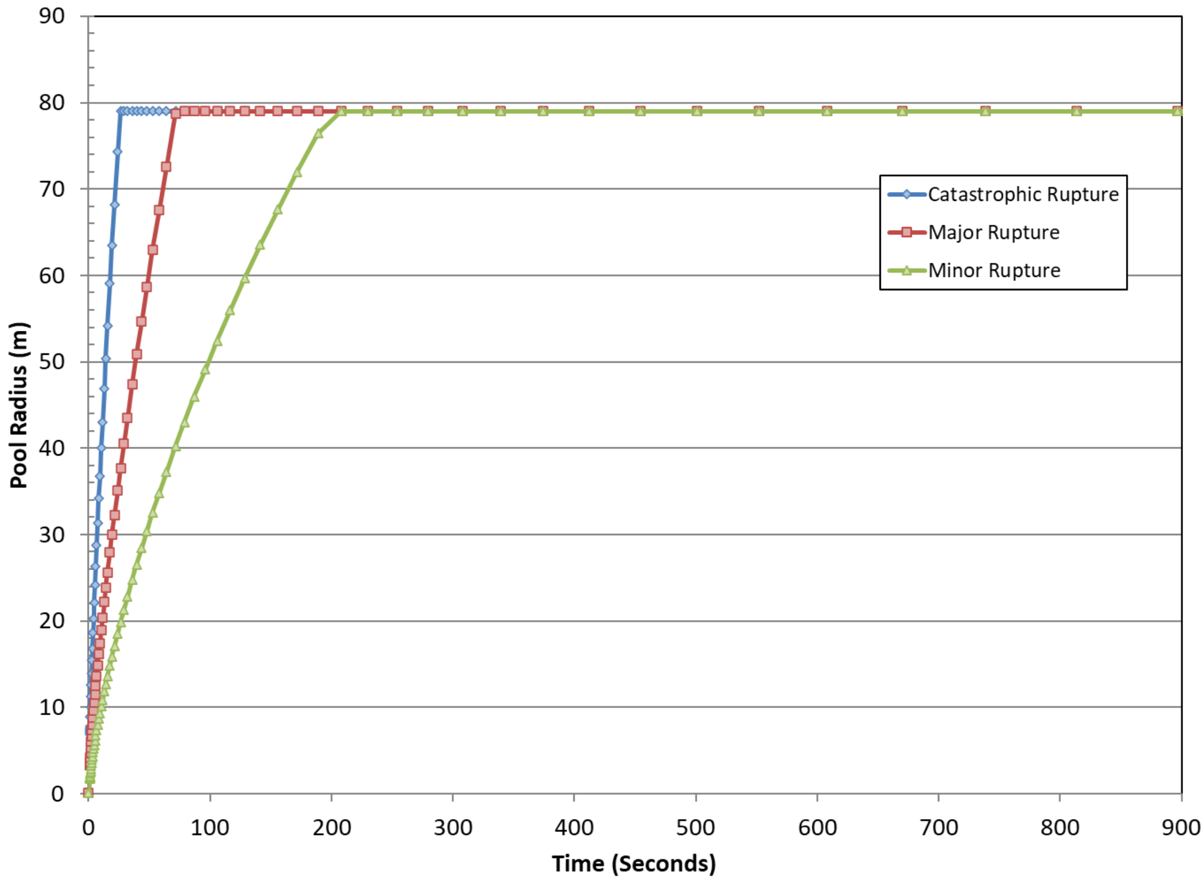


**Figure B-10 Time Series of Ammonia Pool Spill Radius for Ammonia Storage Tank Releases**

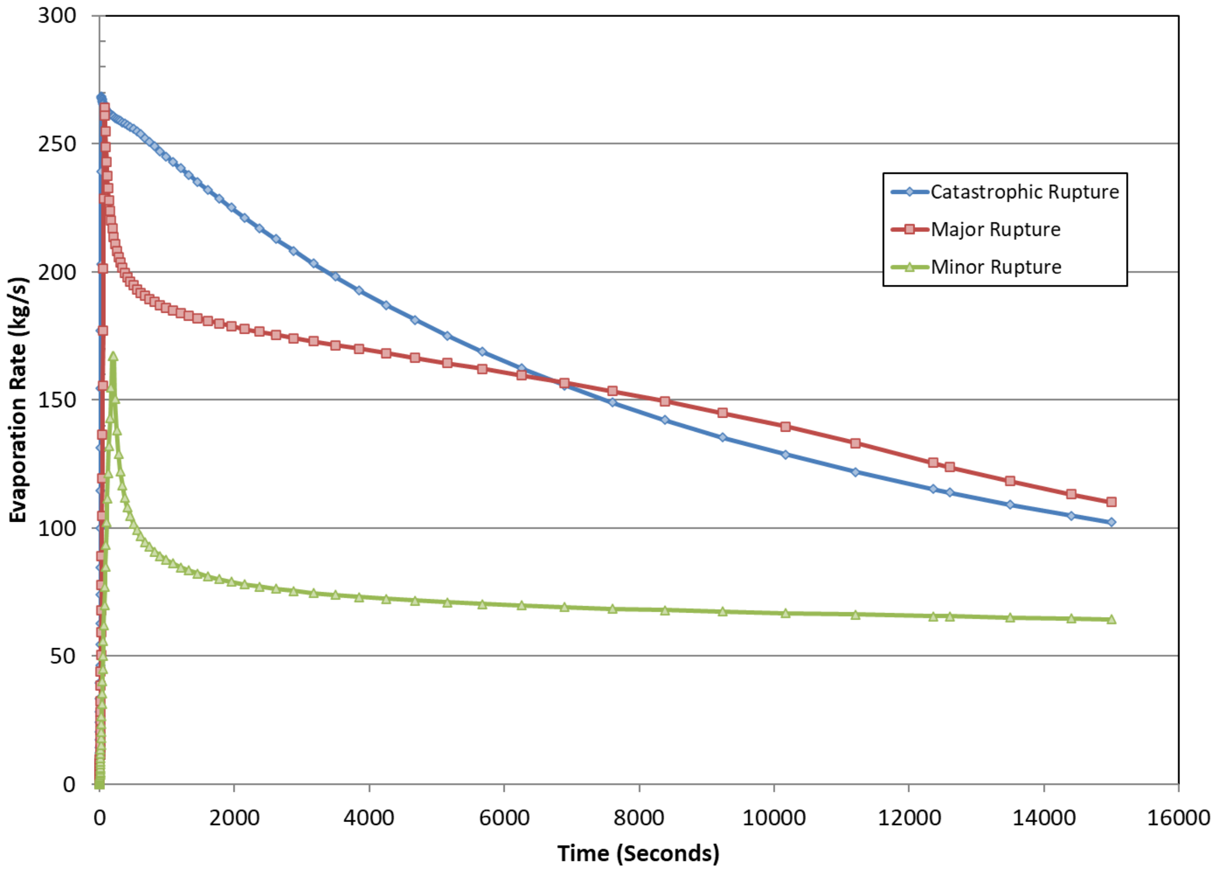


**Figure B-11 Evaporation Rate from Ammonia Pool during an Ammonia Release from a Storage Tank**

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# Appendix C CONSEQUENCE RESULTS TABLES

**Table C-1 Maximum Downwind Extent to LFL for Gas Stream Release Scenarios**

| Process | Description | Maximum Downwind Extent (m) by Meteorological Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **A1.5** | **B2** | **C2** | **C4** | **D2** | **D5** | **D10** | **E3** | **E5** | **F1.5** | **F3** |
| Low-Pressure Hydrogen Piping | Piping from Electrolyzer to Header | 57 | 59 | 59 | 81 | 59 | 97 | **211** | 62 | 69 | 58 | 64 |
| | Piping from Header to Reactor Compressor | 58 | 61 | 61 | 81 | 59 | 96 | **218** | 64 | 71 | 59 | 67 |
| High Pressure Mixed Gas Stream | Reactor Inlet Piping | 64 | 67 | 67 | 76 | 67 | 78 | **93** | 68 | 74 | 64 | 71 |
| | Recycle Stream | 38 | 41 | 41 | 59 | 38 | **78** | 67 | 37 | 41 | 36 | 37 |

**Table C-2 Maximum Downwind Extent to LFL/2 for Gas Stream Release Scenarios**

| Process | Description | Maximum Downwind Extent (m) by Meteorological Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **A1.5** | **B2** | **C2** | **C4** | **D2** | **D5** | **D10** | **E3** | **E5** | **F1.5** | **F3** |
| Low-Pressure Hydrogen Piping | Piping from Electrolyser to Header | 63 | 66 | 69 | 142 | 64 | 204 | **314** | 77 | 122 | 64 | 72 |
| | Piping from Header to Reactor Compressor | 63 | 66 | 69 | 143 | 66 | 204 | **322** | 77 | 122 | 66 | 73 |
| High Pressure Mixed Gas Stream | Reactor Inlet Piping | 88 | 92 | 93 | 102 | 92 | 108 | **134** | 96 | 106 | 93 | 102 |
| | Recycle Stream | 52 | 53 | 58 | 98 | 59 | **136** | 106 | 61 | 71 | 57 | 63 |

**Table C-3 Maximum Downwind Extent to AEGL-2 for Gas Stream Release Scenarios**

| Process | Description | Maximum Downwind Extent (m) by Meteorological Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **A1.5** | **B2** | **C2** | **C4** | **D2** | **D5** | **D10** | **E3** | **E5** | **F1.5** | **F3** |
| Mixed Outlet Stream | Piping between Reactor and Waste Heat Boiler | 91 | 96 | 95 | 121 | 93 | 126 | **545** | 104 | 120 | 95 | 107 |
| | Piping between Waste Heat Boiler and Cooler | 123 | 129 | 123 | 179 | 121 | 337 | **529** | 146 | 154 | 120 | 137 |

**Table C-4 Maximum Downwind Extent to AEGL-3 for Gas Stream Release Scenarios**

| Process | Description | Maximum Downwind Extent (m) by Meteorological Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **A1.5** | **B2** | **C2** | **C4** | **D2** | **D5** | **D10** | **E3** | **E5** | **F1.5** | **F3** |
| Mixed Outlet Stream | Piping between Reactor and Waste Heat Boiler | 70 | 73 | 73 | 87 | 73 | 90 | **182** | 77 | 85 | 71 | 79 |
| | Piping between Waste Heat Boiler and Cooler | 91 | 95 | 95 | 115 | 93 | 132 | **177** | 99 | 112 | 91 | 102 |

**Table C-5 Maximum Extent to Thermal Radiation Hazard Extents for Hydrogen and Ammonia Production**

| **Process** | **Description** | **Maximum Downwind Extent (m)** | |
|---|---|---|---|
| | | **5 kW/m$^2$** | **342 (kW/m$^2$)$^{4/3}$ s (TDU)** |
| Low-Pressure Hydrogen Piping | Piping from Electrolyzer to Header | 70 | 0 |
| | Piping from Header to Reactor Compressor | 210 | 30 |
| High Pressure Mixed Gas Stream | Reactor Inlet Piping | 270 | 20 |
| Mixed Outlet Stream | Piping between Reactor and Waste Heat Boiler | 40 | 0 |
| | Piping between Waste Heat Boiler and Cooler | 30 | 0 |
| Reactor Outlet Recycle | Recycle Stream | 80 | 10 |

**Table C-6 Maximum Downwind Extent to AEGL-2 for Liquid Ammonia Pool Spills from Ammonia Separation Process**

| **Process** | **Description** | **Maximum Downwind Extent (m) by Meteorological Condition** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **A1.5** | **B2** | **C2** | **C4** | **D2** | **D5** | **D10** | **E3** | **E5** | **F1.5** | **F3** |
| Ammonia Separation | Piping between cooler and ammonia storage tank | 313 | 406 | 688 | 501 | 1,290 | 859 | 631 | 2,301 | 1,829 | 3,494 | **4,405** |

**Table C-7 Maximum Downwind Extent to AEGL-3 for Liquid Ammonia Pool Spills from Ammonia Separation Process**

| Process | Description | Maximum Downwind Extent (m) by Meteorological Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A1.5 | B2 | C2 | C4 | D2 | D5 | D10 | E3 | E5 | F1.5 | F3 |
| Ammonia Separation | Piping between cooler and ammonia storage tank | 102 | 131 | 222 | 156 | 408 | 267 | 192 | 679 | 543 | 936 | **1,198** |

**Table C-8 Maximum Extent to Thermal Radiation Hazard Extents for releases from the Ammonia Separation Process**

| Process | Description | Maximum Downwind Extent (m) | |
|---|---|---|---|
| | | 5 kW/m$^2$ | 342 (kW/m$^2$)$^{4/3}$ s (TDU) |
| Ammonia piping | Piping between cooler and ammonia storage tank | 40 | 10 |

**Table C-9 Maximum Downwind Extent to AEGL-2 for Liquid Ammonia Pool Spills from the Ammonia Export Pipe**

| Process | Description | Maximum Downwind Extent (m) by Meteorological Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A1.5 | B2 | C2 | C4 | D2 | D5 | D10 | E3 | E5 | F1.5 | F3 |
| Ammonia Separation | Piping between cooler and ammonia storage tank | 1,662 | 2,451 | 4,086 | 3,817 | 7,168 | 7,126 | 5,056 | 15,501 | 17,766 | 6,049 | **> 20,000** |

**Table C-10 Maximum Downwind Extent to AEGL-3 for Liquid Ammonia Pool Spills from the Ammonia Export Pipe**

| Process | Description | Maximum Downwind Extent (m) by Meteorological Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A1.5 | B2 | C2 | C4 | D2 | D5 | D10 | E3 | E5 | F1.5 | F3 |
| Ammonia Separation | Piping between cooler and ammonia storage tank | 553 | 711 | 1,184 | 1,108 | 2,026 | 2,022 | 1,418 | 4,082 | 4,673 | 1,572 | **8,263** |

**Table C-11 Maximum Extent to Thermal Radiation Hazard Extents for releases from the Ammonia Export Pipe**

| Process | Description | Maximum Downwind Extent (m) | |
|---|---|---|---|
| | | **5 kW/m$^2$** | **342 (kW/m$^2$)$^{4/3}$ s (TDU)** |
| Ammonia piping | Piping between storage tank and marine terminal | 250 | 90 |

The downwind extent to the selected ammonia criteria was found to be sensitive to the vapourization rate and weather condition. The trajectory of the ammonia plume will change as it mixes with air. Initially the plume contains mostly ammonia and so is less dense than ambient air and therefore tends to rise. The trajectory changes as more air mixes with the plume, and eventually the plume will travel parallel with the ground. The time it takes for the ammonia plume to stop rising is related to the vapourization rate. If the vapourization rate is sufficiently low and the atmospheric turbulence – which is governed mostly by the wind speed and the atmospheric stability – are sufficiently high, it is possible for the plume to stay close to ground level during the whole release. Higher vapourization rates will require more mixing with ambient air before the plume stops rising and flows with the wind. As a result, higher vapourization rates can require higher wind speeds and less stable atmospheres – in other words, conditions that lead to more turbulence – to keep the plume close to ground level. It is this sensitivity that leads to the smaller release scenario having farther downwind extents for lower wind speeds and more stable atmospheres, when compared to the same meteorological conditions for the larger release sizes.

**Table C-12 Maximum Downwind Extent to AEGL-2 for Liquid Ammonia Pool Spills from the Storage Tank**

| Process | Description | Maximum Downwind Extent (m) by Meteorological Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **A1.5** | **B2** | **C2** | **C4** | **D2** | **D5** | **D10** | **E3** | **E5** | **F1.5** | **F3** |
| Ammonia Storage Tank | Catastrophic Failure | 1,410 | 2,330 | 2,980 | 3,870 | 270 | 7,810 | 6,730 | 330 | **19,310** | 230 | 390 |
| | Large Release | 1,400 | 2,340 | 1,910 | 3,440 | 270 | 6,810 | 5,520 | 370 | **17,000** | 260 | 360 |
| | Small Release | 1,200 | 1,660 | 2,880 | 2,290 | 5,360 | 4,210 | 3,160 | 11,550 | 10,130 | 230 | **20,000** |

**Table C-13 Maximum Downwind Extent to AEGL-3 for Liquid Ammonia Pool Spills from the Storage Tank**

| Process | Description | Maximum Downwind Extent (m) by Meteorological Condition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A1.5 | B2 | C2 | C4 | D2 | D5 | D10 | E3 | E5 | F1.5 | F3 |
| Ammonia Storage Tank | Catastrophic Failure | 420 | 700 | 350 | 1,200 | 180 | 2,320 | 2,020 | 260 | **5,160** | 210 | 300 |
| | Large Release | 420 | 720 | 260 | 1,070 | 180 | 2,030 | 1,660 | 240 | **4,560** | 210 | 300 |
| | Small Release | 380 | 510 | 900 | 700 | 1,580 | 1,250 | 930 | 3,110 | 2,790 | 210 | **6,210** |